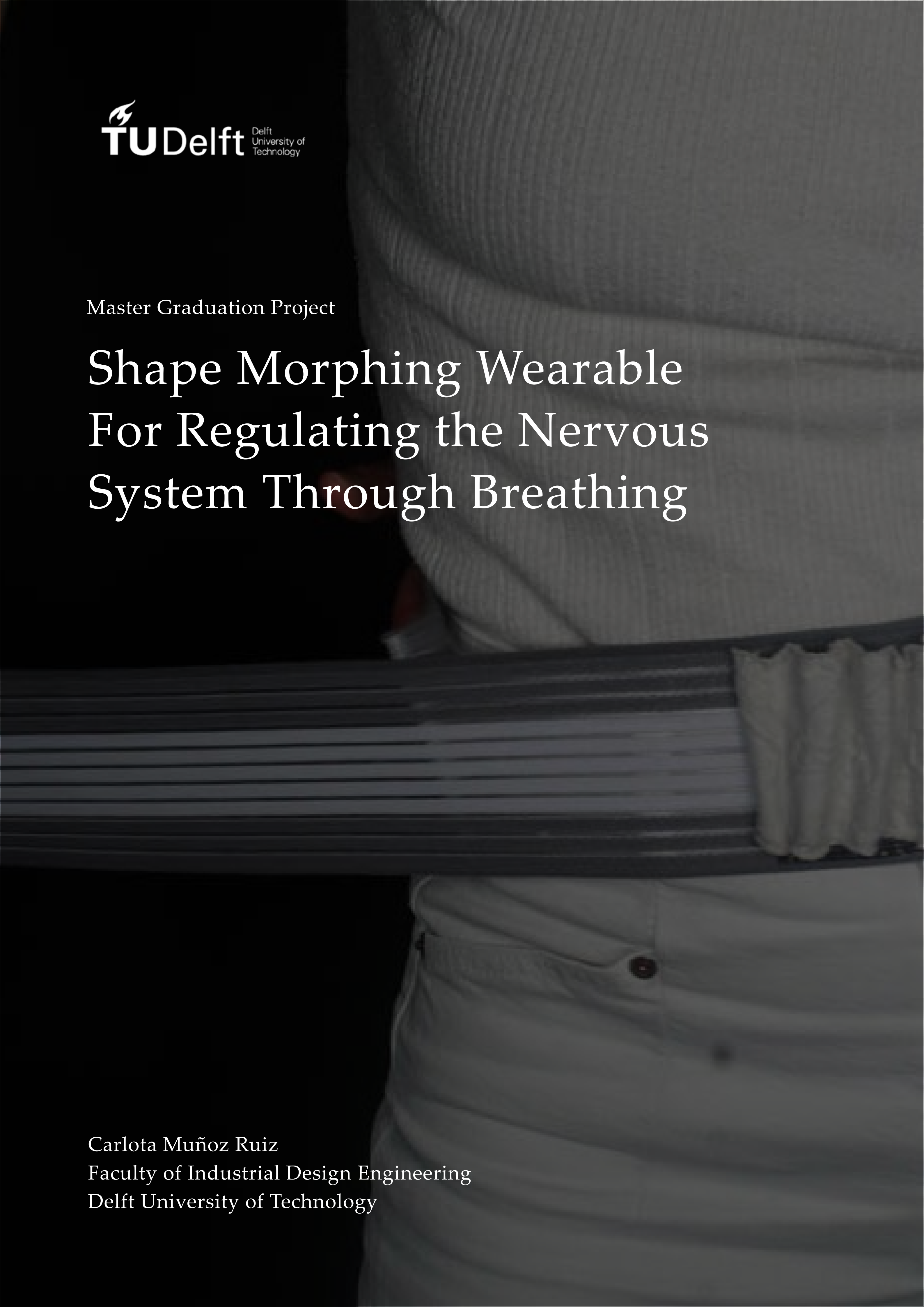

Master Graduation Project

Shape Morphing Wearable For Regulating the Nervous System Through Breathing

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Link to showcase video
https://youtu.be/8eJOR7VQzww

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This graduation project significantly expanded my knowledge and skills in the exploration of smart materials, textile design, mental health, and electronics, particularly through hands-on laboratory work. I extend my deepest gratitude to my supervisors, Sepideh and Stefano, who not only shared their expertise in an enthusiastic and constructive manner but also believed in my abilities and encouraged me to develop this complex and intriguing project. Thanks to them, we created a positive and enriching working environment, filled with creative ideas and continuous improvement. Their critical and wise guidance, combined with their positivity, was essential in helping me navigate challenges throughout the process. Thank you for this opportunity; you did an outstanding job, and I hope we remain in touch.

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Executive Summary

This project addresses the gap in current stress-regulation treatments by developing a smart textile wearable that integrates shape-morphing materials and body monitoring sensors to regulate the nervous system through conscious breathing. Anxiety, recognized as the leading chronic stress-related disorder globally by the World Health Organization, often remains inadequately treated due to the lack of advanced mental health solutions –which fail to integrate into daily life, resulting in underutilization and insufficient awareness. Consequently, existing solutions are either focused solely on body monitoring or haptic feedback, typically involving bulky and noisy electromechanical systems. This project aims to bridge this gap by combining both elements into a discreet, non-intrusive abdominal wearable, designed for everyday use to enhance individual awareness of anxious conditions and facilitate self-management.

By utilizing Shape Memory Alloys (SMAs) for their advantageous power-to-weight ratio and ease of integration into textiles, this project explores their potential to simulate diaphragmatic breathing rhythms, aiding users in managing anxiety. Guided by the Material Driven Design (MDD) methodology, the project synthesizes theoretical and empirical research to develop a wearable prototype that accurately replicates breathing rhythms through SMA, monitors heart rate, and ensures user comfort and a soothing experience. Experimental studies with 0.5mm NiTiCu SMAs in zigzag configurations demonstrate the feasibility of reducing response time and controlling expansion movements at a high deformation strain, enhancing the simulation of breathing rhythms. A new SMA re-training method was identified, which conserves time, effort, and energy without necessitating high temperatures above 500ºC.

User studies indicate a strong preference for active engagement in haptic breathing guidance, which enhances focus and personal connection to the device. The wearable's slow, organic expansion-contraction movements on the abdomen closely mimic natural diaphragmatic breathing, facilitating synchronization and promoting a sense of calm. The prototype's dual association with medical and personal contexts, combined with its portability, supports versatile use across different settings and postures, thereby contributing to a positive user experience. The findings demonstrate the device's efficacy in heightening user awareness and managing high stress, presenting a promising solution for health applications.

This project provides significant insights into the integration of SMAs and smart textiles for mental health applications, presenting a noiseless, lightweight, discreet, and non-invasive solution.

Keywords: Shape Morphing Materials, Shape Memory Alloys, Smart Textiles, Nervous System Regulation, Anxiety Relief, Wearable Devices, Haptic Feedback, Health Applications.

Glossary

Abbreviations:

SME: Shape Memory Effect

SMA: Shape Memory Alloys

As - Af: Austenite start - finish temperature

Ms - Mf: Martensite start - finish temperature

NiTi SMA: Nitinol Shape Memory Alloy

NiTiCu: Nickelw-Titanium-Copper

MDD: Material Driven Design

Definitions:

Anxiety: A feeling of worry, nervousness, or unease about something with an uncertain future outcome, often accompanied by physical symptoms such as increased heart rate and sweating.

Chronic-Stress: A state of prolonged tension from internal or external stressors, which may cause various physical and psychological symptoms and negatively impact health.

Self-Awareness: Conscious knowledge of one's own character, feelings, motives, and desires, enabling an individual to understand their own emotional responses and behavior.

Self-Management: The ability to control one's own behavior, emotions, and thoughts, especially in challenging situations, and to achieve personal goals.

Haptic Perception: The ability to understand and identify objects through the sense of touch, which involves the perception of texture, shape, temperature, and other physical properties.

Conscious Breathing: Deep diaphragmatic slow breathing aimed at promoting relaxation and reducing stress by focusing on the breath.

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Introduction

Project Introduction

PROBLEM DEFINITION

The World Health Organization (2024) reports that anxiety disorders, the most prevalent mental health issues, impact about 4% of the global population, yet only a quarter of those affected receive treatment. This is primarily due to limited awareness of anxiety as a treatable condition and a lack of advanced mental health solutions. Current treatments focus on acute anxiety episodes –panic attacks– using medication or therapy. Some individuals use external devices or apps for self-regulation through body signal monitoring or guided relaxation exercises. However, these solutions are not integrated into daily life for self-practice and early anxiety prevention, leading to underutilization and a lack of awareness. Experts indicate that anxiety often arises from unaddressed, accumulated stress: "Individuals with anxiety need reliable methods to ground themselves and regain control, whether through therapy, technological aids, or mindfulness practices like meditation". Solutions do not effectively combine both technologies—such as body signal sensors or advanced materials—and relaxation techniques like 'Conscious Breathing' in a positive and comfortable experience. Despite its effectiveness for the nervous system, 'conscious breathing' is not commonly utilized in medical devices. Slow, deep diaphragmatic breathing, when practiced daily, offers numerous health benefits, including improved blood oxygenation, circulation, and brain function, enhancing wellness, emotion regulation, and self-management of stress-related disorders.

There is significant potential to enhance treatments by integrating shape-morphing materials (SMM), such as shape memory alloys (SMA), with body monitoring technology in wearables. SMM are smart materials that change shape in response to external stimuli, such as heat. By integrating SMA into textiles, the device becomes versatile, portable, and flexible, providing inherent soothing and comfort qualities suitable for everyday use. The project aims to create a smart textile wearable for the abdomen that monitors heart rate to detect anxiety and activates 'conscious breathing' techniques through SMA. SMA actuators will mimic the breathing rhythm through haptics (expansion and contraction), encouraging users to synchronize with the rhythm. Conductive threads will connect the SMA-textile mechanism with electronic components and discreetly. This smart wearable will help non-clinical individuals manage daily anxiety, enhancing their awareness and self-management through soothing experiences.

PROJECT SCOPE

The goal is to enhance anxiety awareness and self-management through 'conscious breathing' techniques by combining shape-morphing textiles with body monitoring sensors in a comfortable wearable. This project targets non-clinical individuals seeking discreet stress-relief solutions for self-practice to prevent anxiety episodes in daily life. It introduces a novel method to guide 'conscious breathing' rhythms through haptics, offering a noiseless, organic, non-intrusive, and portable solution.

The project will result in a prototype that, first, accurately replicates the breathing rhythm system using SMA actuators and haptics while tracking the user's heart rate via sensors. This involves three elements: active elements (SMA actuators), passive elements (textile), and controlled elements (sensors). And, second, integrates into knitwear to provide a comfortable and soothing user experience.

To achieve this, extensive research is required in areas such as anxiety and nervous system regulation, the integration of electronics into textiles, shape-morphing materials (especially SMA), and smart wearable-user interaction. The design process is mainly inspired by the Materials Driven Design Method, focusing on the technical characterization of temporal behavior and experiential characterization through user studies. This holistic approach aims to validate both the mechanism's functionality and the user experience's comfort, identify limitations, and pinpoint areas for improvement.

RESEARCH QUESTIONS

The main focus of this project is to answer the following research questions, divided into two main themes:

Theme 1: Utilizing Shape Morphing-based Technology for Nervous System Regulation

RQ1.1 Which current treatments for regulating the nervous system (e.g., anxiety) incorporate shape-morphing-based technologies? What are the knowledge gaps between medical treatment and design-focused solutions?

RQ1.2 How can Shape Memory Alloys (SMA) integrated into textiles accurately simulate the breathing rhythm system? What intensity, location, and mechanism enhance user perception?

Theme 2: Exploring User-Smart Wearable Interaction (HCI)

RQ2.1 How can a smart wearable enhance users' awareness of anxiety to regulate their nervous system?

RQ2.2 How can materials enhance the integration of the wearable into daily life to enhance well-being while avoiding intrusiveness?

PREVIOUS PROJECTS

Two projects from previous students on SMA and haptic wearables are referenced throughout the report:

'Sereni Sleeve: Designing Shape Memory-Based Wearables for Anxiety Modulation' by June Kim. Insights from this project relate to SMA integration into textiles and electronics, as well as key considerations for prototyping a wearable design and its evaluation on users.

'Shape Memory Origami for Haptics' by Mila Lücker. This project helped deepen the understanding of SMA's technical properties and behavior through its design guidelines and lab experiments. Additionally, it provided inspiration for the experiential characterization of the user studies.

Methodology and Experimental Set-Up

The methodology used in this project is mainly inspired by parametric study and Materials Driven Design (MDD). Thus, both technical and experiential characterization studies are integrated. Additionally, the project iteratively combines a theoretical foundation (literature review) with empirical exploration, such as prototyping, material tinkering, and interviews, to generate more meaningful and feasible ideas.

PARAMETRIC STUDY

A parametric study is a scientific methodology used for technical characterization and validation. By establishing key parameters such as response time and displacement, experiments can be conducted and compared accurately. This approach ensures the generation of reproducible data, allowing for precise assessment of system performance and helping optimize the design by identifying the most effective parameter combinations.

MATERIAL DRIVEN DESIGN (MDD)

The MDD is a systematic approach for designers working with known or unknown materials. Developed by E. Karana et al. in 2015 at Delft University of Technology, it sets the material as the main driver to facilitate the design process. Figure 1 illustrates the MDD process divided into four main phases. Phase 1 focuses on 'Understanding the Material' through tinkering -hands-on exploration- and a benchmark analysis of current solutions. In addition, the user study provides further knowledge on how the material/prototype is perceived and therefore the materials experience levels is used as a framework to analyze the results. This helps define a technical and experiential characterization of the material in an integrated manner. Phase 2 creates a 'Material Vision' with the opportunities of the material to identify a new potential purpose. In Phase 3, the designer identifies how to translate the intended vision into qualities by identifying experiential patterns. Lastly, Phase 4 combines all the previous knowledge acquired into a design process. In this phase, previously generated ideas will take shape into a final product concept. This process is iterative and adjustable to each project. In this case, only Phases 1, 2, and 4 are implemented.

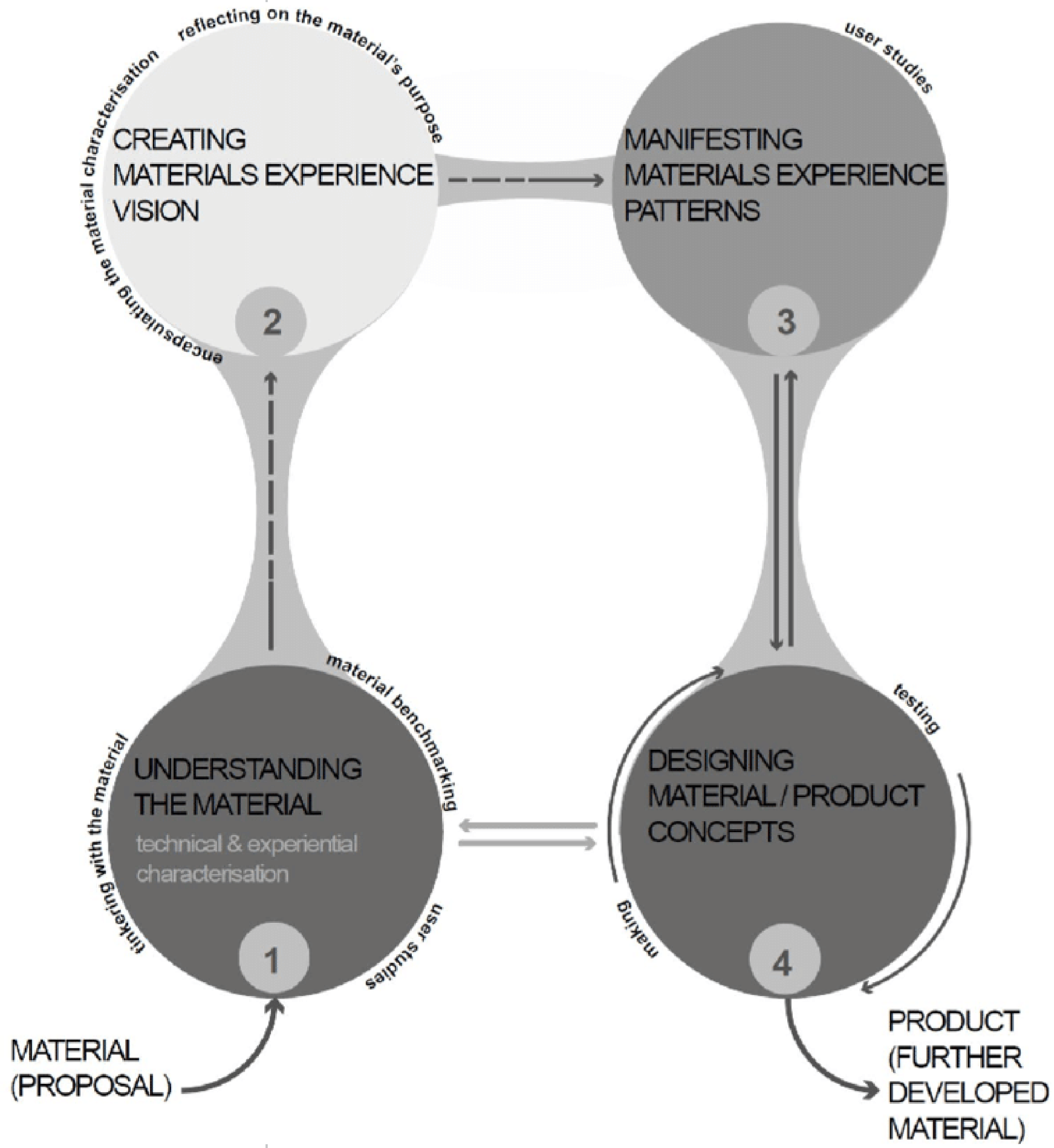


Fig. 1: The three primary phases of the Material Driven Design (MDD) method emphasized in the project.

REPORT STRUCTURE

This project is organized into three main parts:

PART I: Contextual Analysis
This section delves into the three expertise areas across three chapters (see Figure 1):

1. Stress Regulation
2. Smart Wearables for Health
3. Shape Morphing Materials

Each chapter includes both a theoretical analysis (Literature Review: theoretical foundation and benchmarking) and an empirical analysis (Applied Practices: hands-on exploration and interviews).

PART II: Conceptualization and Embodiment
This section outlines the design requirements, develops and evaluates ideas and concepts, and finalizes the design. The final design is validated in terms of functionality and user experience.

PART III: Conclusions
This section synthesizes the new insights gained, detailing contributions, limitations, recommendations for future work and a self-reflection of the overall project.

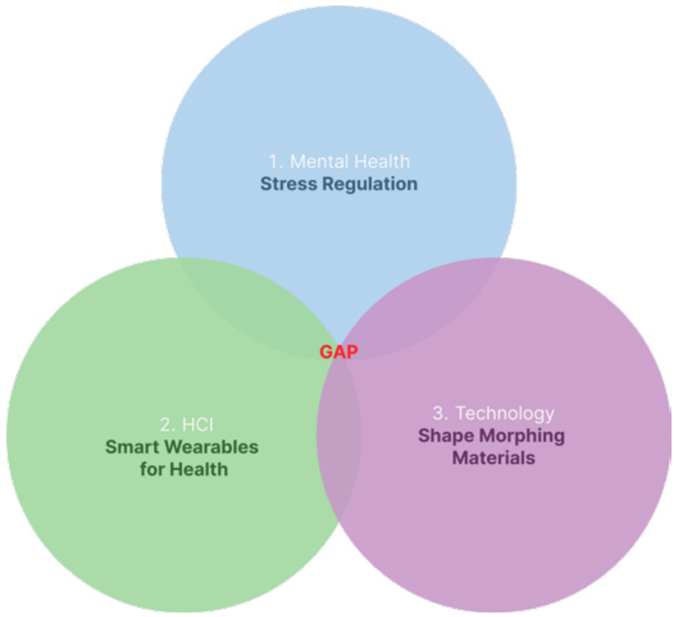


Fig. 2: Identified gap between the three main expertise areas analyzed in the project.

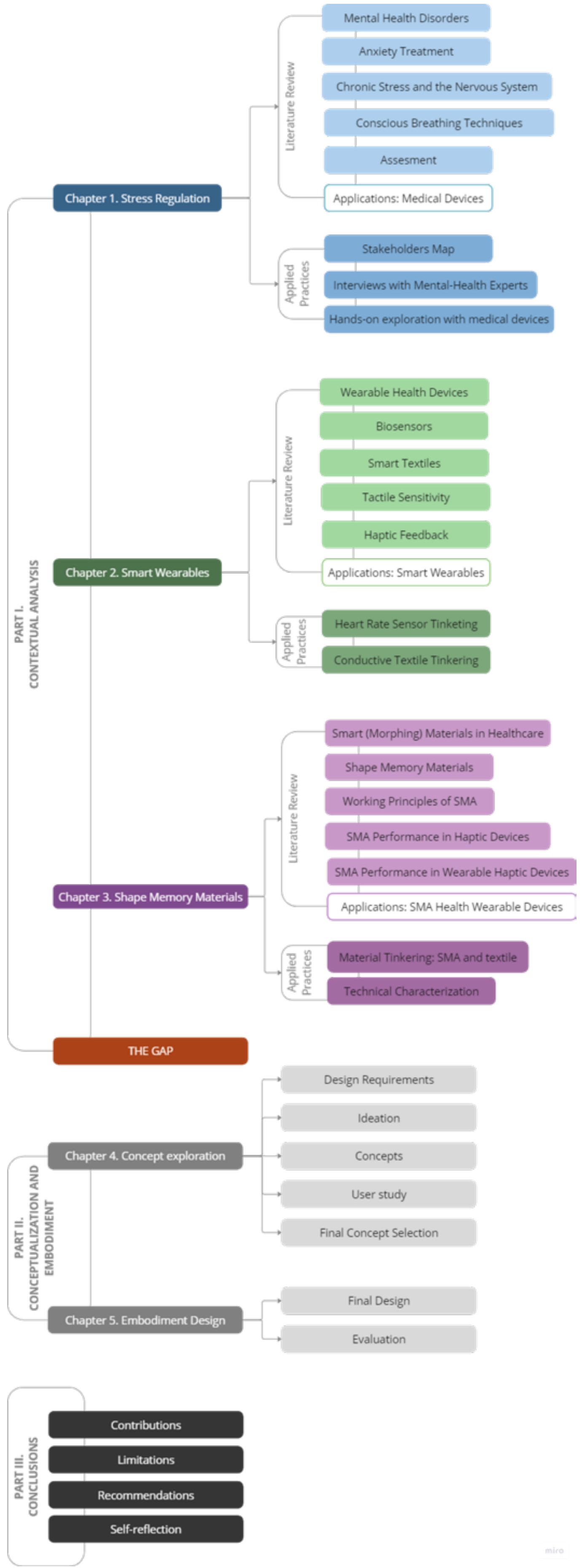
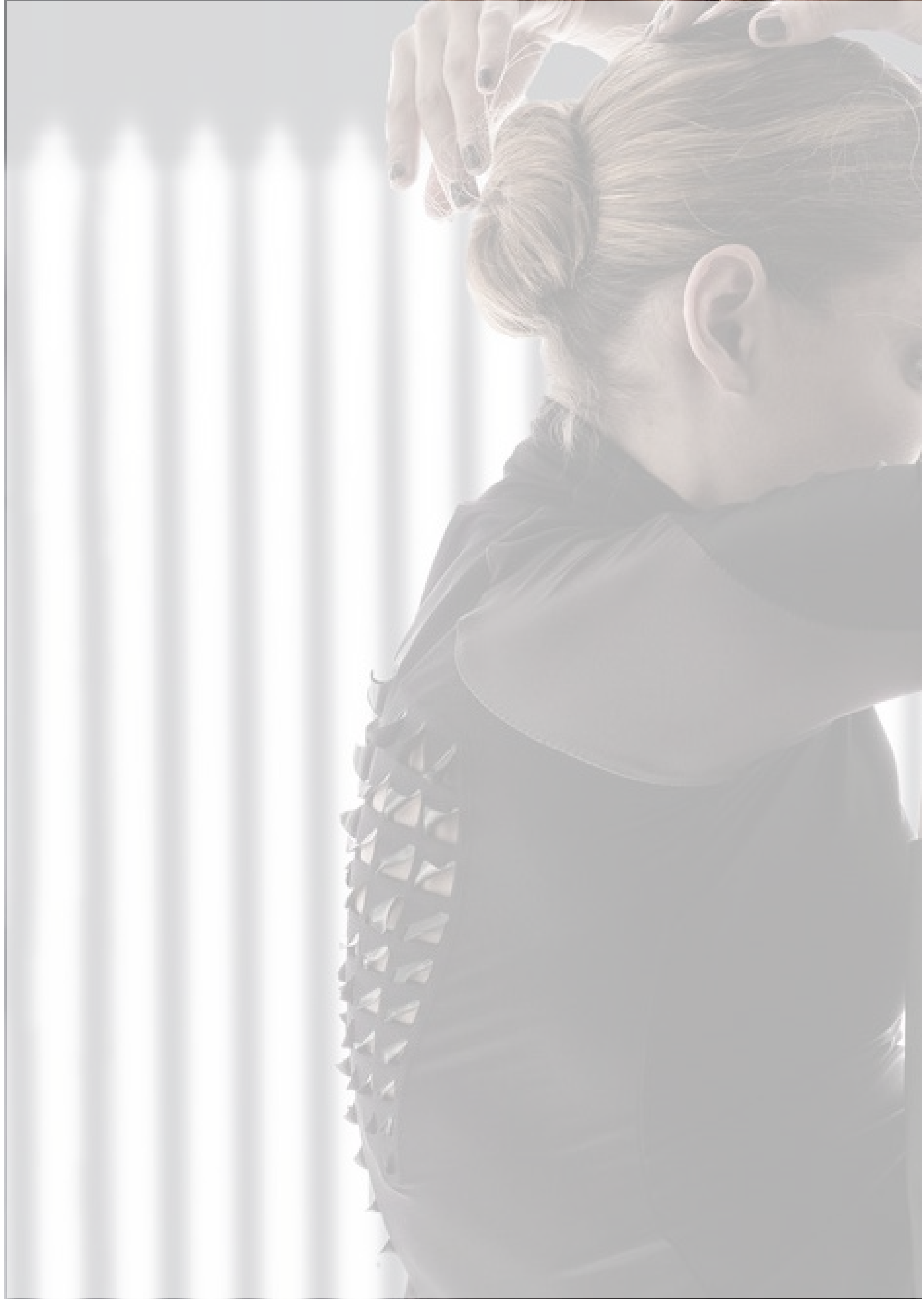


Fig. 3: Report's structure divided into three main Parts and five Chapters.

PART I.
CONTEXTUAL ANALYSIS



Chapter 1.
Stress Regulation

Chapter 1 explores 'Stress Regulation,' beginning with a comprehensive review of the literature on anxiety, a rising global mental health issue. It focuses on treatment methods, particularly breathing techniques, and examines current medical and design solutions for anxiety regulation through body signal monitoring. This theoretical foundation is extended with practical applications, including stakeholder analysis, expert interviews, and hands-on experiments with medical devices.

1.1 | Literature Review

1.1.1 Definition

MENTAL HEALTH DISORDERS

According to the World Health Organization WHO (2022), “Mental health is a state of mental well-being that enables people to cope with the stresses of life, realize their abilities, learn well and work well, and contribute to their community”. Mental well-being is influenced by both psychological factors (emotional skills) and biological factors (genetics) (CDC, 2024). Recent years have seen a significant deterioration in mental health, particularly among young people, due to the devastating effects of the pandemic, wars, unemployment, rising living costs, the climate crisis, and social media pressure (EU Public Health, 2024).

One in every eight people worldwide lives with a mental disorder (WHO, 2022). In Europe, over 84,000 people died due to mental health problems, causing costs estimated at more than 4% of the EU GDP—over EUR 600 billion (EU Public Health, 2023). Figure 4 shows that in the U.S. more than one in five adults lives with a mental illness, totaling 57.8 million in 2021 (NIMH, 2024).

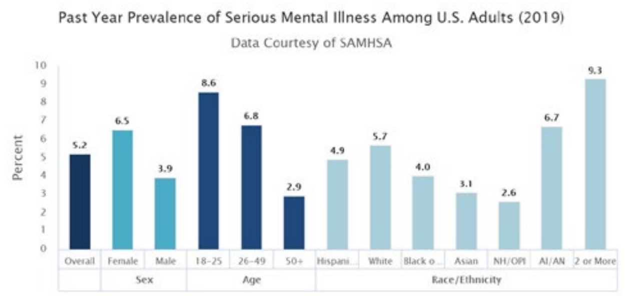


Fig. 4: Prevalence of Any Mental Illness among U.S. Adults in 2021 (NIMH, 2024).

Studies report that serious mental illnesses are more prevalent in women (twice as likely as men), in young adults aged 18-25 years (significantly lower among those over 50), and in people of two or more races. Regardless of age, sex, income, or ethnicity, everyone is at some risk of suffering from one or more mental health disorders (ADAA, 2024). Neglecting mental well-being exacerbates symptoms of disorders such as depression, schizophrenia, post-traumatic stress disorder, eating disorders, bipolar disorder, and anxiety.

Thus, for identifying stress-release techniques, such as breathing, it is crucial to first analyze anxiety, chronic stress, and the nervous system correlation.

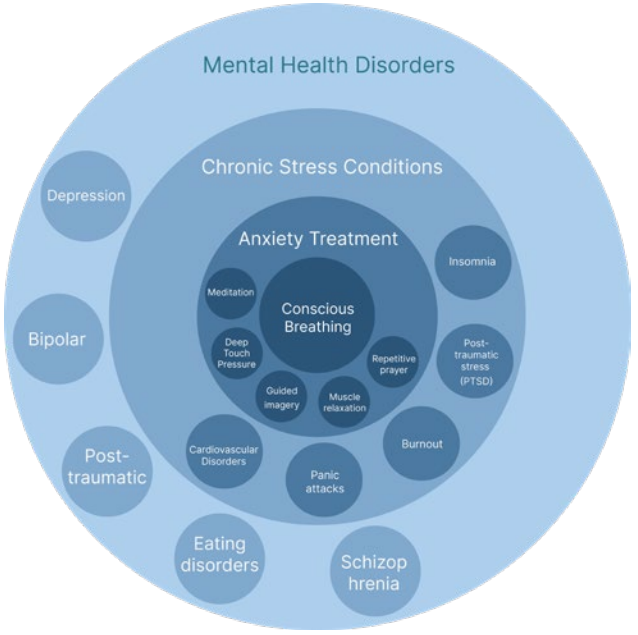


Fig. 5: Overview of mental health areas analyzed in Chapter 1.

ANXIETY TREATMENT

According to both the World Health Organization (WHO) and the Anxiety and Depression Association of America (ADAA), anxiety is the most common mental health disorder, affecting 301 million people worldwide in 2019. Despite being highly treatable, only one in four people receive treatment (ADAA, 2024). Nearly half of young Europeans report unmet needs for mental health care (EU Public Health, 2023), underscoring the urgent need for global action on mental health. Entities like WHO, the European Commission, and the Government of the Netherlands are leading initiatives and providing financial support (EU Public Health, 2024; Government of the Netherlands, 2022).

Providing effective treatment tailored to each individual’s unique needs and preferences remains a major challenge. Treatment strategies often combine psychotherapy, medication, and self-help techniques (Felman, 2024), offering opportunities for designing innovative treatments.

CHRONIC STRESS AND THE NERVOUS SYSTEM

Stress, the cause of anxiety and other conditions like depression, insomnia, PTSD, and heart disease, prepares the body to handle challenges from internal or external stressors. Chronic stress, caused by intense, repetitive, or prolonged stressors, negatively impacts well-being (Chu et al., 2024). While stress is necessary for managing everyday life obstacles and internal growth, it should not reach a chronic state.

Chronic stress triggers physiological responses such as increased heart rate, excessive sweating, hyperventilation, and muscle tension (McGrath et al., 2020). Professionals can assess physiological stress by analyzing the Autonomic Nervous System, particularly the balance between sympathetic and parasympathetic areas (Polyvagal theory, Magnon et al., 2021). The sympathetic system acts like a car’s gas pedal, providing energy for a fight-or-flight response, while the parasympathetic system functions as the brake, calming the body and reducing stress (Harvard Health, 2024). Activating the parasympathetic system slows the heartbeat and breathing, leading to relaxation and anxiety relief (Moonbird, 2024).

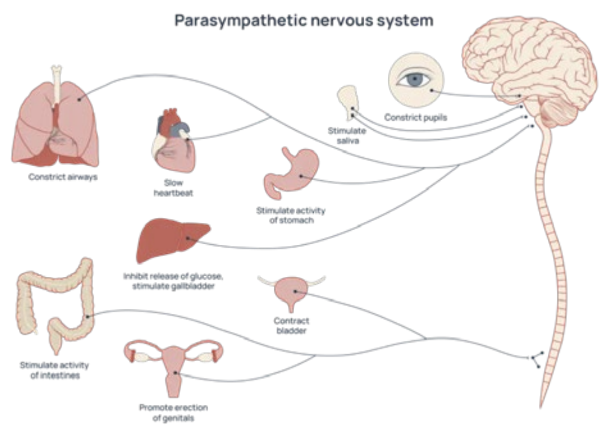


Fig. 6: Physiological Response of the Parasympathetic Nervous System (Moonbird, 2024).

CONSCIOUS BREATHING TECHNIQUES

Chronic stress can be managed through various techniques, depending on the individual and the stress level. Clinical settings often prefer medication and therapy, but non-intrusive techniques are emerging in both clinical and non-clinical settings. Mindfulness techniques, including meditation, Deep Touch Pressure (DTP), guided imagery, repetitive prayer, and muscle relaxation, have gained significant interest for stress reduction (Worthen & Cash, 2023; Harvard Health, 2024).

Among these techniques, breathing exercises, particularly those involving deep, slow diaphragmatic breathing, have proven effective for managing stress universally by decreasing sympathetic and increasing parasympathetic tone (Birdee et al., 2023). Leading health organizations such as the NHS, Harvard Medical School, WHO, and MIT recommend integrating these techniques into daily life (Figure 7). Medical experts now prefer terms like “Nervous System Regulation” over anxiety and “Breathwork” over deep, slow diaphragmatic breathing (NHS, 2022; The Breathwork Movement, 2024). Breathwork, defined as “any form of conscious breathing to influence certain processes in body and mind” (Moonbird, 2024), contrasts with the passive observation of breathing in meditation. This project will refer to it as “Conscious Breathing”.

Conscious breathing involves actively controlling long, deep breaths from the abdomen in a rhythmic pattern. Techniques like the 4-7-8 method, where one inhales through the nose for 4 seconds, holds the breath for 7 seconds, and exhales forcefully through the mouth for 8 seconds, are commonly used. This cycle, repeated up to four times, stimulates the parasympathetic nervous system, slowing the heart rate and decreasing blood pressure. For people with less experience, it is recommended the easier technique 5-5-5 (Ma et al., 2017; Fletcher, 2023).

Fig. 7: World’s leading health and wellness organizations support breathing techniques (Moonbird, 2024).

The benefits of conscious breathing, such as improved heart and lung function and reduced blood pressure, significantly enhance the quality of life for those with chronic stress and anxiety (Magnon et al., 2021b; Moonbird, 2024). These findings suggest effective ways to assess anxiety through its correlation with physiological parameters.

ASSESSMENT

Anxiety and chronic stress can be measured both psychologically (self-reported systems) and physiologically (heart and breathing rate) through the Autonomic Nervous System. Conscious Breathing reduces blood pressure and heartbeat, which can be measured by a decrease in Heart Rate (HR) and an increase in Heart Rate Variability (HRV), both instantly and over time. HRV, an indicator of the body's adaptability to stress, shows that conscious breathing can train the body to have a natural relaxation response and enhance its stress-managing mechanism. HRV and other quantitative and physiological parameters are called biomarkers, used for clinical assessment, monitoring, and predicting health states through biofeedback (Moonbird, 2024; News-Medical, 2023).

Other biomarkers or physiological effects of anxiety include increased heart rate, changes in skin conductance, rapid breathing/hyperventilation, changes in blood pressure, muscle tension, gastrointestinal symptoms, sweating, trembling, disrupted sleep patterns, and weakened immune response (Hoehn-Saric & McLeod, 2000). Based on current medical tools, three biomarkers are most commonly measured due to their high reliability and correlation with anxiety: increased heart rate, changes in skin conductance, and rapid breathing/hyperventilation (see Table 1). These biomarkers will be analyzed further in the next section

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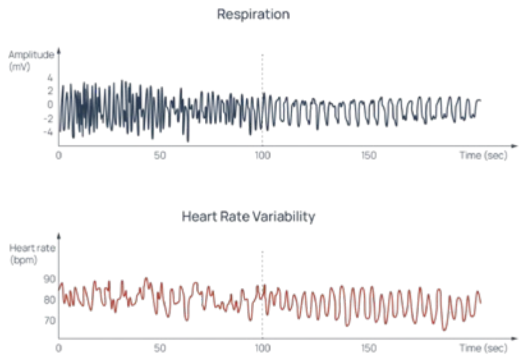


Fig. 8: Breathing techniques impact on Respiration and Heart Rate Variability (Moonbird, 2024).

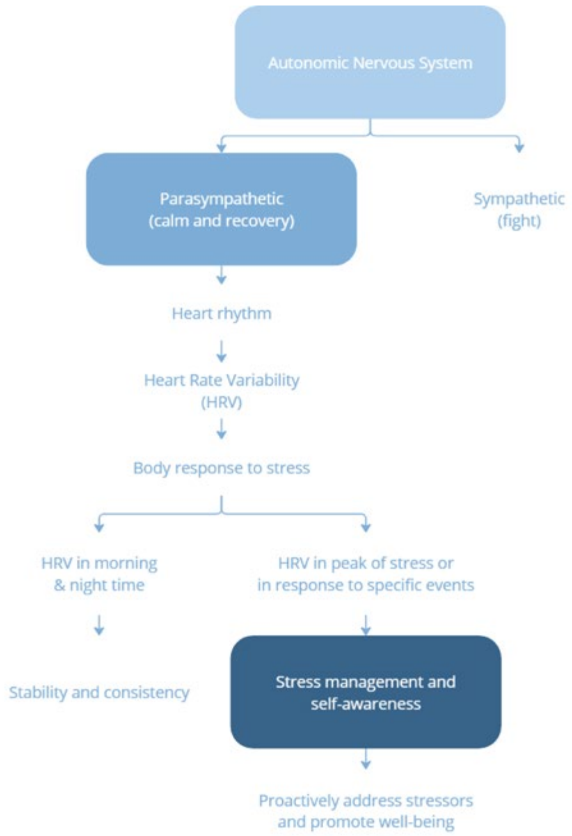


Fig. 9: Correlation between the Autonomic Nervous System, HRV, and stress-management and self-awareness.

1.1.1 Applications

MEDICAL SOLUTIONS

There is a growing trend to innovate solutions for managing anxiety, integrating design ideas into medical devices to make them more effective in everyday life. Among the physiological effects of anxiety, three are most effectively measured with current medical tools: increased heart rate, changes in skin conductance, and rapid breathing/hyperventilation. Table 1 shows what biomarkers are identified, how the sensors measure the biomarkers and give biofeedback, and where are located in the body.

DESIGN SOLUTIONS

Based on the current medical solutions, some design applications are analyzed related to measuring HRV, rapid breathing, and changes in skin conductance, as shown in the Table 1.

Medical Solutions					Design Solutions
WHAT		HOW		WHERE	
Physiological effects of anxiety	**Biomarkers (Parameter measured)**	**Sensor**	**Biofeedack (Measurement type)**	**Body location**	**Examples**
Increased Heart Rate	**Heart Rate Variability (HRV)** (ms) *Widely used* ↓ Low HRV ↑ High stress	• Optical Heart Rate Sensor	It uses photoplethysmography (PPG) to detect changes in blood volume	Wristband (most common) and fingertip	• **Device Sensor-based:** *Scosche*, Garmin, Fitbit *Scosche Rhythm 24*, *Polar H7*, *Apple Watch* • **Mobile Apps-based** (Phone camera): HRV4Training *HRV4Training* can measure via phone camera or receive and store measurements from other devices connected
		• Electrocardiogram (ECG or EKG) Sensor	It measures the electrical activity of the heart by placing multiple electrodes on the body	Two electrodes placed on the skin's surface: chest strap and/or fingertips	• Mostly in **clinical** settings • Device: MDcubes and Apple Watch *MD Cubes*
Rapid Breathing/ Hyperventilation	**Respiration Rate (RR)** (brpm) ↑ High RR ↑ High stress	Accelerometer and gyroscope sensors OR • Respiratory Inductance Plethysmography (RIP) (chest/ Abd circumference) • Pneumotachographs • Pulse Oximeters (fingertip)	It includes accelerometers or other motion sensors to detect chest movements	Two electrodes placed on the skin's surface: wristband or chest strap (better)	• Devices: Muse, Garmin and Google Fibit Sense • Respiration Rate Apps *Muse* PPG + accel & gyros. With breath meditation (weather sounds) *GoogleFitbit Sense* Includes sensors of: Optical Heart Rate Sensor, EDA, 3-axis accelerometer, ECG, etc *Garmin Forerunner 945* With optical breathing exercises
Changes in Skin Conductance	**Electrodermal Activity (EDA)** (µS) ↑ High EDA ↑ High stress	Galvanic Skin Response (GSR) Sensor or electrodermal activity (EDA) Sensor	It detects changes in the skin's electrical conductivity caused by sweat gland activity	Fingertip (most common) and wristband	• Devices: Oura Ring *Oura Ring*

Table 1: Overview of Chapter 1. Applications divided into medical and design solutions.

HRV, measured through optical sensors, is widely used due to its simplicity, effectiveness, and affordability. Examples include the armband Scosche Rhythm 24, the chest strap Polar H7, and the Apple Smartwatch, which integrate the sensor into elastic fabric to adapt to the body during workouts. HRV analysis is displayed in their respective apps.

Fig. 10: Optical Sensor Devices: [A] Scosche Rhythm 24, [B] Polar H7, and [C] Apple Smartwatch.

Other alternatives, like HRV4Training, measure heart rate using a phone camera. This method involves placing the user's fingertip on the camera for one minute, guiding breathing exercises, and monitoring HRV over time. HRV4Training, focused on athletes, associates HRV data with the type of training to provide better biofeedback and can connect to external devices for storing measurements.

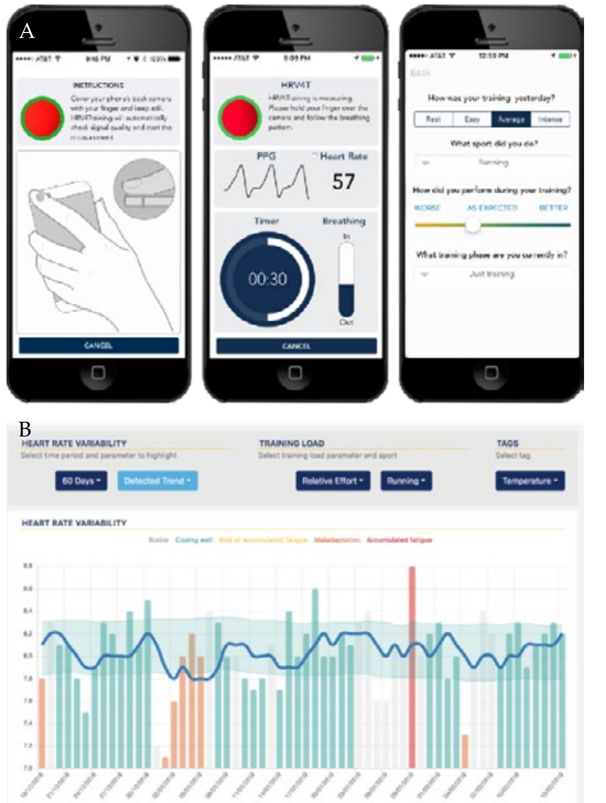


Fig. 11: HRV4 Training app: (A) HR measuring process and (B) data stored

HRV can also be measured via ECG, as seen in the MD Cubes device. However, this method requires precise placement on two different body parts to create a closed circuit through the heart, and minimal movement can interfere with signal measurement.

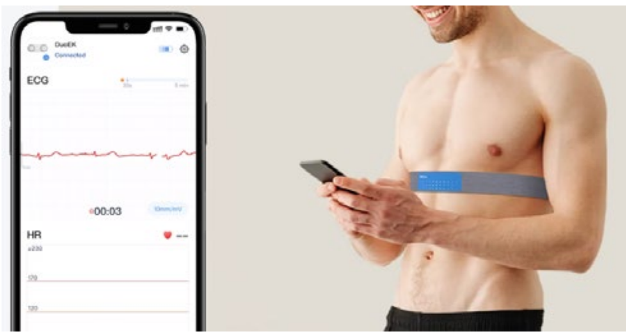


Fig. 12: MD Cubes device.

Respiration rate is calculated by designs combining optical sensors with motion sensors (accelerometer and gyroscope), such as GoogleFitbit Sense. Other devices, like Muse and Garmin Forerunner 945, include breathing exercises and provide optical guidance.

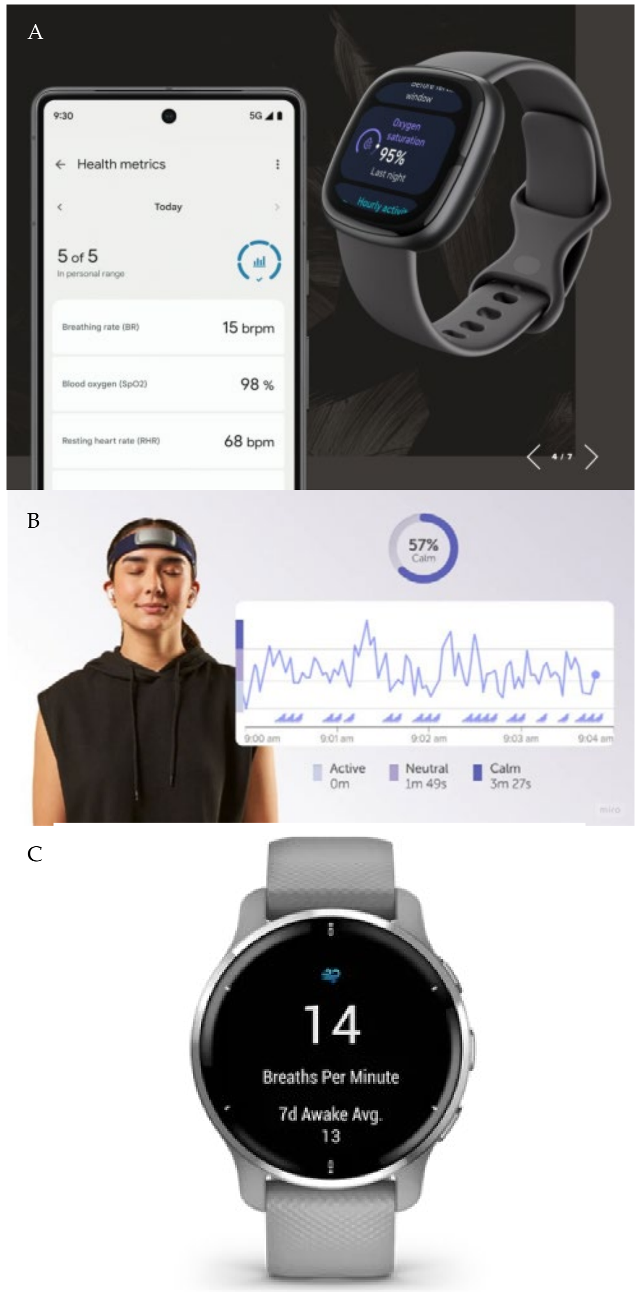


Fig. 13: Optical-motion sensors: [A] GoogleFitbit Sense, [B] Muse, and [C] Garmin Forerunner 945.

Electrodermal Activity (EDA) measures stress through increased sweat. Revolutionary wearables like the Oura Ring monitor heart rate and sleep cycles but are often expensive and less preferable to other fitness and sleep trackers (Redwood-Crawford, 2024).

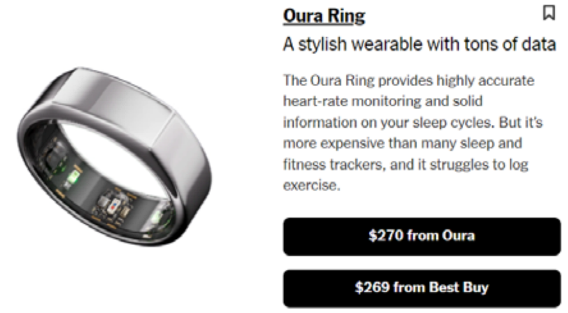


Fig. 14: Oura Ring.

SUMMARY

The literature review brings new insights that could be relevant for future design. People with anxiety conditions are looking for discreet, non-invasive ways to increase self-awareness and self-management. Treatment for non-clinical settings is mainly unclear and uncovered. Yet, experts highlight the correlation between Conscious Breathing and stress as it could be a more "universal" and effective way to manage anxiety. The most effective way to deal with anxiety is by stimulating the Sympathetic Nervous System and regulating its perceived stress, both psychologically and physiologically. A manner to achieve it is by extending the exhalation when breathing, guiding rhythm, and communicating with the user throughout the relaxation process. Anxiety can be measured with physiological indicators, called biomarkers, and the most promising one is Heart Rate measured with optical sensors (PPC technology) due to its simplicity, efficiency, affordability, and easy daily use integration. Biofeedback, or feedback from biomarkers, is key for increasing awareness of health conditions and improving self-management. It is shown in the examples that feedback can be given with or without the app. Current solutions suggest wrist, hand, arm, abdomen, and chest as optimal body locations for measuring biomarkers. Moreover, they insist on giving Heart Rate feedback and guidance to the user through visual, sound, or tactile breathing exercises.

1.2 | Applied Practices

1.2.1 Stakeholders map

For collecting the information from different sources and reduce bias, it is identified the stakeholders in a map. Governmental entities and mental health organizations mainly provided the insights gathered in the literature review. Psychologist also play a key role on understanding anxiety and current solutions and therefore some interviews are carried out in this section. The stakeholders related to the device manufacture need to be considered, as it is in the following chapters of this PART I. The final user has the main target of the project and, in particular, its self-management of anxiety by pre-training for episodes of high stress (explained previously). User's perspective is alquired later on through user studies.

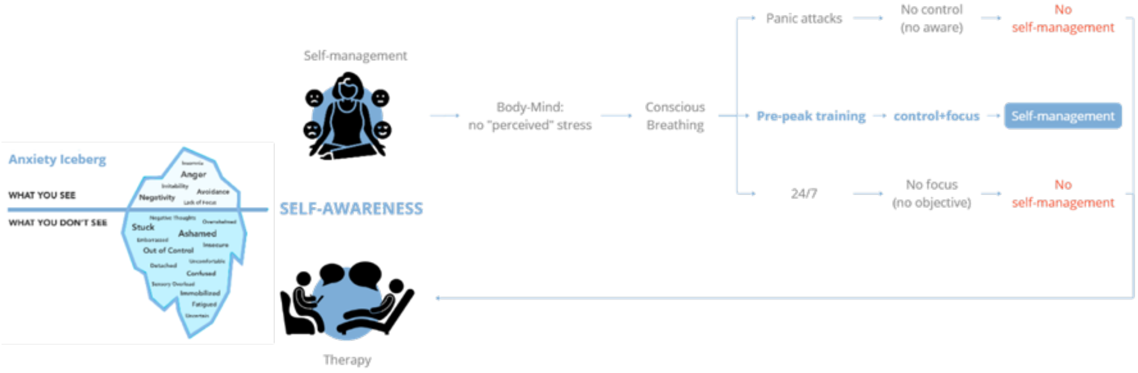


Fig. 15: Self-management in different anxious scenarios

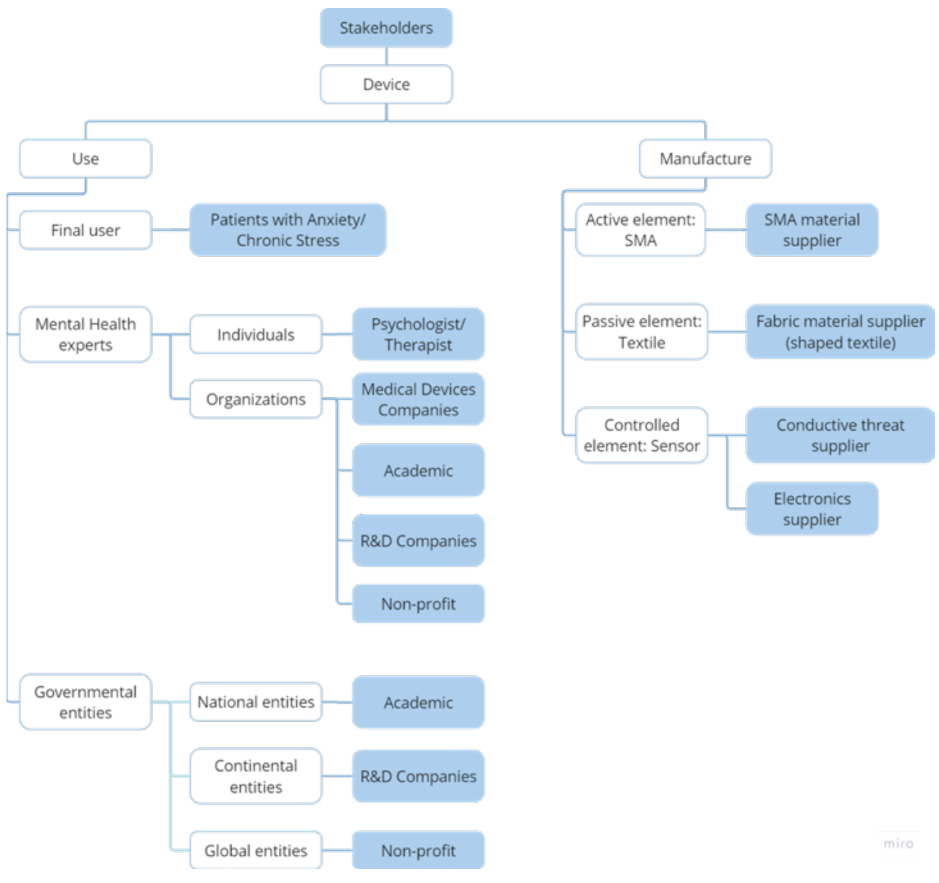


Fig. 16: Stakeholders map of envisioned medical device

1.2.2 Interview with mental health professionals

To better understand stress treatment approaches in clinical and non-clinical settings, two interviews were conducted with mental health professionals.

METHOD: The interviews were semi-structured and guided by a template (Appendix 4). This allowed more flexibility during the sessions. The aim was to explore which techniques are more effective, how they are measured, and how they are adapted to each patient and integrated into everyday life. These new insights were considered when creating the prototypes. One interview was conducted in-person, and the other online.

PARTICIPANTS: The two interviewees included a psychologist and an 'integrative medicine' professional, all from Spain, with varying levels of expertise.

RESULTS: The interviews highlighted the importance of understanding a patient's condition through a combination of physiological and psychological symptoms, which can indicate the mental state and how to approach anxiety disorders. Common physical symptoms include sweating, shaking, stomach pain, and hyperventilation, while a negative perspective on life and extreme self-criticism are psychological indicators of anxiety.

An effective and common technique to calm a person involves bringing the mind and body to the present situation through stimuli. Diaphragmatic breathing is widely used in both clinical and non-clinical settings to achieve this 'present connection.' The method involves placing one hand on the lung area and the other on the diaphragm to observe their movements. If the hand on the diaphragm moves, it indicates correct breathing and anxiety release. Another technique involves repetitively tapping body parts for rhythmic connection (e.g., EMDR technique).

Professionals emphasized the importance of practicing this body-mind 'present' connection daily to build a routine and see improvement. Daily practice of techniques such as diaphragmatic breathing works as a short-term anxiety release and a first step for clinical therapy. Patients are increasingly seeking discreet self-management alternatives due to the stigma of mental health issues and lack of awareness about available resources.

TAKEAWAYS: The interviews provided a closer view of how anxiety is approached clinically. Breathing exercises from the diaphragm are a general strategy used for short-term calming. Making the patient aware of their condition, such as watching their hands move with breathing, is crucial. For long-term impact, daily practice is necessary to train the connection between body, mind, and the present "safe" situation. Understanding physiological and psychological indicators of anxiety is key to addressing the user's situation correctly. Although professional therapy can delve deeper into the problem and identify the cause, experts insist that the first stage is self-management and self-awareness through techniques like Conscious Breathing.

1.2.3 Hands-on exploration with medical devices

To gain more practical insights into medical devices for anxiety, basic experiments were conducted. A pulse oximeter helped understand how PPG technology works, measuring Heart Rate (a biomarker) through the fingertip and providing biofeedback. Trying a breathing app (iBreath) also provided information about the user experience, such as synchronizing with rhythm through visual cues and calming sound alerts. The app allowed for testing breathing techniques highlighted in the literature review: 5-5-5 for beginners and 4-7-8 for advanced users.

Fig. 17: Hands-on exploration with (A) iBreath App and (B) Pulsometer.

1.3 | Discussion

This chapter gathered multiple relevant insights about anxiety management for future design implementation. Everyday practice is crucial for becoming aware of anxious conditions and self-managing them. Thus, there is potential in designing a wearable solution for non-clinical scenarios (home, work, streets) that users can benefit from daily—either through constant monitoring throughout the day or during anxious conditions.

Mental health leading organizations and experts urgently seek effective solutions, yet current medical designs focus on athletes and sleep disorders, not anxiety. This opens the possibility of transferring the technology (PPC) and designs (textile wearables) of these devices to anxiety regulation. Biomarkers and biofeedback play an optimal balance; however, current solutions mainly provide physiological feedback (Heart Rate measurements). Therefore, considering Heart Rate as a good anxiety biomarker and including Conscious Breathing guidance as positive impactful biofeedback could lead to effective user results.

From the interviews and benchmark, the body location of the wearable plays a crucial role in user impact. It is essential to determine where it is better perceived while being comfortable. Should the user wear it all day or just at specific moments? This leads to considering the wearable material as a key design parameter, along with its washability and maintenance.

Chapter 1 takeaways and its relevance for the project are summarized in the following tables:

Key Insights from Chapter 1

- Non-clinical anxiety treatment lacks clarity and coverage, unlike sports.
- People with anxiety seek discreet, non-invasive methods to enhance self-awareness and manage daily stress.
- ‘Conscious breathing’ is an ancient, universal technique for stress relief used in both clinical and non-clinical contexts. However, it requires practice and concentration.
- Regulating the Parasympathetic Nervous System through the mind-body connection is an effective way to alleviate physical and psychological stress.
- Current solutions either monitor body signals (biomarkers and biofeedback) or provide stress-relief techniques, but a combination of both is missing.
- ‘Conscious Breathing’ focuses on the abdomen, with body signals commonly measured on the wrist, hand, arm, abdomen, and chest.
- Guidance through visual, auditory, or tactile feedback is necessary for effective breathing exercises.
- Relying on external devices (such as smartwatches or apps) can distract users during breathing exercises.

Relevance for the Project

1. A wearable device that combines input and output can enhance user awareness of anxiety and improve stress relief.
2. A textile-based solution can integrate breathing techniques into daily routines.
3. Focusing on training the mind-body connection through breathing is essential for managing anxiety moments, such as those experienced in therapy.
4. Breathing techniques with extended exhalation rhythms, like the 5-5-5 and 4-7-8 patterns, are easy to follow and effective.
5. An optimal solution should address both psychological and physiological aspects.
6. Heart Rate (HR) can be measured using optical sensors (PPC), which are simple, effective, affordable, and easy to incorporate into daily life.
7. Biofeedback HRV has shown positive results in improving anxiety.
8. Breathing exercises can be guided using tactile technology, eliminating the need for an app.

Table 2: Overview of key insights from Chapter 1 and their relevance for the project.

Chapter 2.
Smart Wearables for Health

The second chapter examines wearable devices in the healthcare sector, focusing on biosensors and the role of smart textiles in stimulating tactile sensitivity through haptic technology. It includes examples of smart medical wearables that utilize smart materials technology, breathing techniques, and haptics. To enhance the theoretical understanding, hands-on exploration with heart sensors and conductive textiles offers new insights for future design considerations.

2.1 | Literature Review

2.1.1 Definition

WEARABLE HEALTH DEVICES

The rapid advancement of electronic device technology has led to the emergence of personal wearable mobile devices (or simply 'wearables'), ranging from accessories to clothing. These devices can continuously sense, collect, and store physiological data to enhance quality of life, with applications in navigation for visually impaired people, Apple Pay, sports tracking, and adaptive clothing (Seneviratne et al., 2017). Figure 18 shows that the healthcare wearable device segment is expanding due to the Internet of Things (IoT) revolution (Dias & Cunha, 2018).

Wearable Health Devices (WHDs) monitor health at both activity/fitness and medical levels, providing clinicians with data for early diagnosis and treatment guidance (Figure 19). WHDs collect data in activity monitoring and medical scenarios, analyzing vital signs such as ECG, heart rate, blood pressure, respiration rate, blood oxygen saturation, and skin temperature (Dias & Cunha, 2018), such as the examples presented in Chapter 1. Heart rate activity is a major focus, incorporating biosensors into textiles. Key considerations include the integration of biosensors/electronics, optimal material properties, and strategic body placement for user experience.

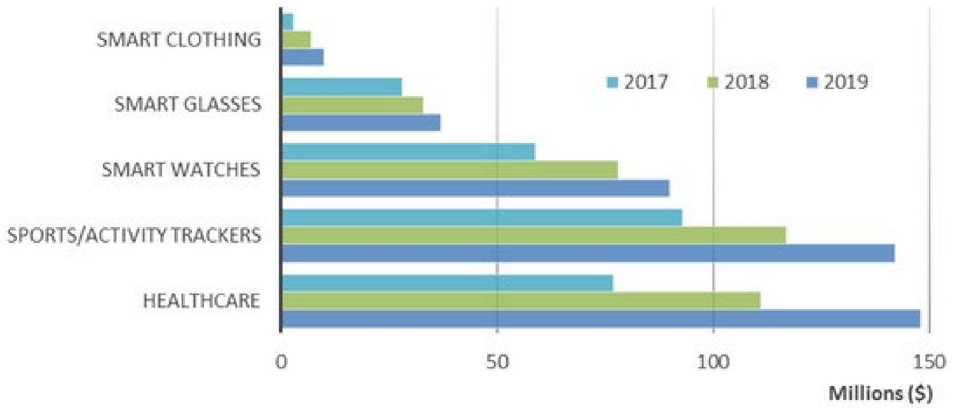


Fig. 18: Trend of global market value of wearable computing devices, in millions, between 2017 and 2019 (Dias & Cunha, 2018).

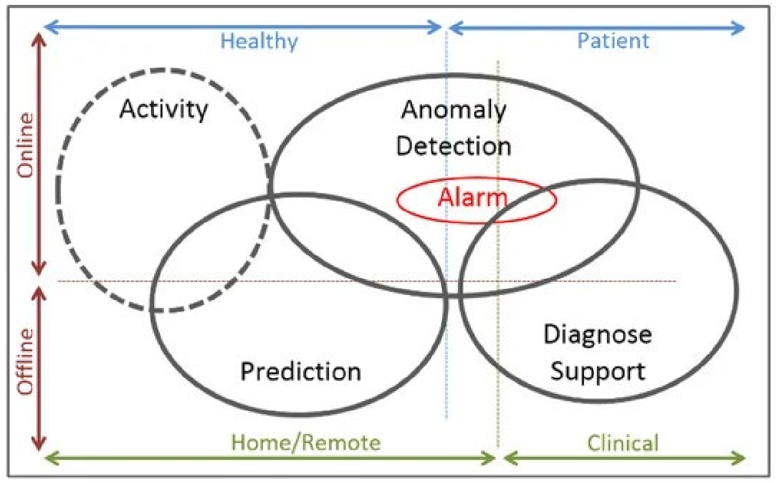


Fig. 19: Schematic overview of the four data collecting scenarios of WHDs (Dias & Cunha, 2018).

BIOSENSORS

In Chapter 1, various methods to measure heart rate and calculate Heart Rate Variability (HRV) were discussed, with Optical Sensors deemed promising. An example is the Pulse Sensor connected to an Arduino board, providing instant biofeedback on heart rate and an ECG graph. Resting Heart Rate typically ranges between 60 and 100 bpm, with lower rates for well-trained athletes. The Maximum Heart Rate is calculated as 220 minus the person's age. The Pulse Sensor also displays HRV within 20 to 100ms (Standard Deviation of RR Intervals (SDNN)) (Sun et al., 2020).

New manufacturing technologies are integrating biosensors into textiles. Conductive yarn can create pressure sensors during the weaving process, measuring skin biomarkers and activating actuators for haptic feedback (Sun et al., 2020), eliminating the need for conventional sensors, wires, and circuits.

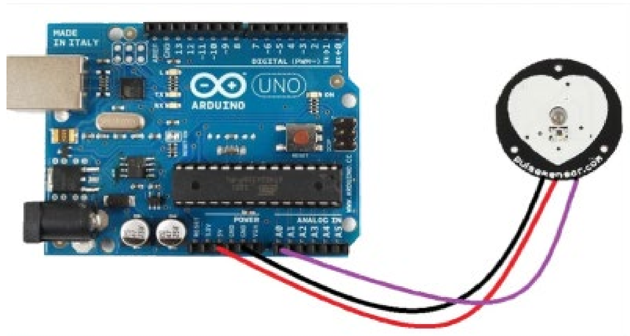


Fig. 20: Pulse sensor connected to Arduino board.

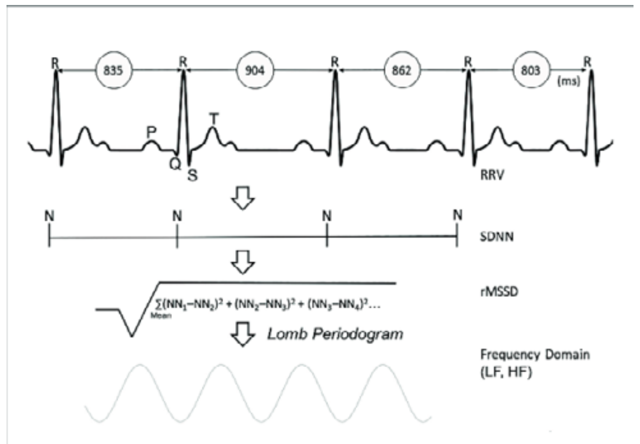


Fig. 21: HRV measurement based on heartbeat (Sun et al., 2020).

SMART TEXTILES

Clothing and textiles come into direct contact with 90% of the skin surface, revealing significant insights about a person's health. Consequently, smart clothes equipped with noninvasive sensors present a promising solution for health monitoring (Axisa et al., 2005). Smart textiles or e-textiles can reflect physiological or psychological states, creating opportunities to enhance sensory awareness (somatics) and manage mental well-being. These textiles can detect body indicators of anxiety through biosensors and activate a tactile system, called haptics, to augment body sensations. This helps the wearer understand their emotions and take positive actions to manage stress (Coulter, 2023).

A textile wearable is particularly appealing for this project because it can integrate all necessary components for proper functioning while fitting into everyday life. People are constantly in contact with textiles, which can adapt comfortably to the user's body. As a Wearable Health Device, the textile should meet key aspects (Refiber Designs, 2022; Parisi et al., 2024; Binder and Redström, 2006):

- Comfort: The textile must be comfortable to wear for extended periods. Stretchy fabrics like spandex and polyester adjust perfectly to the body and allow skin respiration, making them suitable for sports applications. The fabric's elasticity can be influenced by the manufacturing technique (knitting is typically more elastic than weaving) and the yarn direction (some are more elastic in the weft/warp directions, while others are more elastic diagonally due to the spaces in between).

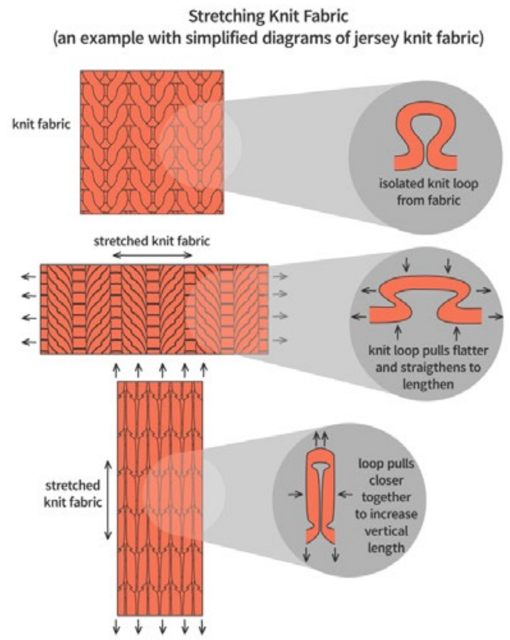


Fig. 22: Stretching knit fabric (Refiber Designs, 2022).

- Washability/Hygiene: The textile must be easy to clean and maintain, ensuring hygiene and durability for regular use. This includes the ability to withstand repeated washing without degrading the embedded sensors or actuators.
- Portability: The wearable must be lightweight and unobtrusive, allowing users to carry and use it throughout their daily activities without inconvenience.
- Perceptive/Aesthetic Appeal: The design should be visually appealing and discreet, encouraging user acceptance and regular use. For example, soft fabrics, such as cotton and merino wool, enhance the personal connection between the wearable and the user, fostering positive feelings.
- Soothing Experience: This mainly depends on the type of fabric. Stretchy fabrics adjust to the body, allowing skin respiration, while soft fabrics enhance the personal connection with the user. The elasticity of the fabric can also contribute to the overall comfort and soothing experience.

By incorporating these properties, a textile wearable can effectively integrate all necessary components for health monitoring and stress management, making it a viable solution for everyday use. The comfort of a wearable is highly linked to where it is placed on the body, as mentioned in the examples of Chapter 1, like chest, arm, leg, abdomen., etc. Yet, not all body parts perceive tactile sensations at the same level.

TACTILE SENSITIVITY

The body perceives the tactile signal at different levels depending on the skin location and the type of tactile stimulus (Luo et al., 2020). The body uses receptors on the skin to capture the stimulus and transmit it to the Somatosensory Cortex in the brain. Some body parts have more receptors than others and therefore perceive more signals (Azañón & Longo, 2019).

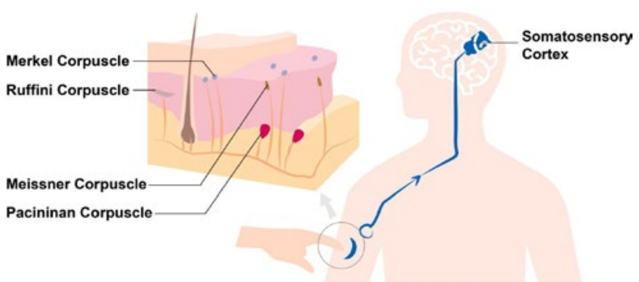


Fig. 23: Somatosensory Cortex receiving tactile input (Liu et al., 2023).

Certain body parts, like the forehead, abdomen, and fingers, have higher sensitivity. Women generally have higher tactile sensitivity than men (Myles et al., 2007). Thermal sensitivity is highest in areas like the face, hand, upper arm, abdomen, and fingers (Luo et al., 2020).

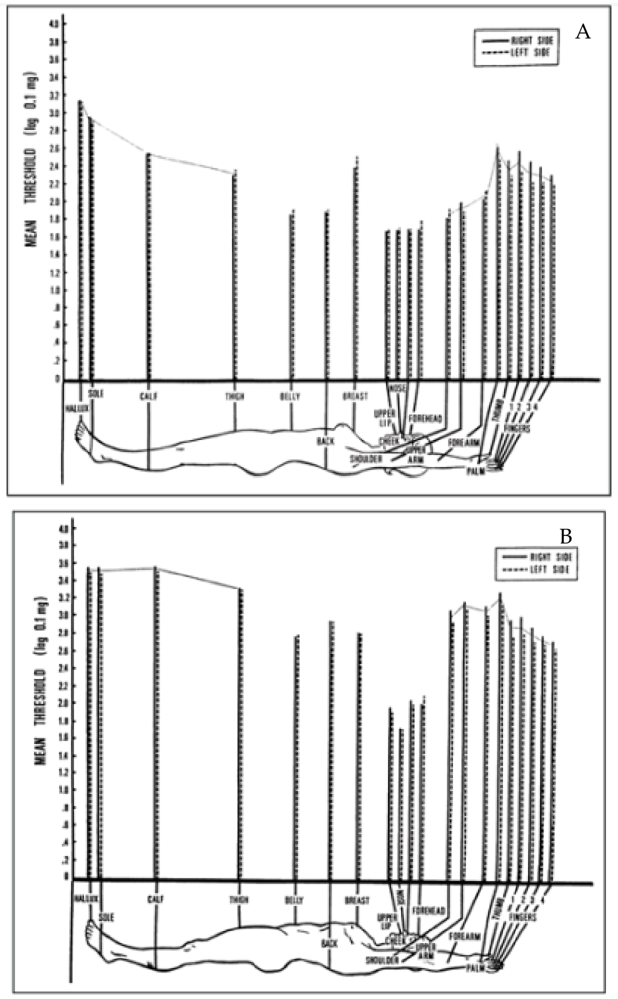


Fig. 24: Tactile sensitivity in [A] women and [B] men for different areas of the body (Myles et al., 2007).

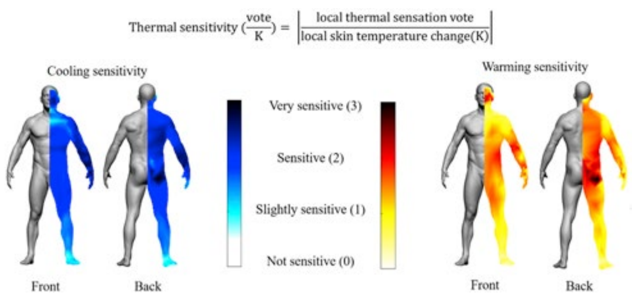


Fig. 25: Thermal sensitivity (Luo et al., 2020).

HAPTIC FEEDBACK

Once the wearable device receives the input from the sensors, it provides an output to the user, typically through sounds, visuals, or even temperature. However, innovative designs propose haptic technology as a new alternative for discreet and effective feedback. Haptic technology involves tactile feedback by applying forces, vibrations, or motions to the user (Yadav et al., 2013). It can be perceived actively or passively through the cutaneous or kinesthetic systems (Rodriguez et al., 2019).

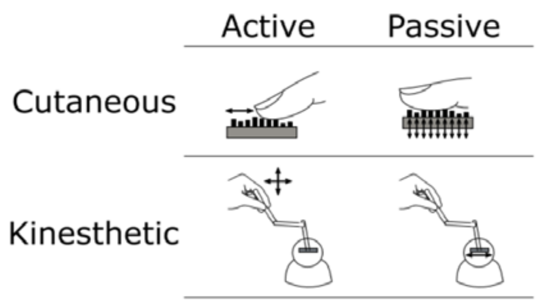


Fig. 26: Classification of haptic interaction according to the exploration modality: cutaneous active, cutaneous passive, kinesthetic active, and kinesthetic passive (Rodriguez et al., 2019). sensitivity (Luo et al., 2020).

Based on the user's haptic perception, devices are classified into three primary categories)Figure 27): graspable, wearable, and touchable (Lücker, 2023). A 'graspable' system delivers tactile information via a handheld device, primarily engaging the kinesthetic system. It facilitates active exploration of the environment or passive reception of tactile feedback, such as vibrations. Secondly, a 'wearable' system is affixed to a body part, conveying sensations directly to the skin through shear force. This system can actively provide information through varying vibration levels based on skin temperature changes or passively detect biomarkers, such as heartbeats. Lastly, a 'touchable' system offers feedback when the user actively strokes its surface or when the surface moves passively, exemplified by navigation devices designed for visually impaired individuals.

Wearable haptic feedback can include pressing, squeezing, stroking, pinching, and dragging (Liu et al., 2023). Examples include pneumatic air compression for pressure feedback and servo motors for squeezing actuation. In the studies, researchers investigated the psycho-physical characteristics of the system including absolute detection and Just-Noticeable Difference (JND) thresholds (Muthukumarana et al., 2020). In comparison to vibrotactile and thermal feedback, squeezing feedback is particularly more pleasant for communicating feelings (Liu et al., 2023) .

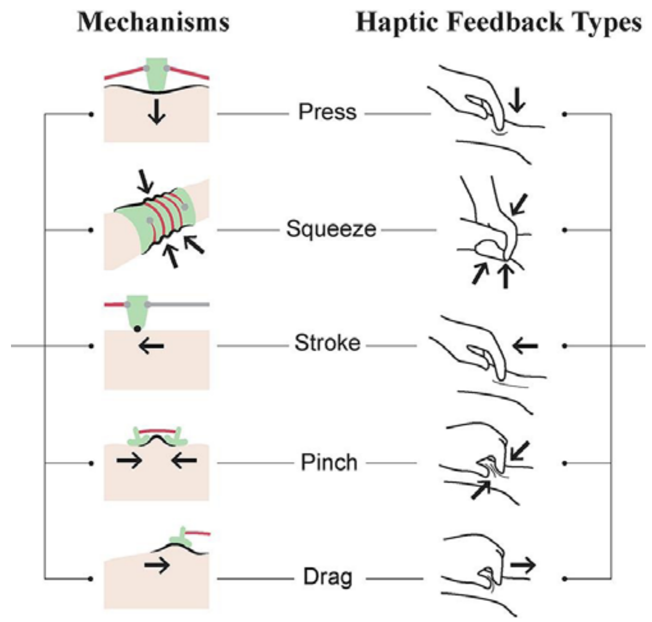


Fig. 28: Haptic Feedback Types and their respective mechanisms on Wearables (Liu et al., 2023).

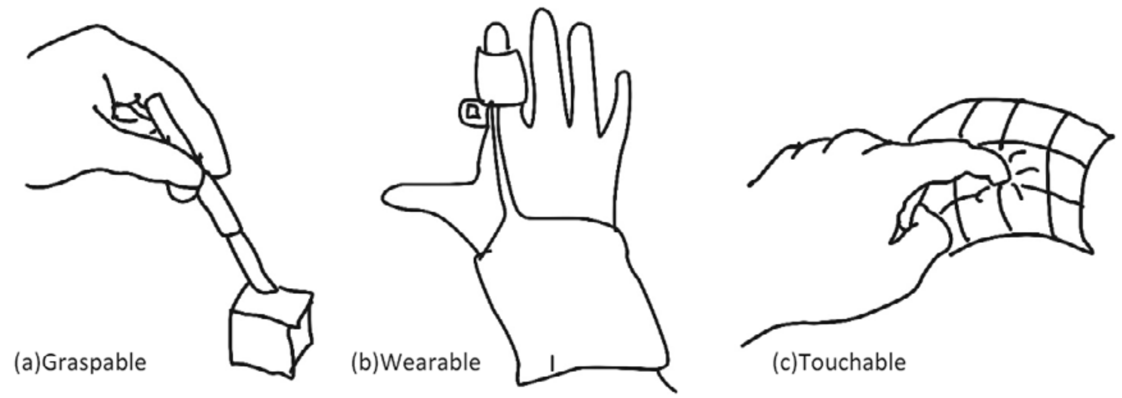


Fig. 27: Classification of haptic feedback devices, graspable (a) left, wearable (b) middle, and touchable (c) right (Lücker, 2023).

2.1.2 Applications

Chapter 1 discussed medical devices focusing on biomarker measurement. Increasingly, Human-Computer Interaction (HCI) studies explore interfaces that help people focus on their inner body, such as through breathing (Prpa et al., 2020). This section presents medical wearable examples with advanced properties for enhanced HCI, incorporating biosensors, haptic feedback, breathing guidance, and morphing materials (detailed in Chapter 3).

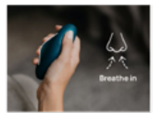
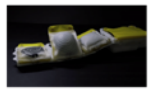
	WHAT	WHO/WHEN	WHERE	HOW	
Product	**Medical purpose**	**Target Group**	**Body Location**	**Technical properties**	**Feedback**
The Emotional Clothing collection  Finney, A. (2022, February 3). Emotional Clothing responds to the wearer's changes in stress levels. Dezeen. https://www.dezeen.com/2021/12/12/iga-weglinska-emotional-clothing-stress-body-changes/	Increase the awareness of stress/ anxious feeling and invite to practice mindfulness and breathing.	People with stress and visually-impaired people	Upper part of body (garment)	• Sensors that react to the wearer's heart rate and temperature and Galvanic Skin Response (GSR) • Conductive thread	Colour or lighting changing
Moonbird  Moonbird. (2024). Moonbird: the world's first handheld breathing coach. https://www.moonbird.life/science/	Actively practice slow and deep breathing with tactile guidance cues to reduce stress and sleep disorders	People with stress, anxiety and insomnia	Hand and fingers	• A sensor measures heart rate • Mechanical motors to simulate breathing	Tactile breathing exercises: expansion (inhale) and compression (exhale)
Breathing Garment  Kilic Afsar, O., & Ishii, H. (2021, July). Breathing garment: a respiratory regulation garment for voice pedagogy. MIT Media Lab. https://www.media.mit.edu/projects/breathing-garment/people/	Encourages optimal posture and breathing patterns for voice pedagogy	Singers and althletes	Trunk, specially abdomen	Omni Fiber technology: robotic fibers recording the movement data from the strain sensors woven into the garment.	Haptic feedback whether in the form of soft vibration, compression or lateral skin stretch.
BioLogic  Ishii, H. (2016, February 16). A living, breathing textile aims to enhance athletic performance. MIT Media Lab. https://news.mit.edu/2016/living-breathing-textile-aims-to-enchance-athletic-performance-0216	Ventilate high temperature and sweat from the body and enhance its sports performance	Athletes	Trunk and feet	Bacteria Bacillus subtilis natto embebbed into fabric	Opening and closing flaps around heat body zones
aSpire  Choi, K. Y. (2021). ASPiRE: Clippable, mobile Pneumatic-Haptic Device for breathing rate regulation via Personalizable Tactile Feedback. MIT Media Lab. https://www.media.mit.edu/projects/aspire/overview/	Regulate breathing rate in out-of-home environments with a portable clippable device	People that want to practice breathing in any scenario	Anywhere in touch with a belt/ strap: waist-belt, seat-belt, straps of backpack and cross-bag	• Pneumatic system with individual control • Customized stretchable pressure sensor	Haptic feedback in non-machine natural tactile pressure
FibeRoto  Kilic Afsar, O., Forman, J., & Nicita, S. (2023). FiBeRoBo: Fabricating 4D fiber Interfaces by Continuous drawing of temperature tunable fibers. MIT Media Lab. https://www.media.mit.edu/projects/fiberobo/overview/	Cloth that can compress around when exposed to heat	Everyone: altheles, medical patients, fashion designers, animals...	Anywhere	Novel body-temperature shape-changing fiber based on liquid crystal elastomers.	Any type of haptic feedback

Table 3: Overview of Chapter 2. Applications of smart wearables.

An example of a design that combines biomarker measurement with relaxing haptic exercises is Moonbird. This device guides slow breathing through tactile hand exercises, effectively reducing stress within five minutes and improving sleep quality in insomnia cases by 78%. It offers real-time biofeedback on heart rate (HR) and heart rate variability (HRV) and can be operated with or without an accompanying app (Moonbird, 2024). Although it is a 'touchable' design rather than a wearable, it provides valuable insights into this combined mechanism and suggests opportunities for integrating 'touchable' and wearable technologies.

Fig. 29: Moonbird device for breathing guidance (Moondbird, 2024)

The Emotional Clothing Collection of fashion designer Iga Węglińska tries to enhance awareness of the wearer's stress levels with color and lighting-changing garments. It uses heart rate and skin temperature sensors to detect stress and connect the components with conductive threats (Finney, 2022).

Fig. 30: Emotional Clothing of fashion designer Iga Węglińska (Finney, 2022).

The MIT Media Lab recognizes the potential of breathing applications using morphing fibers, which are textiles that alter shape in response to external stimuli. For example, the Breathing Garment captures the kinetic expertise of a singer and kinesthetically teaches singers to control various respiratory muscle groups (Kilic Afsar & Ishii, 2021). This garment utilizes soft, pneumatically-actuated fibers. MIT highlights that such technology can also benefit athletes, post-surgery patients, individuals with respiratory diseases (such as COVID-19), and those with sleep apnea disorders.

Fig. 31: Breathing Garment from MIT Media Lab (Kilic Afsar & Ishii, 2021).

Alternatively, to pneumatics, other technologies try to simulate breathing systems for athletes' performance improvement. BioLogic combines biomaterials research with textile design. A bacteria that responds to atmospheric moisture with expansion and contraction is embedded into fabric to ventilate garments. Thus, this synthetic "second skin" reacts to body heat and sweat and opens flaps until the body is cooled down. The brand New Balance is working on developing this technology in sportswear too (Ishii, 2016).

Fig. 32: BioLogic design from MIT Media Labs (Ishii, 2016).

A notable example of a clippable, mobile device for regulating breathing rate (BR) is aSpire (Choi, 2021). This device employs a pneumatic-haptic design to deliver customized tactile feedback, including various stimulation patterns, intensities, and frequencies. The air pouch actuators can individually inflate and deflate. It can be conveniently clipped to a strap or belt for use outside the home. Additionally, experimental tests indicate that aSpire maintains high energy and pleasantness without inducing stress. However, it is noted that the motor generates some noise during operation.

Fig. 33: aSpire from MIT Media Lab: two different tactile patterns (Choi, 2021).

Another interesting example of shape-changing technology is FibeRobo. This innovative liquid crystal elastomer fiber facilitates self-reversing morphing at, or just above, body temperature. Its applications range from medical devices –compression shirts– and athletic wear –self-ventilating clothing– to interactive dining experiences –morphing tablecloths– and transforming fashion pieces (Kilic Afsar et al., 2023).

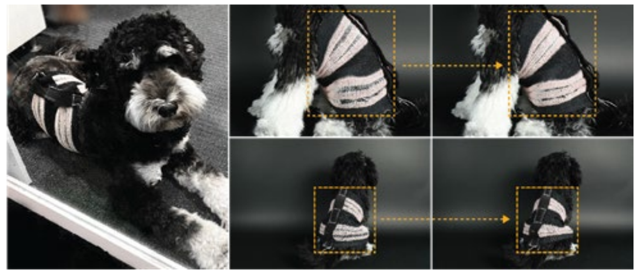


Fig. 34: A dynamic compression garment enables a dog to be hugged from afar (Kilic Afsar et al., 2023).

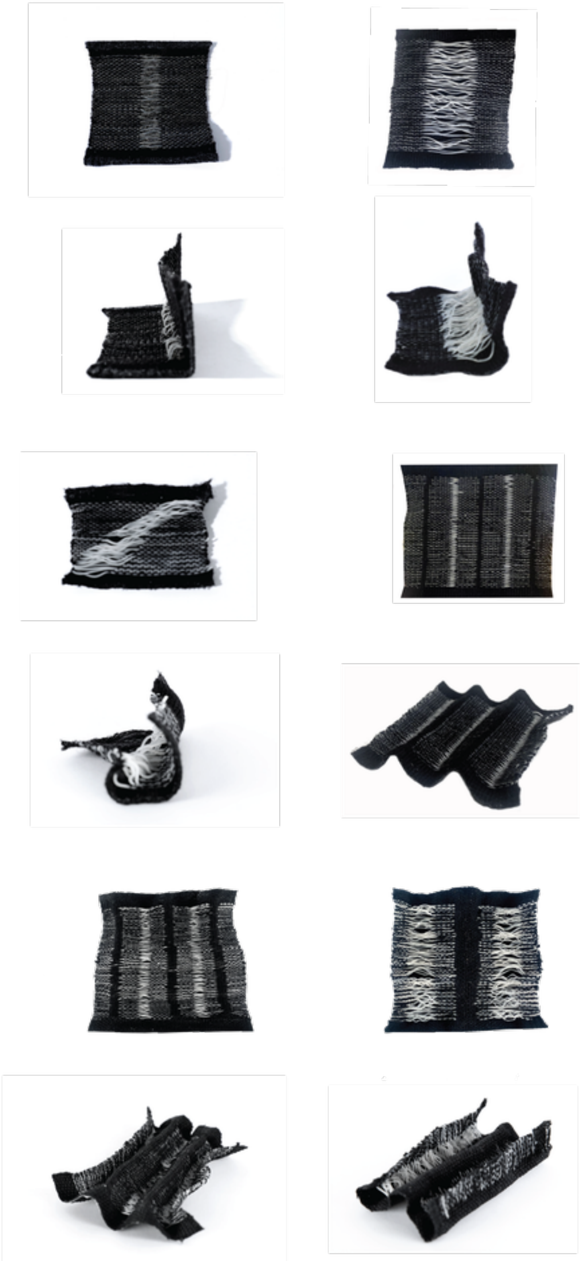


Fig. 35: Different woven samples exhibiting silently reversible shape-shifting in response to heat (Kilic Afsar et al., 2023).

2.2. Applied Practices

2.2.1. Heart Rate sensor tinkering

Exploration with a pulse sensor experiment (PPG technology) for measuring heartbeat provided a basic understanding of its use and electronic components. Yet, it was observed a clear instability of the pulse sensor signal compared to a smartwatch's heartbeat sensor (Figure 37), which would need furhter exploration. An experiment with Arduino microcontroller and the grove mosfet showed good potential for regulating power and therefore avoiding overheating and short-circuits (figure 38).

2.2.2. Conductive textile tinkering

Two experiments with conductive textile and thread revealed their potential as 'cables' and for switching

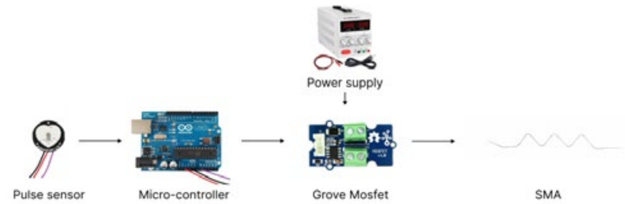


Fig. 36: Overview of the simplified circuit connecting the pulse sensor and the SMA.

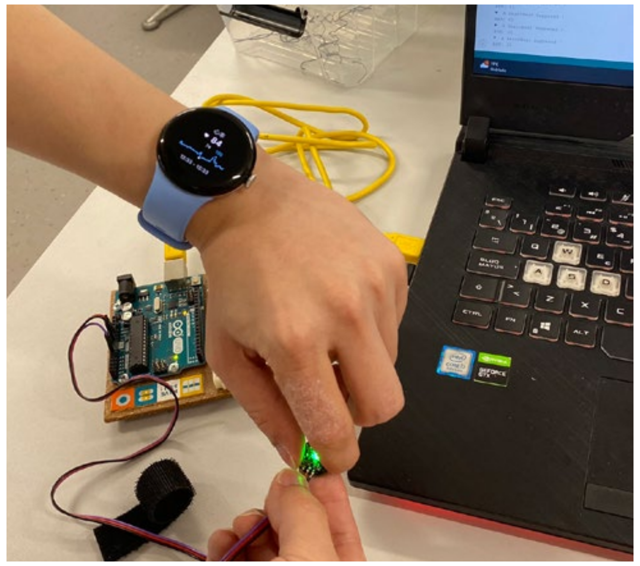


Fig. 37: Testing of the pulse sensor and comparison with the heartbeat sensor of the smartwatch.

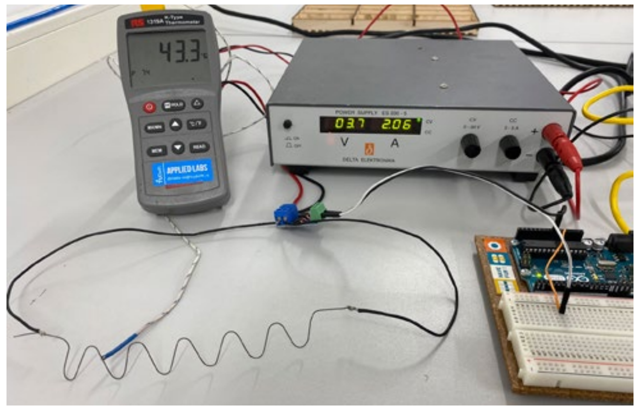


Fig. 38: Testing of the SMA with grove mosfet and micirocontroller.

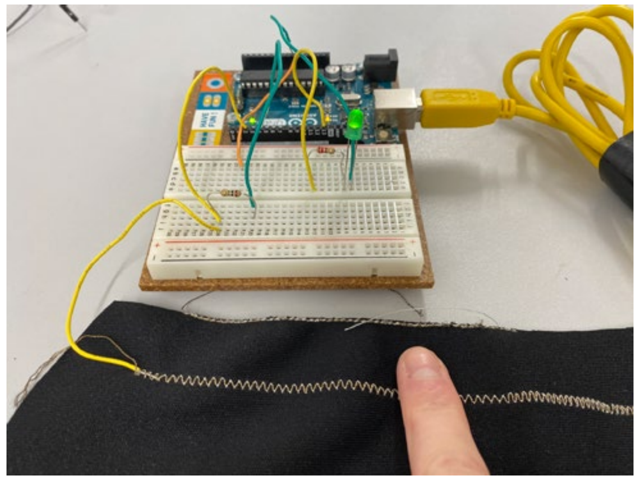


Fig. 39: Testing of conductive threat as a switch on/off sensor.

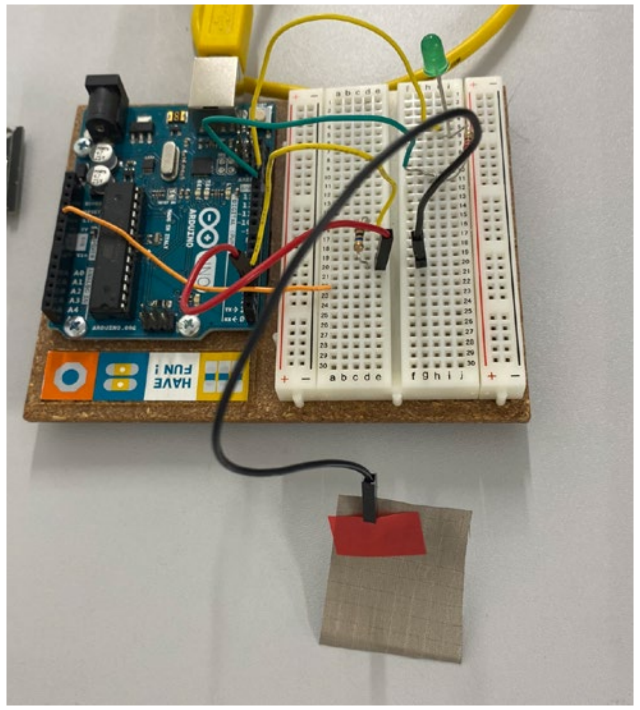


Fig. 40: Testing of conductive textile as a switch on/off sensor.

2.3. Discussion

Chapter 2 offers essential insights into smart wearables, crucial for the design process. Wearable Health Devices (WHDs) are gaining interest in healthcare due to their significant health benefits, including continuous monitoring and rapid diagnosis. A WHD comprises three elements: a sensor for data input (the 'controlled element'), an actuator for haptic feedback (the 'active element'), and a substrate to integrate components into a comfortable device (the 'passive element'). Typical heart rate measurements range from 60 to 100 bpm, while heart rate variability (HRV), an indicator of stress adaptability, ranges from 20 to 100 ms.

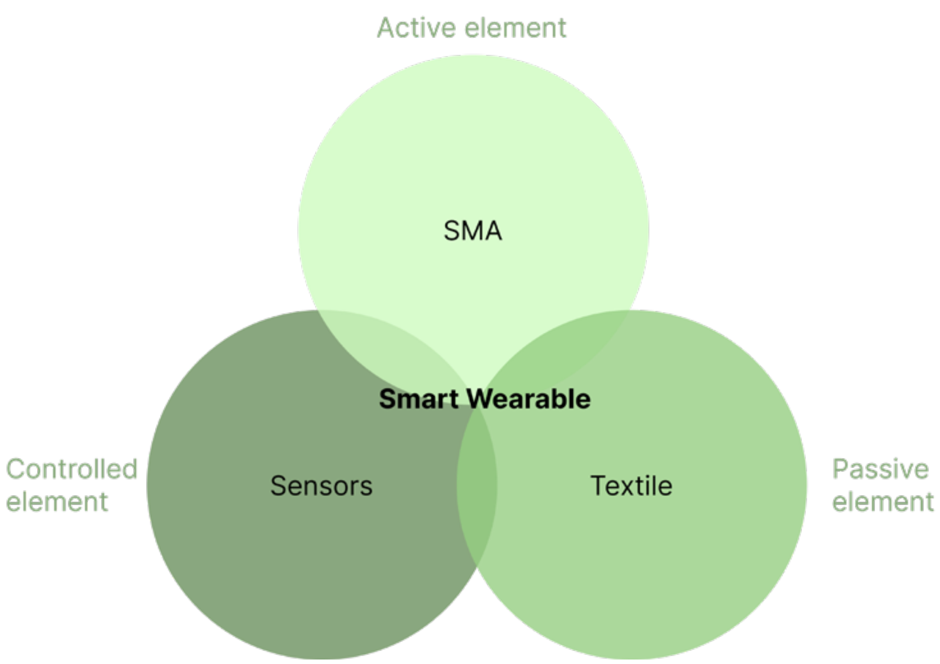
However, there is limited information on shape-changing actuators, primarily found in academic research, such as at MIT. Current designs tend to focus on either shape-morphing materials for sports or breathing-mimicking haptics using pneumatic systems. Thus, a wearable combining shape-morphing materials with heart rate sensors and tactile feedback holds promise for enhancing Human-Computer Interaction (HCI) and well-being.

Smart textiles demonstrate potential for effectively fitting diverse users due to their softness and elasticity, and for integrating conductive properties to measure key anxiety indicators like heart rate and HRV. Conductive thread seems promising for simplifying and comparing electronic circuits, making designs lighter, discreet, and less intrusive.

Additionally, experiential studies of wearables assess the psycho-physical characteristics of the system through the user's perception threshold, combining noticeability and comfort. The most sensitive body parts for pressure and warmth are the head, hands, arms, and abdomen, which have more receptors connected to the Somatosensory Cortex. Therefore, these parameters can be tested with users for both technical and experiential characterization.

Furthermore, haptic biofeedback can be provided in various forms (e.g., squeezing, pressure, compression) and through different devices (wearable, graspable, touchable). For instance, squeezing feedback is ideal for communicating calmness. Combining these feedback types into one design could significantly enhance user impact.

These key insights and their implementation in the project are illustrated in the following figures:



Key Insights from Chapter 2

- Wearable Health Devices (WHDs) provide effective continuous health monitoring for rapid diagnosis.
- WHDs integrate three key elements:
- Controlled: Sensors that collect input
- Active: Components providing haptic feedback
- Passive: Elements that integrate components and enhance user experience through wearability and comfort
- Current solutions do not combine biosensors and haptic feedback. Typically, they use mechanical or pneumatic actuators, which are bulky and noisy. There is a need for innovative, discreet actuator designs, such as integrating morphing materials.
- Breathing is an efficient way to voluntarily and indirectly control our physiological state. Heart rate (HR) typically ranges from 60 to 100 bpm, and heart rate variability (HRV), indicating stress adaptability, ranges from 20 to 100 ms.
- Breathing enhances Human-Computer Interaction (HCI) and well-being by providing user input and tactile biofeedback.
- Psycho-physical characteristics are evaluated via the user's perception threshold, which combines perception (noticeability) and comfort. Squeezing feedback is ideal for communicating calm.
- Haptic devices include wearable, graspable, or touchable forms. The most pressure-sensitive areas are the head, hands, arms, and abdomen.
- Using conductive thread makes electronics discreet and less intrusive.

Relevance for the Project

1. Wearables are intended for daily use, allowing users to focus on themselves and practice breathing techniques voluntarily.
2. Instant feedback on heart rate (HR) and monitored improvement in heart rate variability (HRV) can increase awareness of anxious conditions and their improvement.
3. The wearable design can integrate three elements: an optical heart rate sensor, SMA, and elastic-soft textile.
4. Technical characterization of the design can be assessed through HR, breathing cycles, and haptic feedback.
5. Experiential characterization involves evaluating wearability, user perception, comfort, and calmness.
6. Squeezing feedback can be implemented in wearable (abdomen), graspable (hand), or touchable (any) forms.
7. Conductive thread can replace electronic components like cables and sensors, enhancing the discreteness of the design.

Table 4: Overview of key insights from Chapter 2 and their relevance for the project.

Chapter 3.
Shape Memory Materials

The third chapter explores the theoretical foundation of shape morphing materials, specifically within the healthcare sector's smart materials. It details the opportunities and limitations of Shape Memory Alloys (SMA) in haptic devices and wearable designs. Meaningful examples of SMA highlight its potential for anxiety relief and innovative haptic mechanisms.

The theory is applied at the lab through material tinkering of SMA and textiles, as well as a technical characterization of integrated SMA-textile prototypes.

3.1. Literature Review

3.1.1. Definition

SMART (MORPHING) MATERIALS IN HEALTHCARE

In the previous chapters, it was seen how wearable devices are experiencing enormous growth in health applications along with technology development. The trade-off between the quality of the actuators –rich feedback– and bulkiness creates new opportunities for design innovation (El Saddik et al., 2011).

To address these challenges, smart materials integrated into health wearable devices bring a promising approach. Smart materials are defined as materials that can be active and responsive to various stimuli, such as temperature, electricity, magnetism, humidity, and light (Bengisu & Ferrara, 2018). For instance, flexible sensors in soft robotics can improve mechanical transmission as well as ergonomic comfort (Miriyev et al., 2017). In the last decades, the morphing matter that changes shape and properties due to external stimuli is gaining significant interest from scientists and engineers, leading to its development in various fields, such as biomedical engineering, robotics, energy, and aerospace (Patel et al., 2023). Along with the technical challenges and utilities of morphing materials, researchers are placing high attention on healthcare designs.

SHAPE MEMORY MATERIALS (SMMs)

The phenomenon of shape morphing, or changing, is commonly described by the term shape memory. In the book Materials that Move (2018), Bengisu and Ferrara describe shape memory materials (SMMs) as "smart materials that have the capacity to "remember" a certain shape they were 'trained' to adopt." As part of the group of kinetic materials, they classify SMMs in two frameworks, material-based and stimulus-based. The material-based classification includes shape memory alloys (SMAs), shape memory polymers (SMPs), shape memory ceramics, shape memory composites (SMCs), shape memory gels (SMGs), and electrorheological and magnetorheological fluids. The stimulus-based classification involves materials that are thermoresponsive, magnetostrictive, electroactive, piezoelectric, photoresponsive, and pH-responsive. The temperature change is the most common stimulus.

In the project of Mila Lucker (2023), it is shown a clear overview of SMM classifications based on the "Materials that Move" book (see Figures 41 and 42).

Shape memory materials are based on the shape-memory effect (SME) defined as '...the ability to recover their original shape from a significant and seemingly plastic deformation when a particular stimulus is applied' (Huang et al., 2010). Depending on the material- and stimulus-based, the SME can be one-way, two-way, and multi-way (Bengisu & Ferrara, 2018;

Rao, Srinivasa & Reddy, 2015). One-way SME means that the material returns to one specific 'trained' shape when exposed to an external stimulus –normally heated–, and can be deformed with an applied force. This force can be a human force, a counterforce from the structure (e.g. Textil), or an opposite SME (spring). On the other hand, two-way and multi-way have two or more 'trained' shapes, respectively, when exposed to different stimuli. One example is multi-SME polymers that have shape transitions at multiple melting points. Although two- or multi-way SMEs can offer significant advantages, they require high expertise and equipment for the training process and are less predictable than one-way SME (Huang et al., 2010). Therefore, this project will focus on the effective and controllable functionality of one-way SMA.

Additionally, other phenomena like Superelasticity (in alloys) or visco-elasticity (in polymers) are also commonly observed under certain conditions. Superelasticity, or pseudoelasticity, happens when a material deforms until 8% and returns to its original shape after the load is removed. Some applications are orthodontic braces and highly flexible glasses (Bengisu & Ferrara, 2018). However, for more macro-structures, such as medical wearable devices, the SME superelasticity deformation remains too low, and therefore shape memory will offer more advantages (Huang et al., 2010).

SMA and SMP are showing incredible potential in multiple engineering and medical applications over problematic traditional materials and approaches due to their high performance and good biocompatibility (Huang et al., 2010). For example, in aerospace engineering they are utilized in deployable structures and morphing wings, and in medical devices, they are implemented as stents and filters (Lipscomb & Nokes, 1996; Duerig, Melton & Stöckel, 1990). Since the wearable design of this project focuses on the integration of components and user comfort, shape memory alloy (SMA) is selected and explored further.

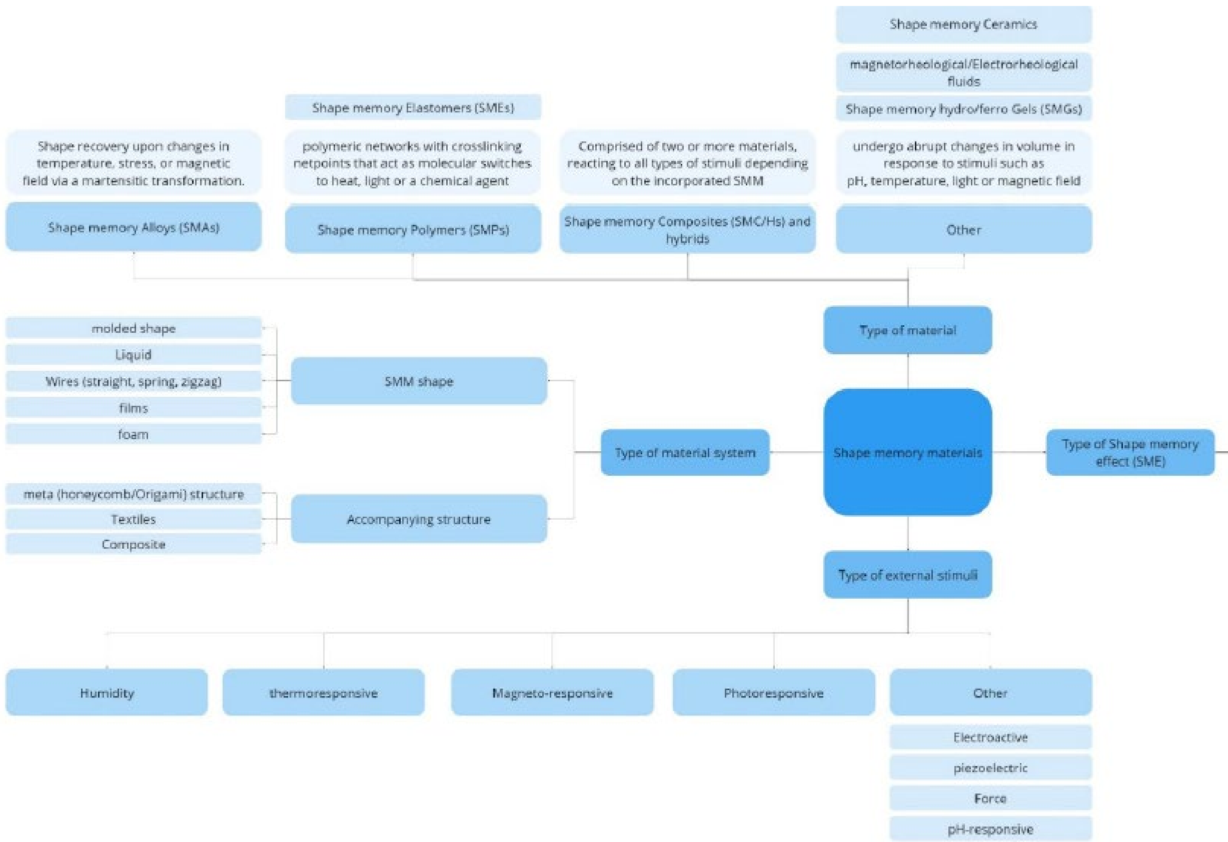


Fig. 41: Overview of shape memory materials classification (Lücker, 2023).

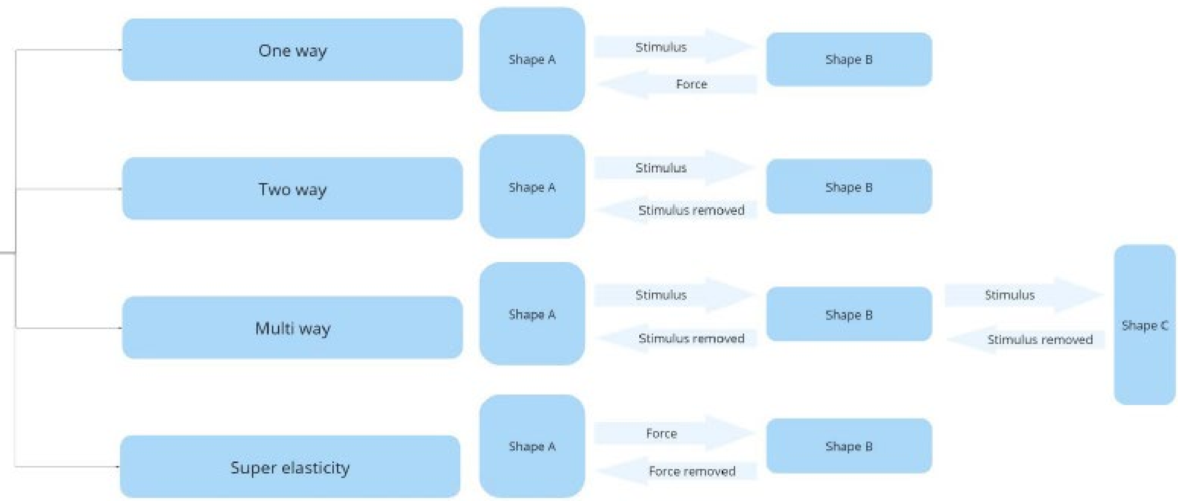


Fig. 42: Shape memory effect (SME) classification (Lücker, 2023).

WORKING PRINCIPLES OF SMA

SMA are metals which can return to their initial shapes after training. This is the result of a shape memory effect (SME) and a temperature memory effect (TME) (Huang et al., 2010). SME is based on a martensitic transformation of the crystal structure within the metal (Bengisu & Ferrara, 2018; Rao et al., 2015).

There are four key temperature stages (from low to high temperature level): Mf (Martensite finish temperature), Ms (Martensite start temperature), As (Austenite start temperature), and Af (Austenite finish temperature). First, the SMA is deformed from a twinned martensite phase to a detwinned state martensite phase (Ms-Mf). Second, it is heated above As and the detwinned martensite phase starts to transform into the austenite phase (Af). Third, it is cooled down again (Ms) and the austenite phase transforms into twinned martensite (Mf). The internal stress generated is released by the different twinned martensite themselves (self-accommodated martensite variants (Sun et al., 2012).

This cooling-heating cycle is called the Shape Memory Effect (SME) and is a reproducible transformation. Each time the SMA is deformed and exposed to the transition temperatures it will trigger the shape change and it will return to its original or ‘trained’ shape (Bengisu & Ferrara, 2018). In order to program the ‘trained shape’, the SMA needs to be shaped and fixed on a frame and, subsequently, heated at the annealing temperature, significantly higher than Af.

The difference between the beginning and end of the cooling (Mf) and heating (Af) transformations is called hysteresis. A short hysteresis means short cycles and vice versa (Sun et al., 2012).

There are many SMA types of composition –Ni-Ti-Cu, CuZn-Al, Cu-Al-Ni, and Ni-Ti– being Nitinol (50% nickel and 50% titanium) , the most frequently used due to its affordability and reliability. However, when a short cycle (or short hysteresis) is required, the addition of Cooper (Cu) is needed (Bengisu & Ferrara, 2018). Nitinol can be manufactured in multiple forms, such as films, foam or liquid, yet wires stand for its optimal integration into device designs.

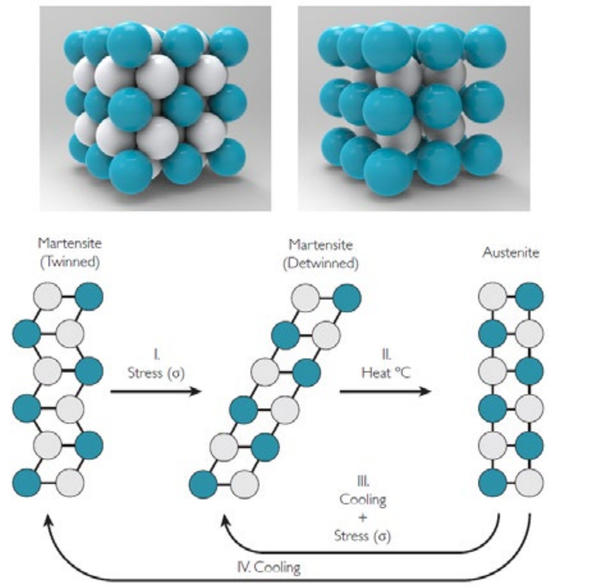


Fig. 43: Crystal structure transformation within SMA (Franssen, 2017).

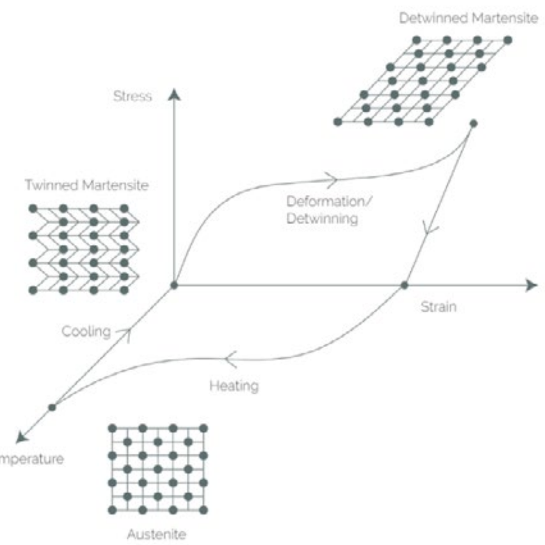


Fig. 44: Visual representation of martensitic phase transformation of an SMA (simplified version of Abdelrahman & El-Hacha, 2021)

SMA PERFORMANCE IN HAPTIC DEVICES

There are some essential parameters of SMA to consider when designing a haptic device: force, displacement, working temperature, cycle time, actuation time, and energy efficiency.

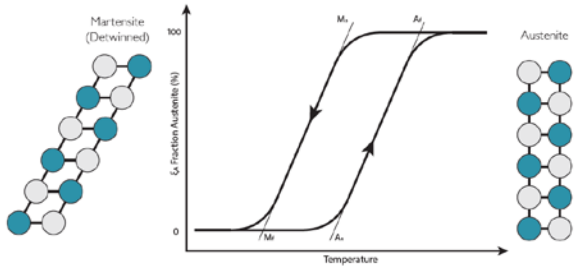


Fig. 45: Hysteresis phase transformation (Franssen, 2017).

- FORCE, DISPLACEMENT AND TEMPERATURE

SMA performance is mainly described by the correlation between the force (actuation stress), the displacement (actuation strain), and actuation temperature. The stress-strain curve graph shows this correlation for both martensite and austenite phases at low and high temperatures (Liu et al., 2023). It highlights that a SMA system generates larger actuation force at higher temperature conditions. The actuation stress of a pre-stretched Nitinol wire is reported to be 100–500 MPa.

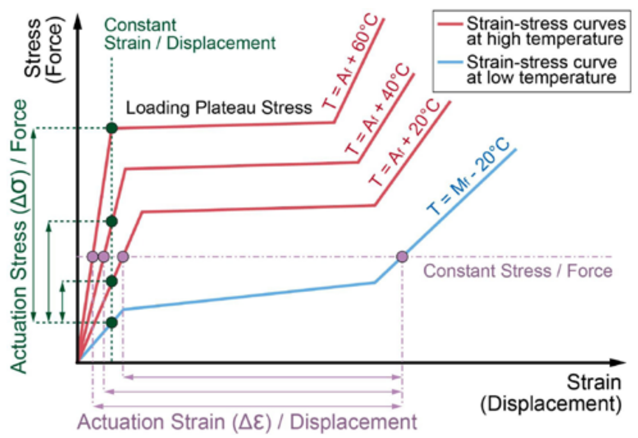


Fig. 46: Actuation stress and strain can be obtained with the stress–strain graph (Rao et al., 2015) .

Additionally, the displacement-temperature and the force-displacement correlations help to predict and control the SMA performance. In the following graphs, it can be observed that when SMA is heated it contracts (negative displacement) and it increases the force. Both graphs show a slow-fast-slow transformation that is important to take into account when creating cycles.

SMA wires stand out for their high power-to-weight ratio, often used in tension due to their actuator efficiency and energy density (Jani et al., 2016). Wire strength varies with composition, training, diameter, and its phase state. For example, commercial NiTi generates 25 times higher work density than electric motors (Jani et al., 2014).

The actuation displacement, or length variation of the actuator, can be measured with the actuation strain, which is equal to the displacement amplification factor.

$$f_{wire} = \frac{\delta^{L}_{wire} - \delta^{H}_{wire}}{l_{wire}} = \Delta\varepsilon_{wire}$$

where δL wire and δH wire is the displacement of SMA wire at low and high temperature respectively, l wire is the original length of SMA wire.

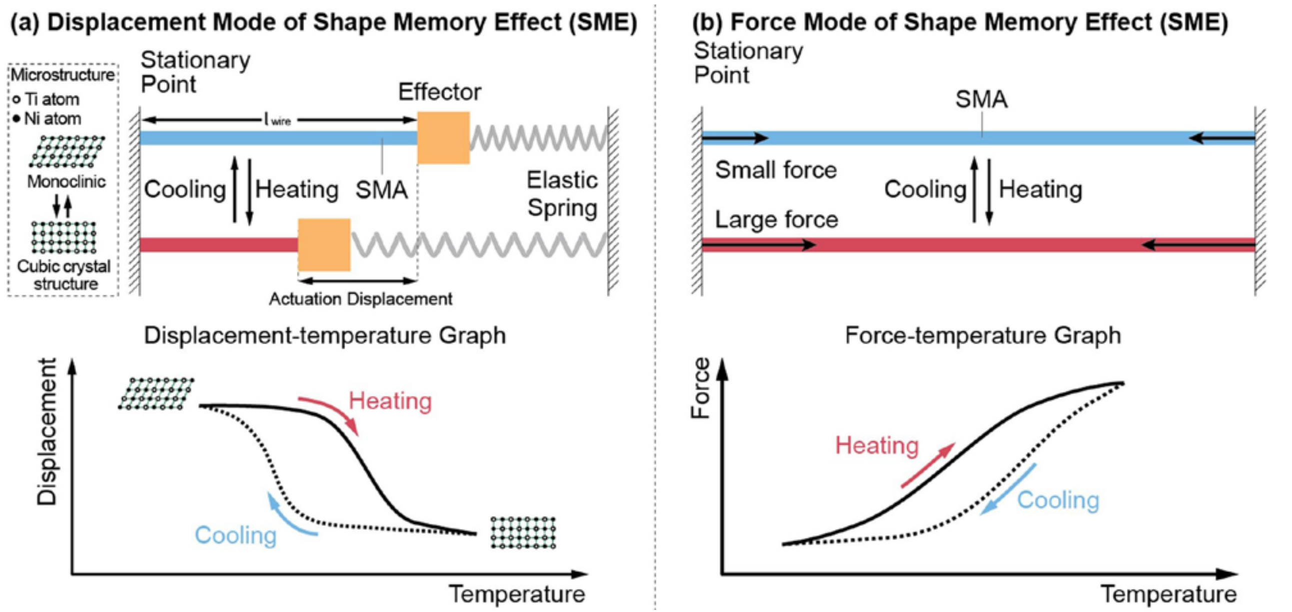


Fig. 47: (a) SMA microstructure, displacement mode, and displacement-temperature graph. (b) SMA force mode and force-temperature graph (Liu et al., 2023).

For increasing the actuation displacement, different mechanisms can be applied, such as zigzag, tube-guided, spring, and knitted actuators. These four mechanisms can be seen in Figure 48.

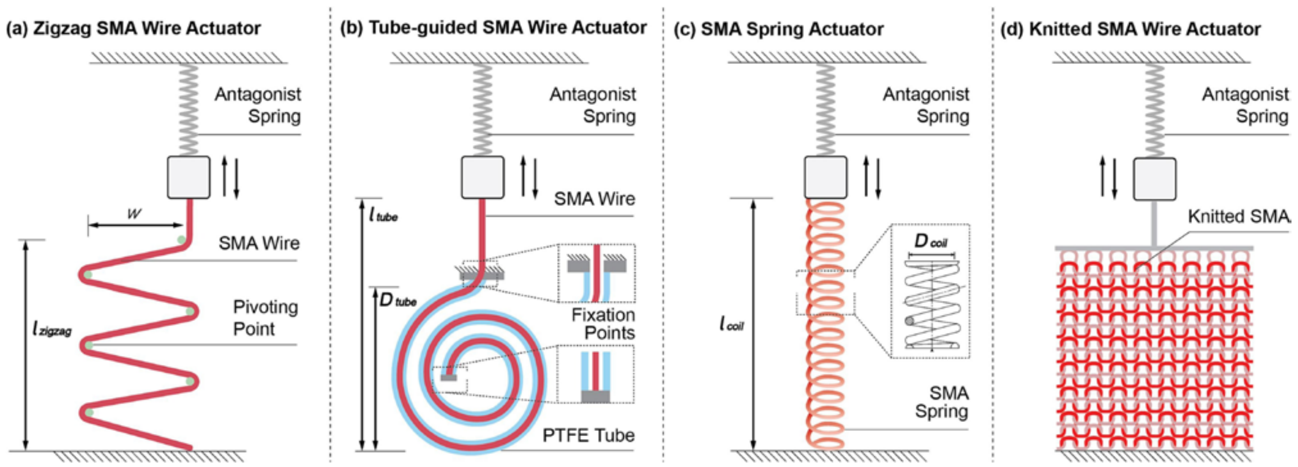


Fig. 48: Constructions for increasing the actuation displacement: (a) Zigzag SMA wire actuator. (b) Tube-guided SMA wire actuator. Note that the tube can be winded in a same diameter circle or in a spiral. If it is in spiral, the Eq. (3) needs to be redefined. (c) SMA spring coil actuator [65]. (d) Knitted SMA wire actuator (Liu et al., 2023).

- ACTUATION TIME, CYCLES AND FATIGUE

The time needed for making each heating-cooling cycle is called actuation time. The actuation time of SMA actuators is reported from 0.5 s to 30 s in the literature (Nakshatharan et al., 2014). The time needed for the SMA to return to 'trained' shape is called response time. Instead of environmental heating, wearable devices actuate when an electrical current is applied to the SMA wire. This is called the Joule effect and can be calculated with the following equation:

$$E_n = I^2 \rho_R L t_{heat}$$

in which I is current, ρ_R is the electrical resistivity, L is the length of the SMA wire, that is the heating time.

Increasing the current can reduce the heating actuation time, yet it will impact on a larger cooling actuation time due to the limited heat transfer rate to the surrounding environment Nizamani & Daudpoto, 2017). Different ways to reduce the cooling time are reported, such as using thinner wires, enhancing airflow or cold fluid flow, or using wires with higher actuation temperatures –faster initial cooling rate–(Liu et al., 2023).

The continuous SMA exposure to cycles can negatively affect the shape recovery performance, also called 'memory loss'. Rao, Srinivasa, and Reddy (2015) distinguished structural fatigue, produced by repeated high cyclic mechanical loads; and functional fatigue, the result of repeated thermomechanical cycling. Both can degrade SMA properties –hysteresis–, decrease transformation strains, and affect transformation temperatures. Some factors that lead to fatigue are the shape manufacturing process, overheating, overstressing/loading, and overstraining (Jani et al., 2014).

- ENERGY EFFICIENCY

When designing SMA wearable devices, the Joule heating and its energy consumption need to be considered. It mainly depends on geometric dimensions and transformation temperatures. It is reported that the maximum energy efficiency of SMA actuators stays in a range of 10–15% which means that is significantly lower than other types of actuators, for example vibration actuators (Liu et al., 2023). A way to reduce the consumption is with counterforces that substitute other active SMA and therefore the supply change is not continuously activated.

- COUNTERFORCE

As mentioned in Chapter 2, wearable devices are composed of three elements: active, passive, and controlled. In this case, SMA actuators are the active element, the textile material is the passive element, and the sensors are the controlled element. This means that the textile material works as a substrate structure for the haptic feedback to the user, in addition to the

user's comfort. The substrate material can facilitate –or accelerate– SMA performance and/or serve as a counterforce. In one-way shape memory effect, after the SMA is heated ('trained shape') a counterforce is needed to bring it back to the deformed shape and start the cycle again. This force needs to be smaller than the force in the austenite stage, but higher than the force in martensite stage (Lucker, 2023).

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

The counterforce can be internal, for instance a bias spring, superelastic wire (passively controlled), or an antagonist SMA (actively controlled); or external, such as skin or a dead weight (Weirich & Kuhlenkötter, 2019). See Figure 49. The shape-changing structure can be classified into stretchable structures, which relies on material/structure –e.g.elastomers or auxetics architecture–; deployable structures, based on the geometry, –e.g. rollable and foldable mechanism like origami–; and variable stiffness materials depending the direction –e.g. anisotropy and multi-stability–(Qamar et al., 2018).

When connecting Nitinol wires to other materials, soldering is not advisable due to the degradation of their properties (Rao & Reddy, 2015). Alternatives include TIG welding, laser welding, or epoxy adhesive. If expertise and equipment are limited, crimps are an effective way to connect electricity and limit heat buildup at the connection site.

SMA PERFORMANCE IN WEARABLE HAPTIC DEVICES

Liu et al. (2023) discuss the advantages of integrating Shape Memory Alloys (SMAs) into wearable haptic devices. SMAs require low voltage, as batteries can activate them; for instance, a 1mm diameter wire with a length of 5 cm only needs 1V. They operate within a high-temperature range, allowing optimal performance between body temperature and 100°C. Thermal insulation, such as kinesiology tape and silicone rubber, can protect the skin from burns at high actuation temperatures. SMAs are highly flexible and have a small form factor, making them preferable to rigid mechanical structures. Thin, bendable, and lightweight SMA wires can be integrated into textiles, eliminating the bulkiness of motors and pneumatics and enhancing the device's aesthetic appearance. SMAs operate noiselessly, unlike electromechanical motors, making them suitable for discrete applications in healthcare. They also exhibit excellent corrosion resistance, with a corrosion rate of approximately 34 μm/year in distilled water containing 3.5% sodium chloride. This resistance makes wearables washable, though waterproof electronic components or removable ones should be considered.

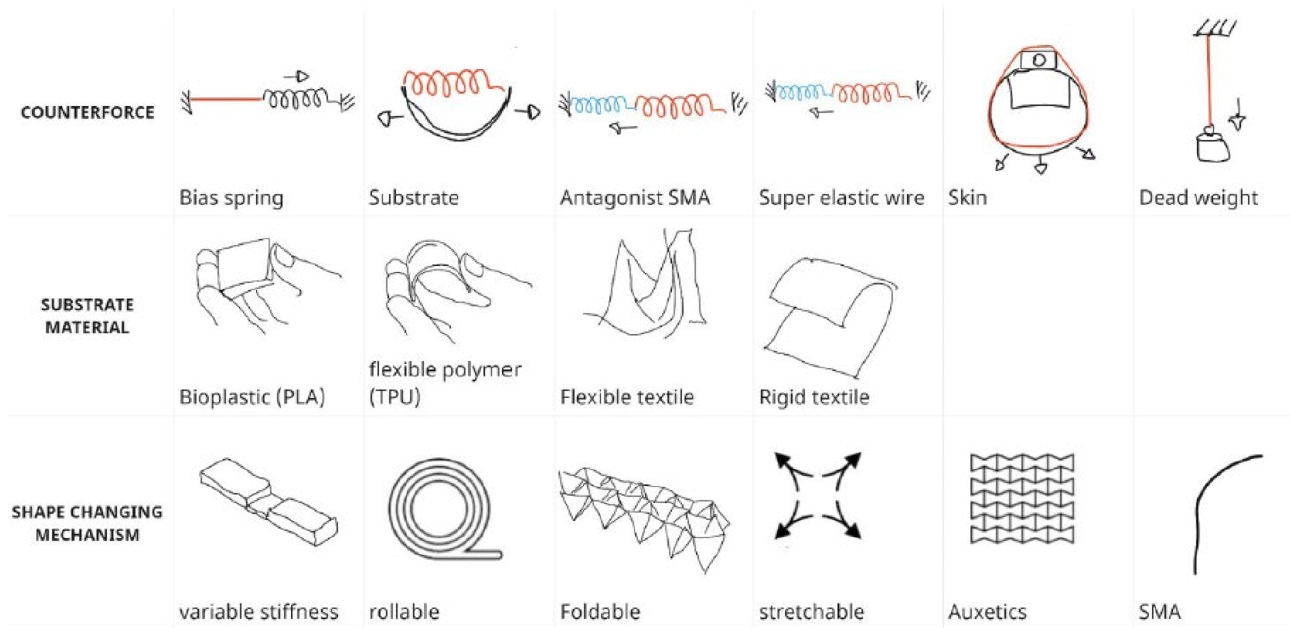


Fig. 49: Overview of the different types of counterforces, substrate structures and shape changing mechanisms found in literature (Lücker, 2023).

3.1.2. Applications

There are numerous intriguing applications of Shape Memory Alloys (SMAs) integrated into medical devices and wearables, showcasing their potential for various innovative uses

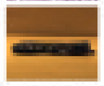
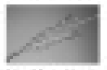
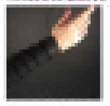
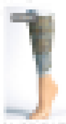
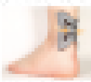
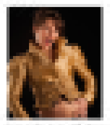
	WHAT	WHO/WHEN	WHERE	HOW	
Product	Medical Function	Target Group	Body Location	Technical properties	Haptic Feedback Type
Biomimetic artificial muscles 	Soft autonomous robot "artificial muscle" that moves via peristalsis. Its flexible design that enables body-morphing capability in tight spaces	Endoscopes, implants and prostheses	N/A	Two main micro springs "muscle groups" as worm/octopus: • Transversal circular (to move forward) • Longitudinal (turn left-right)	Squeezing to propel the robot forward (SMA stretches and contracts)
SMA Surgical instruments 	• Medical stent for replacing heart valve and treating inner body blockages • Minimally invasive surgery	Specialized surgery in body blockages, such as heart valves, arteries, urinary tracts and airways	Inner body channels	• Mesh compacts diameter when deploy in the body and expands inside • Coil springs inside tubes	Squeezing, expansion, bending, torsion
Prosthesis 	Manufacture rapid customized prosthesis via SMA and FFF 3D printing	Prosthetic rehabilitation	Hand and finger, but can be applied to any part of the body	• SMA spring integrated in printed TPU filament	Bending and torsion (bidirectional)
SereniSleeve 	Anxiety Modulation through warmth and pressure sensations typically associated with Deep Touch Pressure (DTP) • noiseless, • lightweight, • discreet	Anxiety	Forearm	• D=1mm, L=2m • Heart shape wire • Electronics disassembly: easy maintenance and washability • Heater layer mesh fabric • FRS sensor	Heating, stroking, hugging and squeezing (FSR activates SMA into 3 pressure configurations)
Affective Sleeve 	Wearable device that produces rhythmic tactile action and breathing guidance to promote calmness and reduce anxiety	Anxiety • Quantitative findings: correlation breathing rate-haptics • Qualitative findings: correlation calmness-haptics	Forearm	• 0.5 mm Nitinol wire with arc shape [illegible] • Act time 45°C • [illegible] between two insulating layers [illegible] each cuff	Pressure
Compression sock 	Orthostatic hypotension treatment through compression • large, simplified connections across the textile surface • dynamic, [illegible] and unobtrusive • limit power consumption • [illegible]	• Elderly affected by OH	Calf ([illegible] garment)	• D=0.305mm SMA knitted into textile • Act. temp.= just above body temperature ([illegible])	Compression stockings
[illegible] 	On-body interfaces deliver expressive tactile feedback on the wearer's body • slim, stretchable, and versatile forms for comfort in diverse locations • Fabricated through machine knitting.	N/A	• Under explored body locations ([illegible] joints and convex body locations) • Highest noticeability rates: [illegible]	• Act. Temp.=45°C • SMA micro-springs in knitted channels	Compression, pinching, brushing, and twisting
Shape memory jacket 	Textile garment that changes shape between evening and daytime	N/A	Upper body part	• Act. Temp=45-50°C • [illegible] wires	Bending and compression

Table 5: Overview of Chapter 3. Applications of SMA-based devices and wearables.

The MIT Media Lab has developed biomimetic soft robots that simulate "artificial muscles" based on the natural movements of worms and octopuses. These robots move using two main "muscle groups": a circular wire wrapped around a metal tube-like body for forward movement, and longitudinal microspring segments along its length for turning. These soft robots can navigate tight spaces within the body and are used in endoscopes, implants, and prostheses (Kim, 2012; Cianchetti et al., 2014).

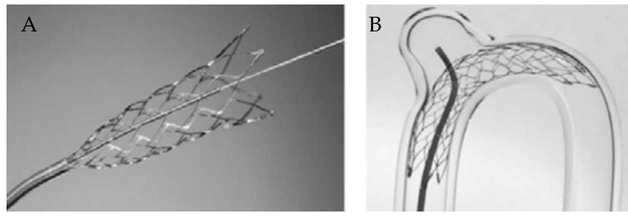


Fig. 52: SMA surgical instruments for (A) heart valve replacement and (B) airflow telesurgery (Simaan et al., 2004).

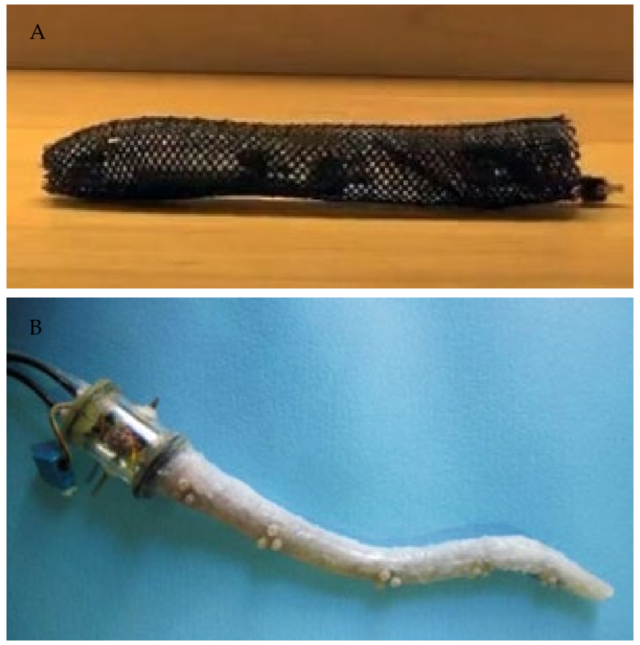


Fig. 50: Biomimetic soft robots (A) from Kim, 2012, MIT and (B) from Cianchetti et al., 2014.

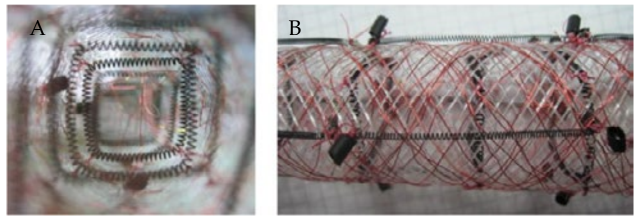


Fig. 51: (A) Transverse and (B) longitudinal SMA springs of Cianchetti et al., 2014.

Other medical applications include SMA-based instruments for specialized surgeries, such as heart valve replacements and procedures for clearing blockages in arteries, the urinary tract, and airways. These instruments facilitate minimally invasive surgeries by entering small, difficult-to-access body channels. For example, an SMA mesh stent can compact when deployed and then expand within the body, while telesurgery instruments use SMA springs for precise bending, expanding, and torsion (Simaan et al., 2004).

SMAs have also been combined with 3D printing to create customized prostheses. Designs for prosthetic hands and fingers integrate SMA springs into printed polymeric filaments, enabling bidirectional bending and torsion (Kaplanoglu, 2012; Atasoy et al., 2016).

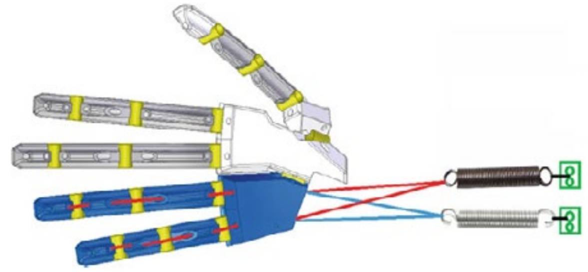


Fig. 53: SMA Prosthetic hand done by 3D printing (Kaplanoglu, 2012) .

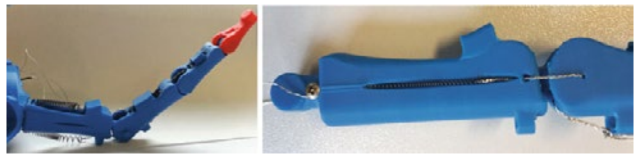


Fig. 54: SMA Prosthetic finger done by 3D printing (Atasoy et al., 2016).

Additionally, wearable devices like the Sereni Sleeve and the Affective Sleeve use SMA technology for anxiety modulation and emotion regulation, respectively. The Sereni Sleeve is a forearm wearable based on the Deep Touch Pressure (DTP) technique. It uses pressure and warmth sensations to provide a noiseless, lightweight, and discreet solution for stress relief. The sleeve incorporates multiple parallel SMA wires, trained into a heart shape, and includes an FRS sensor to activate SMAs into various pressure configurations. The compact design ensures easy removal and washing (J. Kim, 2023). The Affective Sleeve guides breathing rates through sequential tactile stimuli at distinct locations along the forearm, creating a flow of warmth and slight pressure. The fabric temperature varies from 26°C to 38°C, positively correlating the pace of haptic action with changes in physiological signals, thereby aiding in breathing regulation (Papadopoulou et al., 2019).

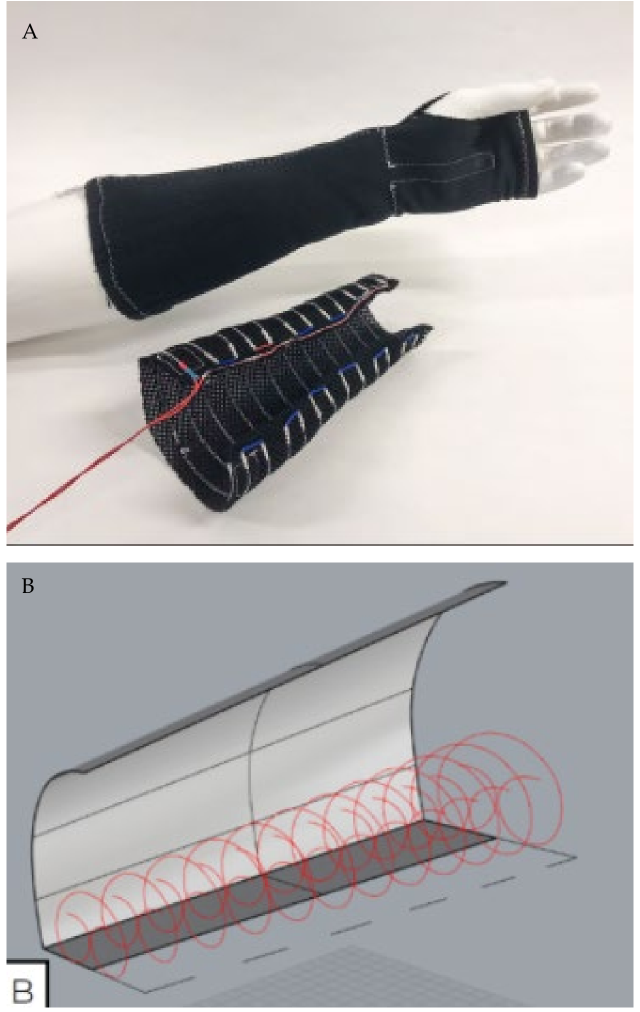


Fig. 55: Sereni Sleeve for anxiety modulation: [A} physical prototype and [B] visual representation of 'heart' shaped SMAs (J. Kim, 2023).

Fig. 56: Affective sleeve diagram breathing guidance with the periodic change of temperature over time (Papadopoulou et al., 2019).

A compression sock developed by the University of Minnesota provides orthostatic hypotension treatment through compression stockings. It amplifies contractions across the textile surface using knitted SMA of 0,381mm diameter, requiring limited energy consumption and operating at temperatures just above body temperature –37ºC and 43ºC–, making it suitable for elderly users (Granberry et al., 2017). Another innovative example is Knit Dermis, an on-body interface that delivers expressive tactile feedback on the wearer's body. The multiple versions include SMA micro springs (actuation temperature of 45ºC) knitted into textiles which provide slim, stretchable, and versatile forms for comfort in diverse body locations. They undertook multiple case studies related to under-explored body locations, haptic feedback (compression, pinching, brushing, and twisting), and comfort/noticeability experiential tests (J. H. Kim et al., 2021).

Fig. 57: Compression sock from the University of Minnesota (Granberry et al., 2017).

Shape memory textiles designed by Marielle Leenders, such as a jacket that shrinks when heated and retains its form until manually adjusted, further illustrate the versatility of SMA technology. It is composed of NiTi wires with actuation temperature of 45-50ºC. These textiles highlight the potential for practical and interactive fashion pieces (Bengisu & Ferrara, 2018).

Fig. 58: KnitDermis case studies based on haptic feedback configurations (J. H. Kim et al., 2021).

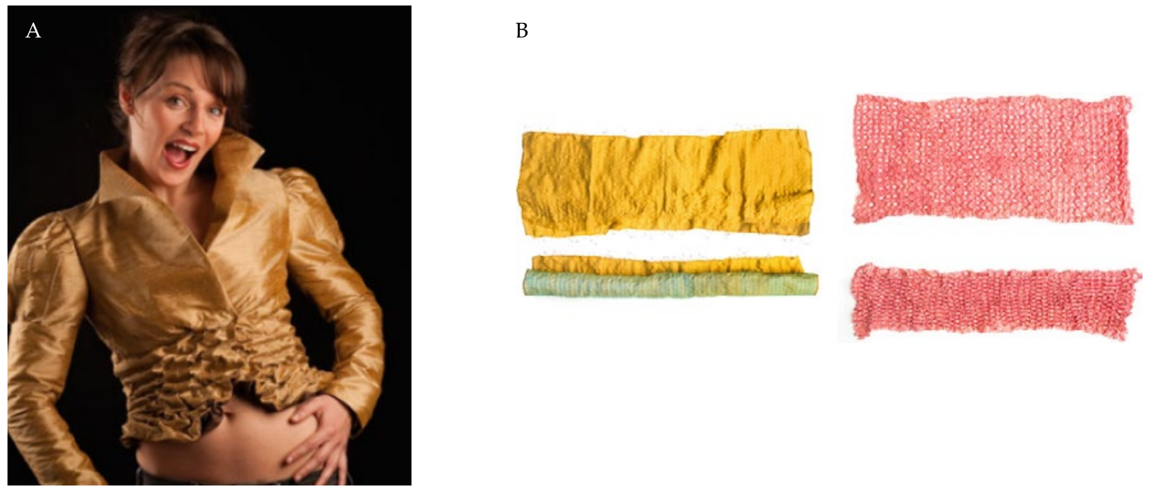


Fig. 59: [A] Shape memory jacket designed and produced by Marielle Leenders and [B] SMA-based textile samples (Bengisu & Ferrara, 2018) .

3.2. Applied Practices

3.2.1. Material Tinkering: SMA shape training and textile attachment

To gain an understanding of Shape Memory Alloys (SMAs), a hands-on exploration in the lab is essential. This involves training the wire to exhibit the shape memory effect. The apparatus required for this process includes screws, a screwdriver, a metal grid with holes for fixing the SMA into the desired shape, a calliper for measuring length and actuation displacement, a thermometer for monitoring the wire's actuation temperature during cycles, a power source for controlled heating, and a timer for tracking heating and cooling durations.

The behavior of SMAs is highly dependent on their specific material composition and the manufacturing process, as detailed in the supplier's Technical Data Sheet (Appendix 8). For this exploration, two one-way memory effect SMA wires were selected: a NiTiCu wire from Flexmet with a diameter of 0.5mm and an austenite finish temperature (Af) of 60ºC, and a NiTi wire from Nanografi with a diameter of 1mm and an Af of 45-50ºC. These wires were examined in various shapes (zigzag, loop, and spring) and sizes (large, medium, and small).

The procedure for training the SMA wires involves several steps:

1. Shaping the Wire: The SMA is fixed into a metal grid using screws and a screwdriver to create the desired shape. Multiple layers of SMA can be fixed simultaneously for a faster process. The wires were shaped into zigzags with three peaks, loops with three peaks, and springs.
2. Heating to Annealing Temperature: With appropriate safety gear, the metal grid with the SMA is placed in an oven at 550ºC for approximately 40 minutes.
3. Cooling: The grid is immediately cooled in water after removal from the oven.
4. Removing Shaping Tools: The SMA is detached from the grid.
5. Observing the Shape Memory Effect: The SMA is deformed at room temperature and then heated to its austenite finish temperature (Af) to observe it returning to the trained shape. Repeating the heating and cooling cycles several times verifies shape recovery, displacement, and response time.

Given that the 1mm diameter wire exhibits longer cooling times and higher force against manual deformation, the 0.5mm wire is explored further in textile attachment, particularly zigzag shape as being simpler to train.

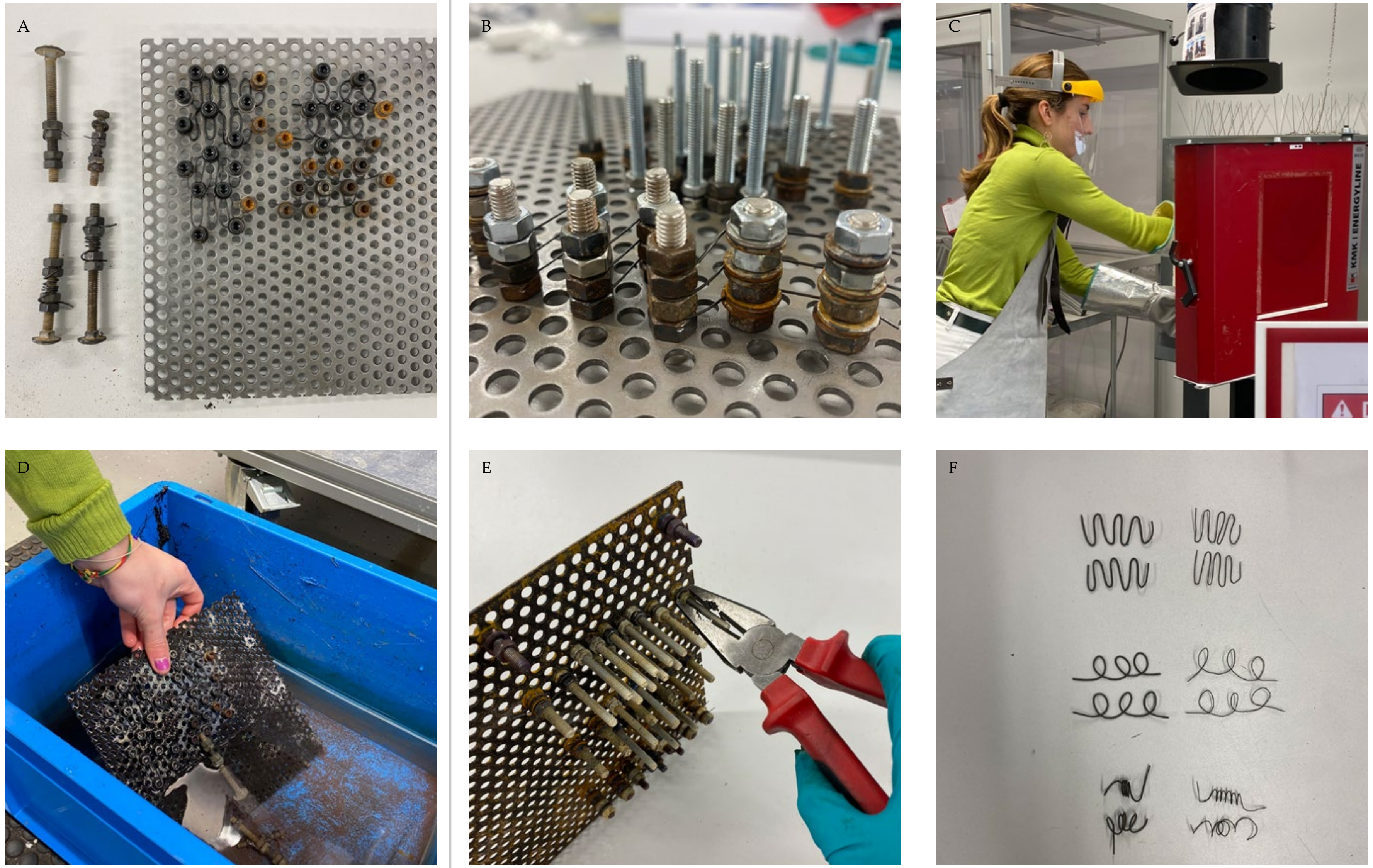


Fig. 60: SMA shape training: [A] Fixing wire's shape into the grid (zigzag, loop and spring), [B] Detail of shaping 3 zigzags in parallel, [C] Heating SMA into the oven at 550º, [D} Cooling the grid, [E] Removing shaping tools, and [F] SMA shaped into zigzag, loop, and spring.

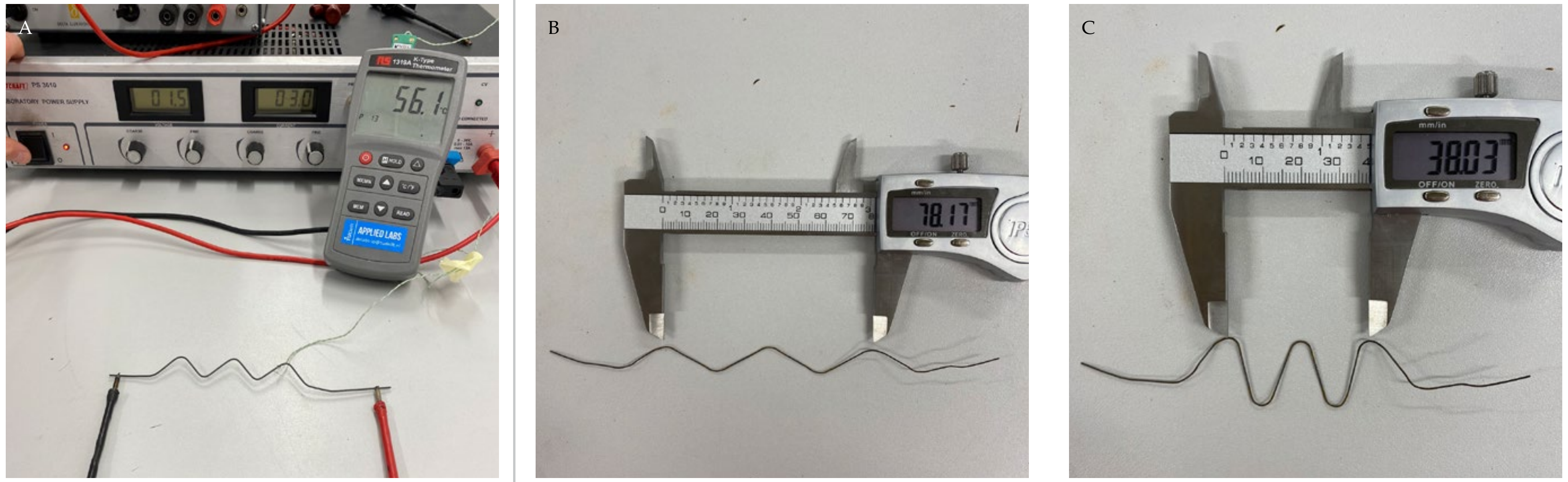


Fig. 61: Shape Memory Effect of SMA: [A] Wire connected to power source and thermometer, [B] Wire length at Martensite temperature, and [C] Wire length at Af.

TEXTILE EXPLORATION

The hands-on integration of Shape Memory Alloy (SMA) into textiles provided valuable insights into how textile properties influence SMA behavior. The SMA was manually deformed to approximately 40% of its initial length, secured to the fabric with tape, and sewn using a stitching pattern with a height and length of 3mm. These parameters will be further examined in the subsequent 'Technical Characterization' section. To assess the displacement of the Shape Memory Effect (SME), the wire's length was measured with a caliper before and after heating to the activation temperature (Af). Consistent with theoretical predictions, empirical results confirmed that overheating (beyond Af) or overloading (exceeding 40%) results in 'memory loss.'

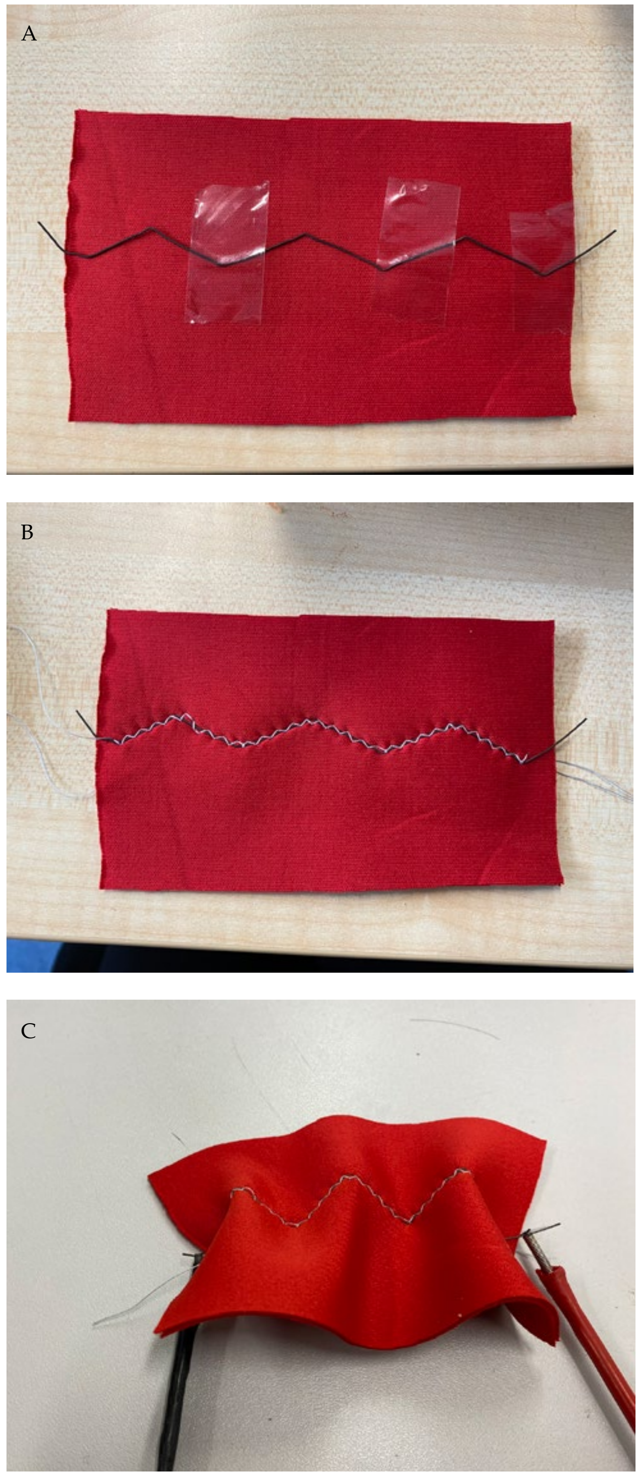


Fig. 62: SMA attachment to neorpene-like textile: [A] SMA taped to substrate, [B] SMA sewn into textile with zigzag stitching, and [C] SMA heated up to Af.

Fig. 63: [A] Sewing machine with stitching pattern H3P3 and [B] stitching pattern exploration.

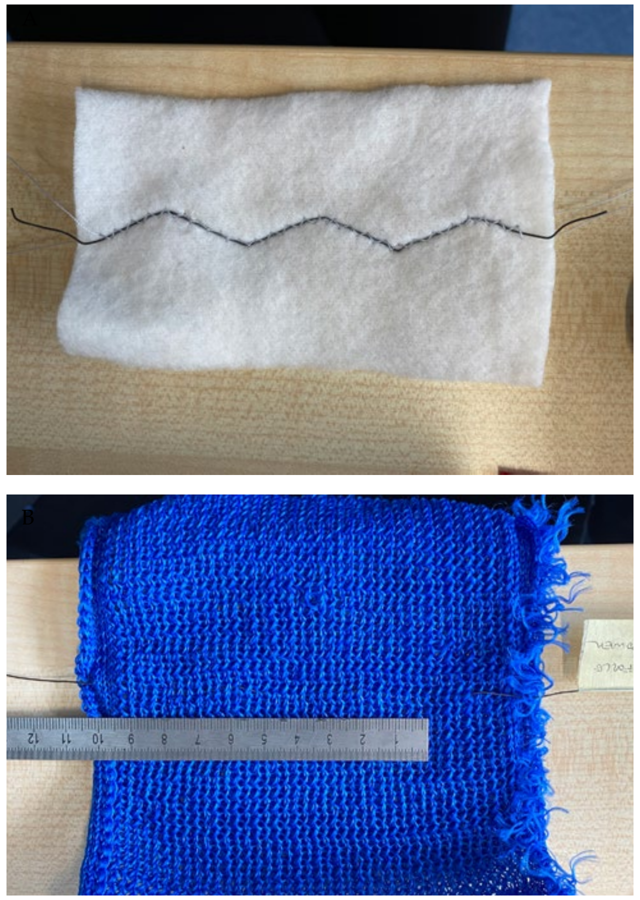


Fig. 64: Textile substrate exploration: [A] cotton and [B] kintted polyester

Furthermore, it was observed that the attachment of SMA to various textile substrates highlights significant differences: stretchy textiles, such as neoprene-like fabric, require a tenser stitching pattern due to their elastic properties, whereas cotton, being stiffer, does not. Stitching can be performed using a sewing machine or manually through the loops of knitted fabrics. Ensuring the textile is tightly attached to the SMA is crucial for synchronized movement. For future designs, it is imperative that the selected textile substrate not only enhances the SMA mechanism but also provides user comfort.

3.2.2. Technical Characterization

After acquiring a foundational understanding of the SMA and textiles through preliminary tinkering, the subsequent step involves technical characterization. This entails empirically applying the theoretical insights from the literature review in a laboratory setting through nine experiments. These experiments investigate the opportunities and limitations of three primary parameters of the Shape Memory Effect (SME) into textiles: actuation displacement, actuation temperature, and actuation ('response') time, across various settings, including wire diameter, size, and shape.

The hands-on experiments explore various aspects of SMA performance (see Appendix 6):

1. Wire Diameter: To compare the performance of Zigzag SMA wires with diameters of 1mm and 0.5mm.
2. Shape Configurations into Textile: To compare the performance of zigzag, loop, and spring shapes of 0.5mm SMA integrated into textile.
3. Stitching Pattern: To compare the performance of zigzag shape SMA wires attached to textile using different stitching patterns (all zigzag, peaks, and only bottom peaks).
4. Zigzag Size: To compare the performance of large, medium, or small zigzag sizes.
5. Loop Vs. Zigzag and Peak Vs. Lateral Stitches: To compare the performance between Loop and Zigzag shape configurations with peak or lateral stitching.
6. Wristband Design: To test the squeezing haptics of a wristband design with SMA integrated.
7. Thermal Insulation Layer Load: To compare the load (force) of SMA integrated into textile with different insulation layers (insulation tape and neoprene-like fabric).
8. Number of Wires: To compare the performance of multiple wires integrated in parallel with kinesiology thermal insulation.
9. Counterforce: To compare the height and response time of the design with and without counterforce.

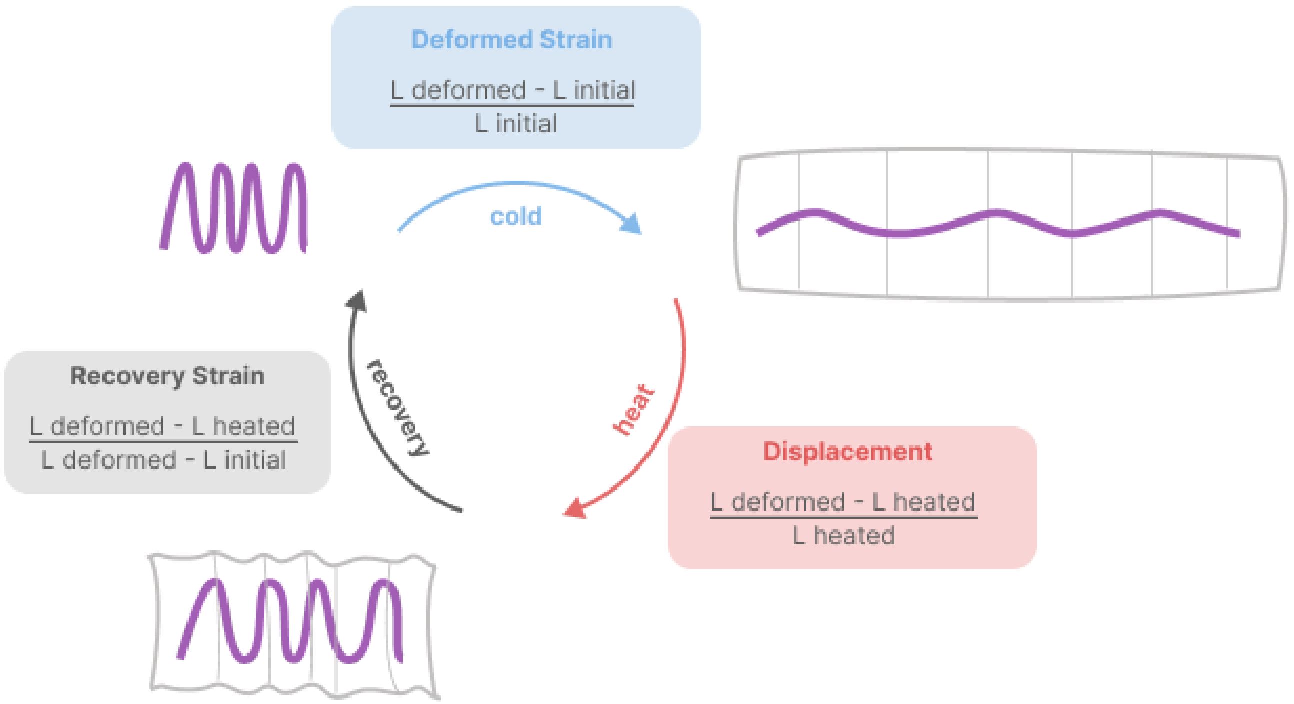


Fig. 66: Visual representation of the technical meaning of Deformed Strain, Displacement, and Recovery Strain in the experiments of the project.

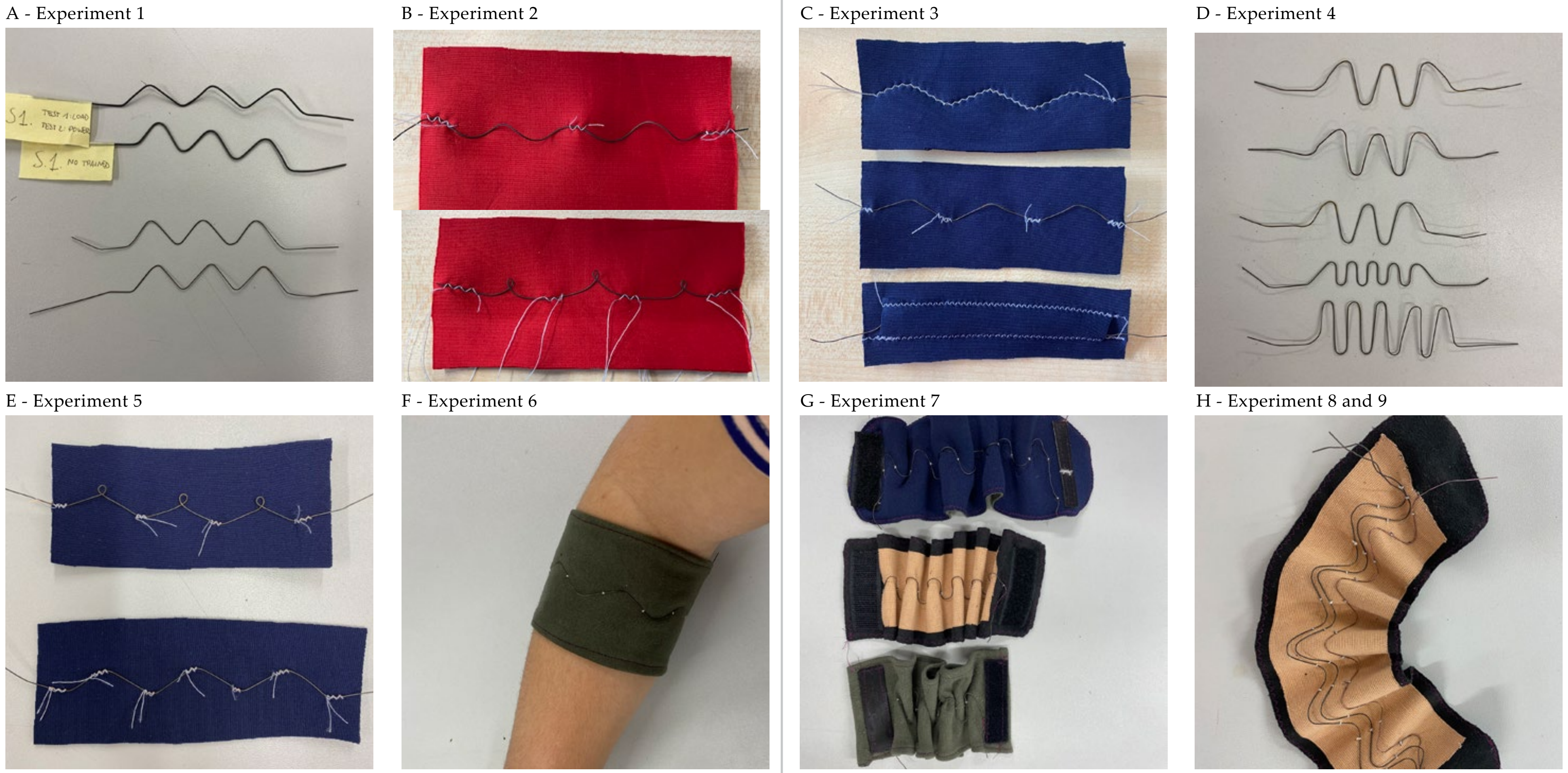


Fig. 65: Technical characterization experiments: [A] Wire Diameter, [B] Shape Configuration into Textile, [C] Stitching Pattern, [D] Zigzag Size, [E] Loop Vs. Zigzag and Peak Vs. Lateral Stitches, [F] Wristband Design, [G] Thermal Insulation, and [H] Number of wires and counterforce (Appendix 6).

3.3. Discussion

The literature review provided several notable insights. There is a positive correlation between haptic action and breathing rhythm in enhancing the perception of calmness, yet the integration of physiological indicators (biofeedback) into the design is lacking. Shape memory materials exhibit significant potential in health applications due to their noiseless, lightweight, discreet, non-invasive, stretchable nature, and favorable power-to-weight ratio compared to electromechanical motors. SMA is particularly promising for delivering organic, natural haptic feedback suitable for wearables, demonstrating ease of integration into materials for prototyping, with textiles representing an intriguing area for further exploration. One-way SMA offers predictably effective performance. Critical parameters for creating SMA cycles, such as breathing rhythm simulation, include activation temperature, time, force, and displacement, with actuation time reducible through the use of thinner wires, higher activation temperatures, and counterforces (e.g., textile stiffness). Considerations for wearable designs in contact with skin include body location, washability, and insulation.

Commonly used SMAs in haptic wearables include straight wires or micro springs with an activation temperature of 70°C and wire diameters of 0.2-0.5mm (Lücker, 2023). While micro springs provide higher displacement, they are challenging to integrate into soft embedded structures, similar to bias springs used as counterforces. Research on non-superelastic effect wires remains limited. Conductive threads offer potential for replacing sensors and electronic components to achieve a more compact and integrated design. User experience can be enhanced by testing perceptibility, noticeability, and comfort, which aid in experiential characterization and system improvement.

Experimental exploration further highlighted key points: SMA with a diameter of 0.5mm reduces recovery time by a factor of ten compared to a 1mm diameter at an electric current of 3A and requires half the electric current for initial perceivable shape change (1.5A for 0.5mm and 3A for 1mm). Applying load or deformation within the austenite transformation phase can lead to 'memory loss'; for 0.5mm diameter SMA, the load must be applied below As=40°C. During the first heating cycle, most samples exhibited higher recovery time and lower displacement, likely due to residual stresses impeding deformation. Among zigzag, loop, and spring shapes, springs offer the fastest response with higher displacement but are more difficult to integrate into textiles. Zigzag and loop shapes present greater potential for slow, organic movement due to their wider range of recovery times (As-Af), with zigzag being the easiest to shape, requiring the least wire length, and optimal for textile integration. Reducing the number of stitches between SMA and textile, and positioning them laterally to the wire, allows for greater wire mobility and reduced recovery time at equivalent displacement and recovery strain. The wire peaks are critical bending points and should be left more free, though proper fixation of wire ends is necessary to ensure entire textile movement. Larger zigzag sizes demand more power and exhibit less shape stability throughout cycles, but achieve higher deformed strain, occupying more space on the textile.

The figures below summarize these insights.

Key Insights from Chapter 3

- There is a correlation between haptic action and breathing rhythm in the perception of calmness, yet physiological indicators are missing.
- Compared to electromechanical solutions, shape memory materials (SMM) are noiseless, lightweight, discreet, non-invasive, stretchable, and offer a high power-to-weight ratio.
- Shape Memory Alloys (SMA) provide organic, natural haptic feedback and are easy to integrate into textiles. One-way Shape Memory Effect (SME) is more predictable for prototyping.
- Key parameters for creating cycles include activation temperature, time, force/load, recovery strain, and displacement. Activation time can be reduced depending on the substrate and textile attachment.
- Considerations for wearables with skin contact include body location, washability, and insulation protection (not above 50ºC).
- SMA straight wires or micro springs with a diameter of 0.2-0.5mm and an activation temperature of 70°C are commonly used in haptic wearables. Textile integration is crucial.
- Conductive threads and textiles enhance design integration, simplicity, and compactness, and can replace some electronic components.
- User experience can be analyzed through perceptibility/noticeability and comfort testing.

Technical Characterization Insights

- A 0.5mm diameter SMA reduces recovery time and power needed, but applying load during the Austenite transformation can result in 'memory loss'.
- Zigzag shapes are easy to integrate into textiles, with lateral stitches being optimal for higher shape recovery.
- Longer wires with larger diameters and combinations with other wires require higher voltage, which reduces recovery time with the same displacement.

Relevance for the Project

1. Incorporating biofeedback into haptic design can enhance the calmness experience. Perception and comfort testing can improve wearable design both technically and experientially.
2. SMA and conductive threads can enhance discreteness, compactness, organic integration, and portability.
3. Key parameters for mimicking breathing rhythms with SMA are activation temperature, time, and displacement. One-way SME will need a counterforce integrated into the textile.
4. For SMA wearables, important considerations include body location, washability, and insulation.
5. Conductive threads and textiles can enhance the compactness and integration of wearable designs. They can replace electronic cables, switch buttons (for turning SMA on/off), and even heart rate sensors, leading to a simpler, lightweight, and 'electronics-free' perception.
6. A 0.5mm SMA in a zigzag shape shows promise for a textile wearable. Balancing power, recovery time, and displacement is crucial to avoid 'memory loss'. These parameters also impact heating-cooling cycles and the starting point.

Table 6: Overview of key insights from Chapter 3 and their relevance for the project.

THE GAP

After analyzing the context of the three expertise areas—stress regulation, smart wearables for health, and shape morphing materials—a knowledge gap has been identified. Current solutions either collect body data, primarily heart rate, for user diagnosis or provide feedback through haptics technology. However, there are no existing solutions that combine both body monitoring and haptic feedback for anxiety relief. Those that do often rely on pneumatic or mechanical systems, which are noisy, bulky, and non-discrete. Haptic wearables based on shape morphing materials are mainly applied to sports (for body ventilation) or fashion (for aesthetics). When applied to anxiety conditions, they do not utilize effective conscious breathing techniques and are not associated with the abdomen, where diaphragmatic breathing occurs. Typically, these wearables are placed on the hand or wrist, making it difficult to correlate with the natural body location for conscious breathing (Research Questions 1.1 and 1.2).

This gap results in individuals with anxiety being unaware of both their physiological and psychological conditions and not being engaged in improving or preparing for anxious episodes in daily life (Research Question 2.1). Everyday solutions like smartwatches or sports bands do not utilize the material in an active role, while shape-changing wearables lack portability and discretion (Research Question 2.2).

POTENTIAL FOR INNOVATION

Despite these challenges, examples show high potential for designing a device that enhances user awareness by combining body data collection and shape morphing textiles with haptic feedback. Studies indicate that Shape Memory Alloys (SMA) can be integrated into textiles, enabling wearables that provide feedback through mechanisms like squeezing and compression. Textiles can enhance these mechanisms and user experience by considering their impact on the wearer (skin contact) and their compatibility with SMA. Breathing rhythms can be mimicked through heating and cooling cycles, allowing the wearer to synchronize easily to release anxiety. Positioning the wearable on the abdomen could assist users in guiding diaphragmatic movement, as done in therapy.

Additionally, conductive textiles can enhance the simplicity, discretion, and user-friendliness of the design. This approach fosters a symbiotic relationship between the user and the device, benefiting both and enhancing Human-Computer Interaction (HCI) through a biofeedback loop.

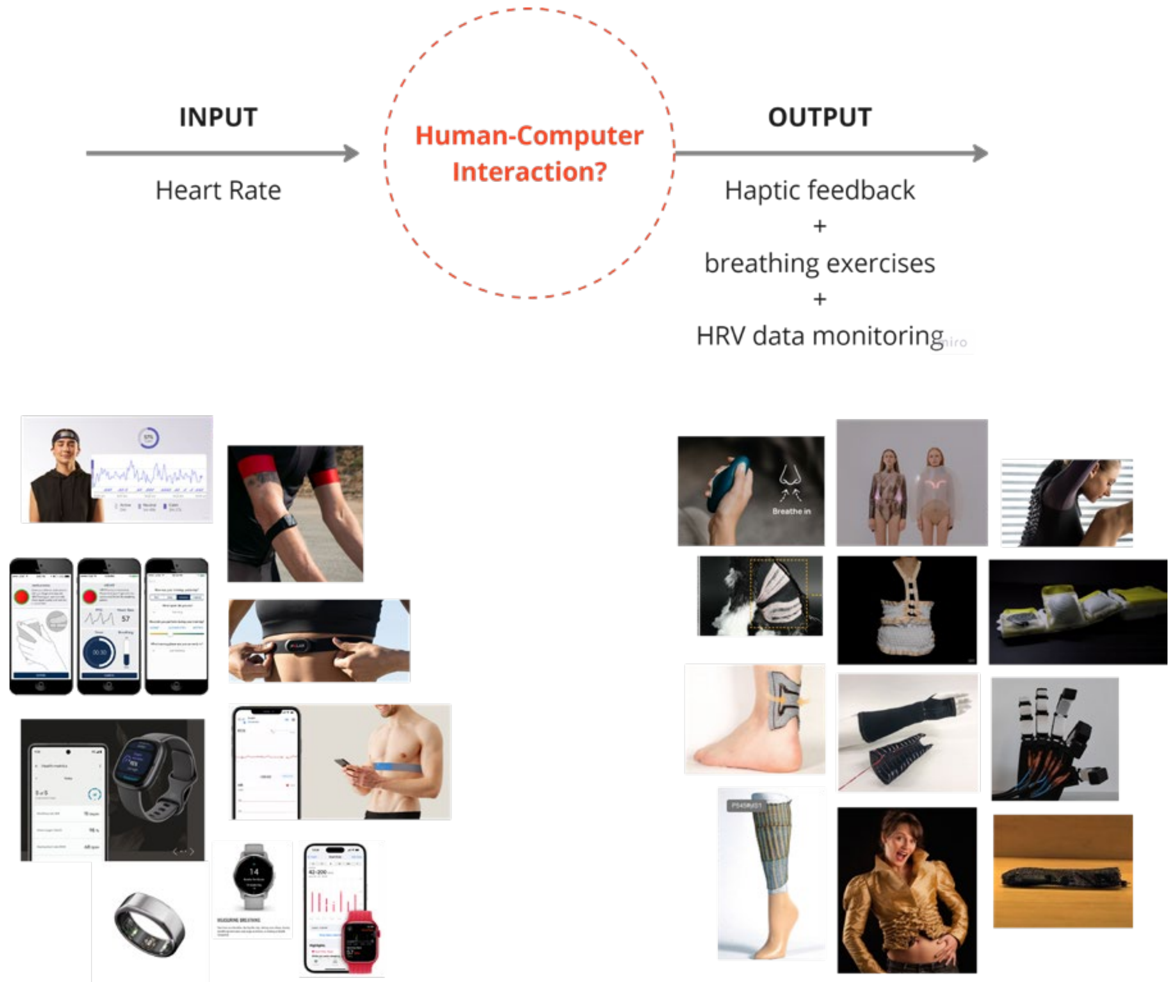


Fig. 67: Visual representation of the knowledge gap identified from the Contextual Analysis: a lack of connection between input and output within wearable devices.

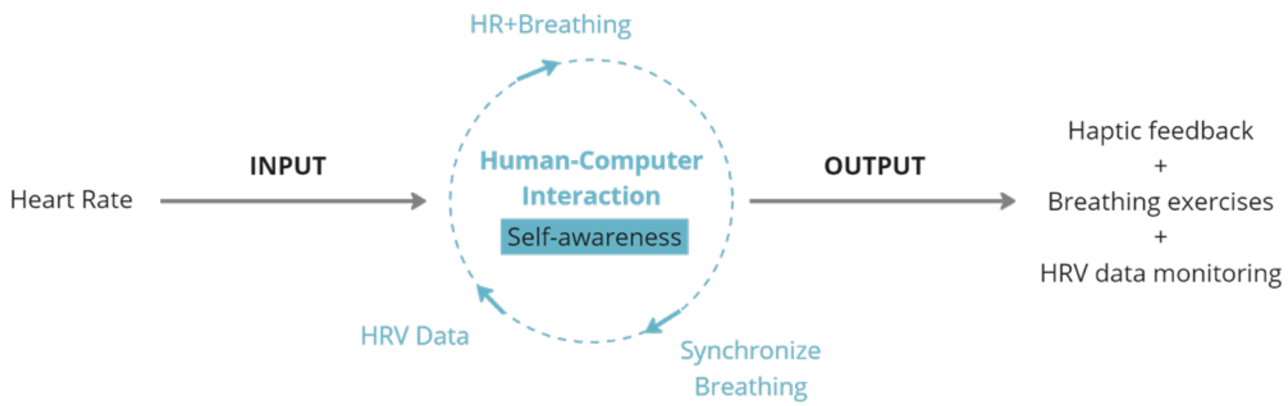


Fig. 68: Visual representation of the envisioned biofeedback loop to enhance HCI and self-awareness.

PART II.

CONCEPTUALIZATION AND EMBODIMENT

Chapter 4.
Concept Exploration

In this chapter, the contextual analysis guides the iterative development of prototypes. Following the established design requirements, ideation leads to the discovery of a novel re-training method. This method is applied to prototype three conceptual designs, which are then evaluated with users. A final concept design is selected for further development in the subsequent chapter.

4.1 Design Requirements

TECHNICAL REQUIREMENTS

Integration of Elements:

- SMA (Shape Memory Alloy): Active component
- Textile: Passive component
- Sensor: Controlled component

SMA Performance:

- The SMA must perform at least 5 cycles of heating and cooling, achieving a shape recovery of over 90%.
- Heating and cooling times should range from 5 to 10 seconds, suitable for simulating beginner breathing techniques (5-5-5 seconds cycle).
- Temperature changes should be gradual and slow to emulate natural abdominal movements.

Textile Integration:

- The SMA should be integrated into the textile with a deformation of at least 100% of the initial trained wire for noticeable shape changes.
- The textile must include an insulation layer to protect the skin from burns (not exceeding 50ºC).
- The textile should be soft and elastic, ensuring comfort and adjustability for wearable use and comfort.
- The textile must be breathable to allow body sweat to pass through and should be washable.

Power Efficiency:

- Ideally, the design must operate with minimal power, such as 3.7v batteries.

Independence and Feedback:

- The mechanism should operate without the need for external devices or mobile apps. Ideally, without the bulky power supply.
- A sensor should measure the user's heart rate at the start and end of the breathing exercise.
- Ideally, the design should provide biofeedback on heart rate improvement and heart rate variability through an app or smartwatch.

Control Features:

- An ON/OFF button to activate or deactivate the SMA mechanism.
- Ideally, the breathing exercises are customizable to the user, for example with a button to switch cycle modes based on the user's expertise level, or haptic intensity based on the user's sensitivity.

AESTHETIC REQUIREMENTS

Functional Mimicry:

- The design should replicate the natural breathing movements of the abdomen using haptic technology to create a tactile experience.

Wearability and Portability:

- The design should be suitable for daily use across various scenarios (home, work, standing up, laying down…).
- It must be discreet, lightweight, aesthetically pleasing, and non-intrusive.

User Experience:

- The design should be intuitive and user-friendly, ensuring a calming and soothing experience to help release anxiety.
- The shape-changing mechanism should be clearly perceivable (noticeable) and easy to synchronize by user's abdominal breathing to successfully enhance awareness and regulate the nervous system.

4.2 Ideation

The theoretical and practical foundations, aligned with the design requirements, highlight potential ideas related to the interrelation between three types of haptics: wearable, graspable, and touchable. With the primary goal of guiding breathing rhythm, this p explores mimicking inhalation and exhalation through haptics, such as squeezing the body using an SMA-textile system.

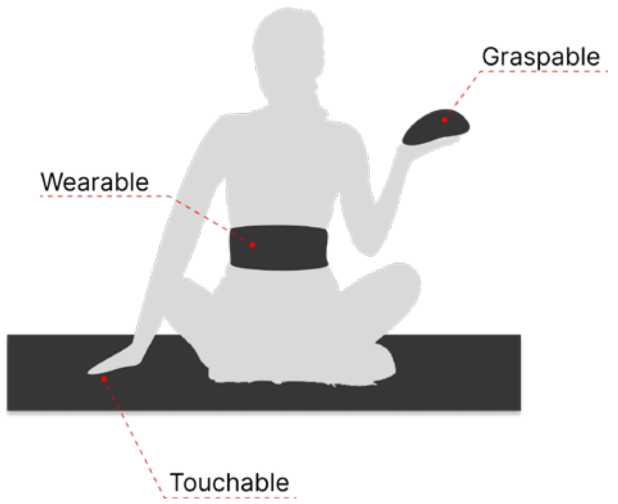


Fig. 69: Visual Representation of SMA-textile applied to wearable, graspable and touchable.

SQUEEZING HAPTICS

A notable idea involves a wristband that squeezes during inhalation (SMA heating) and releases during exhalation (SMA cooling), simulating an abdominal band. A low-fidelity textile prototype was developed to test this squeezing mechanism. Microfiber fabric, chosen for its softness and elasticity, serves as the ideal substrate for a wearable, allowing the SMA to move effectively.

Procedure

A 0.5 mm diameter SMA wire, with an actuation temperature of 60°C and configured in a zigzag shape, was deformed to 141% of its initial trained shape and attached to a microfiber textile band. The SMA-textile prototype underwent 10 heating cycles to Af. During each cycle, response time (time for the SMA to return to its initial shape upon heating), displacement, and recovery strain were measured.

Apparatus

The experimental setup required a power supply with cables to connect to the prototype, a timer for the heating cycles, a caliper for measuring the length (initial, deformed in martensite, and heated in austenite), and a thermometer to prevent overheating.

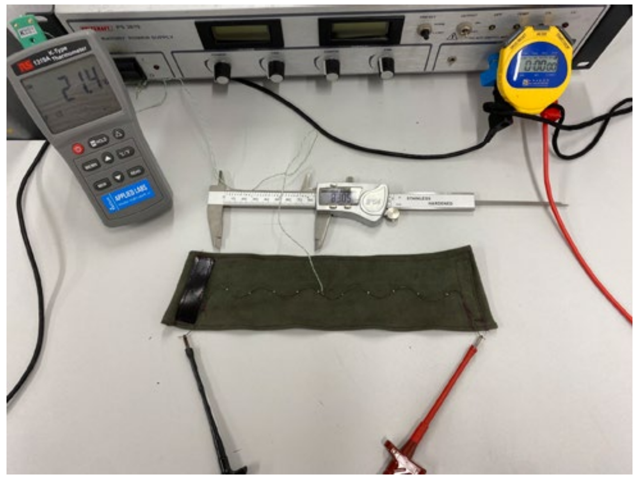
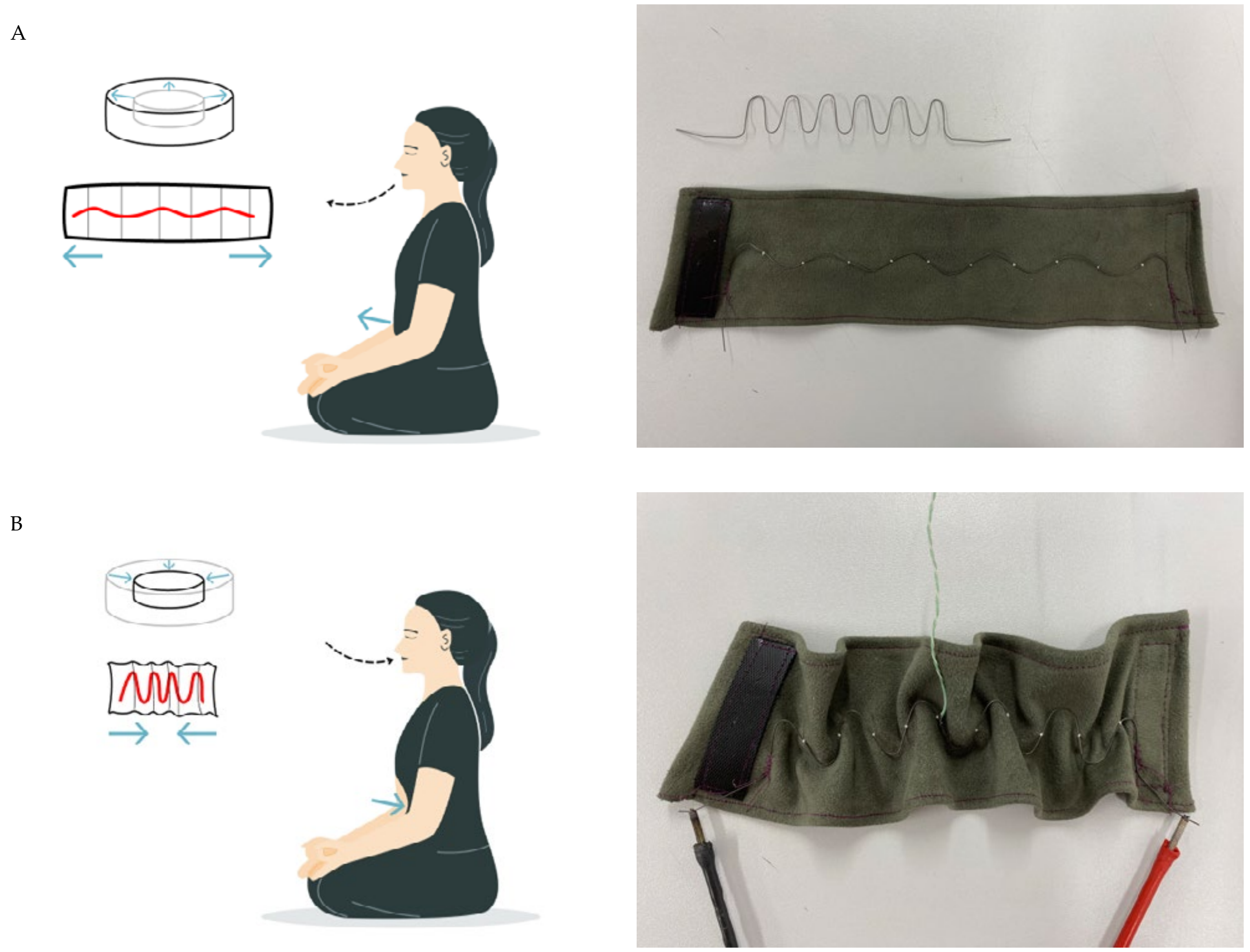


Fig. 70: Set-up for wristband experiment with a thermometer, timer, and caliper tools.

Results and Discussion

Results indicated a high recovery strain of 86% to the initial trained shape and a displacement of 50.6% from deformed to heated states, both of which decreased with each cycle. This reduction is attributed to potential overheating or overloading during the austenite transformation, leading to 'memory loss.' At 3.2V and 1.5A, the SMA exhibited an average recovery time of 9.2 seconds, which also decreased per cycle. Consistent with theoretical expectations, the first cycle had the longest recovery time.



Visual representation of squeezing haptics experiment with the SMA-textile band prototype: (A) expanding when exhaling and (B) contracting when exhaling.

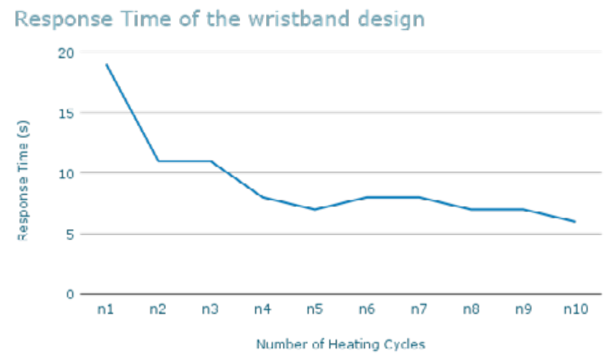


Fig. 71: Test results for the Response Time of the wristband design during 10 heating cycles.

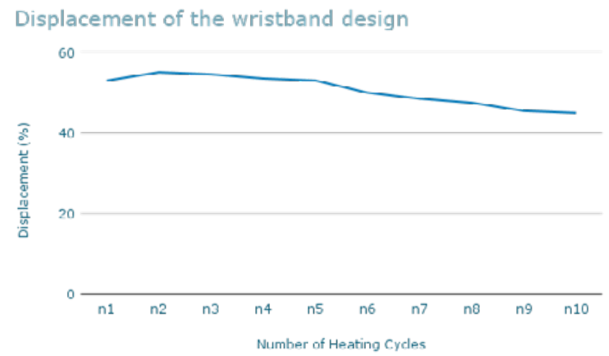


Fig. 72: Test results for the Displacement of the wristband design during 10 heating cycles.

The next phase involves measuring these parameters when the prototype is placed around the arm and secured with Velcro. However, the squeezing action became less perceivable with each heating cycle, eventually disappearing. This is because the arm acts as a counterforce stronger than the SMA, leading to 'memory loss' of the contraction movement. Future designs need a degree of freedom to avoid excessive fixation and load that impede memory retention.

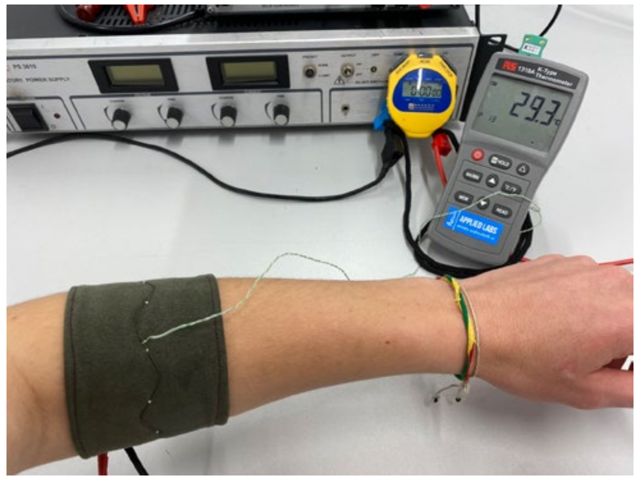


Fig. 73: Wristband design tested around the arm.

Fig. 75: Load test for the wristband design [left-right]: only textile, with neoprene-like fabric insulation, and with kinesiology tape insulation.

THERMAL INSULATION

The wristband experiment also indicated a need to explore textile insulation to prevent excess warmth in contact with the skin. Displacement, recovery time, and load (measured with a gauge tool) were compared between prototypes with and without an insulation layer and among two types of insulation textiles: neoprene-like fabric and kinesiology tape.

Results showed that neoprene-like insulation required a higher voltage (4V compared to 3V for the others) due to its stiffness and thickness, and it also needed more time to return to initial shape, which conflicts with the requirement for a minimal response time. Both neoprene-like fabric and kinesiology tape effectively protected the skin from the SMA's 60°C temperature and exhibited similar displacement. However, kinesiology tape was easier and faster to attach to the textile through adhesive, making it the optimal insulation solution.

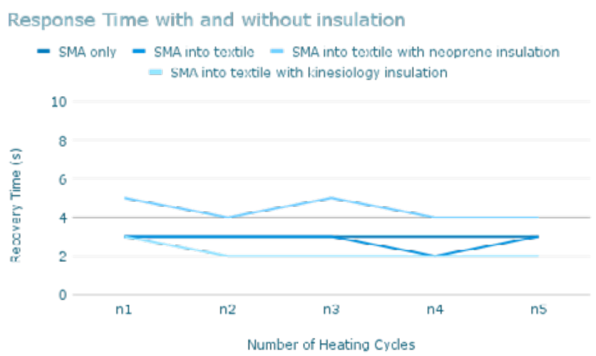


Fig. 74: Test results for the response time of the SMA-textile band: only wire, wire into textile, with neoprene-like fabric insulation and with kinesiology tape insulation.

Fig. 76: Heated wristband design [left-right]: only textile, with neoprene-like fabric insulation, and with kinesiology tape insulation.

NEW RE-TRAINING METHOD

The wristband experiments demonstrated that overloading the shape memory alloy (SMA) using the body as a counterforce during the Austenite phase transformation results in 0% shape recovery. However, by adhering to the principle of applying load at the Austenite finish temperature (Af), the 'memory loss' effect can be transformed into a re-training method. After the SMA is initially trained in an oven at the annealing temperature of 550ºC, it has been established that by manually fixing the NiTiCu-textile structure and applying power to raise its temperature above Af, the SMA can be re-trained to 'memorize' a new shape. This manual fixation can be accomplished using hands, a hammer, or clamps.

The prototype, re-trained using this method, exhibited 100% shape recovery with the expansion movement. Consequently, two potential designs for an abdominal band were evaluated: one with a perpendicular movement relative to the body and another with lateral movement. Due to the complexity and friction issues associated with the lateral expansion mechanism, the perpendicular expansion design was selected as the optimal and more reliable concept for further development.

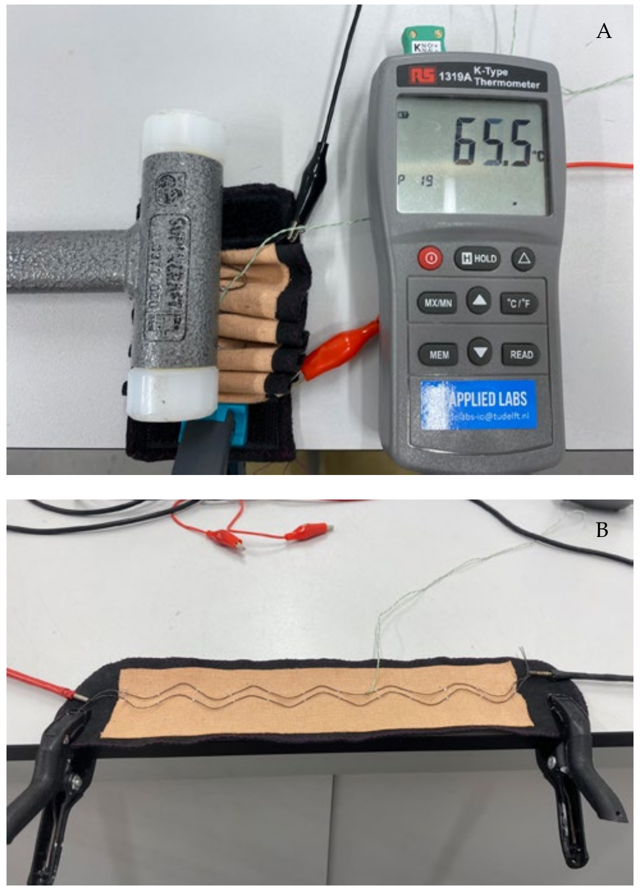


Fig. 77: New re-training method by fixing SMA-textile module and raising the temperature above Af: (A) training to contract upon heating and (B) training to expand upon heating.

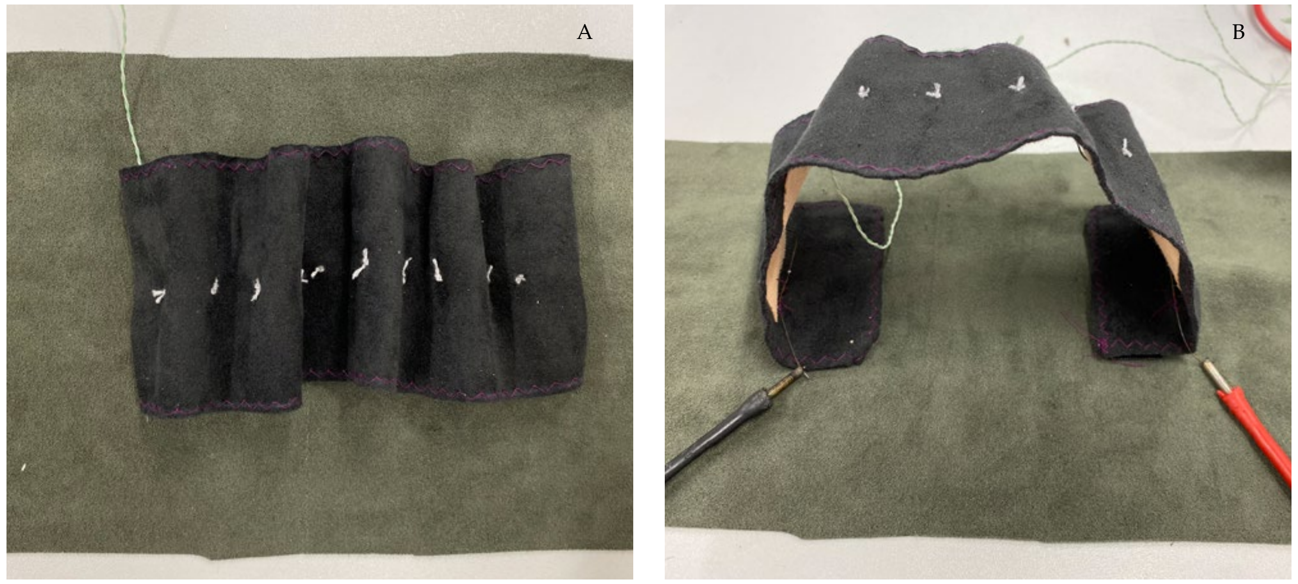


Fig. 78: Module (A) contracted and (B) expanded as a result of the new re-training method.

4.3 Concepts

Building on the new re-training method for inducing shape memory alloy (SMA) expansion upon heating, an abdominal band concept that expands outward from the body is developed. By incorporating kinesiology tape for thermal insulation and double parallel wires for enhanced stability and load-bearing capacity while maintaining consistent displacement and response time, three concepts are designed and evaluated (see experiments in Appendix 6).

Initially, all concepts are re-trained with the SMA integrated into the prototype. The textile is stretched and fixed to a table with clamps, then heated above the Austenite finish temperature (Af) of 60ºC, for example, to 70ºC, to 'memorize' the extended shape.

Among the two modules created, one integrates a counterforce to enable automatic return movement without user intervention. An elastic cord stitched to the textile effectively serves as a counterforce without significantly compromising functionality (see Appendix 6). Consequently, Concept 1 uses the first module without a counterforce, Concept 2 employs the second module with an elastic counterforce, and Concept 3 combines both modules.

The three concepts are based on heating-cooling cycles simulating the Conscious Breathing technique for beginners (5-5-5), which involves 5 seconds of inhalation (SMA heating), 5 seconds of holding breath, and 5 seconds of exhalation (SMA cooling). This cycle is performed five times by users, and two key parameters are evaluated: clearer haptic perception and easier breathing rhythm synchronization. The modules are attached to an elastic band with Velcro for easy relocation and adjustability to the user's abdomen.

CONCEPT 1. USER COUNTERFORCE

Concept 1 (C1) involves a single-module mechanism where the user actively participates. The steps are:

- 5s Inhalation: The module expands outward upon heating.
- 5s Holding Breath: The module maintains the shape at maximum expansion.
- 5s Exhalation: The user manually pushes the module inward toward the body.

CONCEPT 2. AUTOMATIC COUNTERFORCE

Concept 2 (C2) features a single-module mechanism where the process is automated, and the user acts passively. The steps are:

- 5s Inhalation: The module expands outward upon heating.
- 5s Holding Breath: The module maintains the shape at maximum expansion.
- 5s Exhalation: The elastic counterforce automatically pushes the module inward toward the body.

CONCEPT 3. DOUBLE MODULE

Concept 3 (C3) combines two modules aligned on the elastic band, each with an automatic counterforce for returning the textile. The steps are:

- 5s Inhalation: The left module heats up and expands outward, while the right module remains contracted.
- 5s Holding Breath: The left module automatically returns to its initial shape, so both modules are equally contracted.
- 5s Exhalation: The right module heats up and expands outward, while the left module remains contracted.

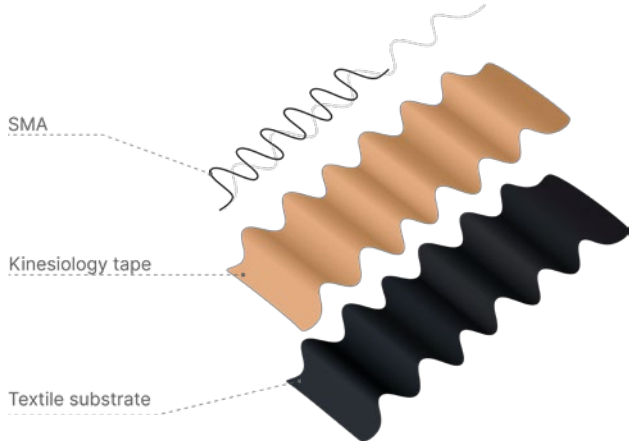


Fig. 79: Visual representation of the components of the module's prototype: SMA, kinesiology tape, and textile substrate.

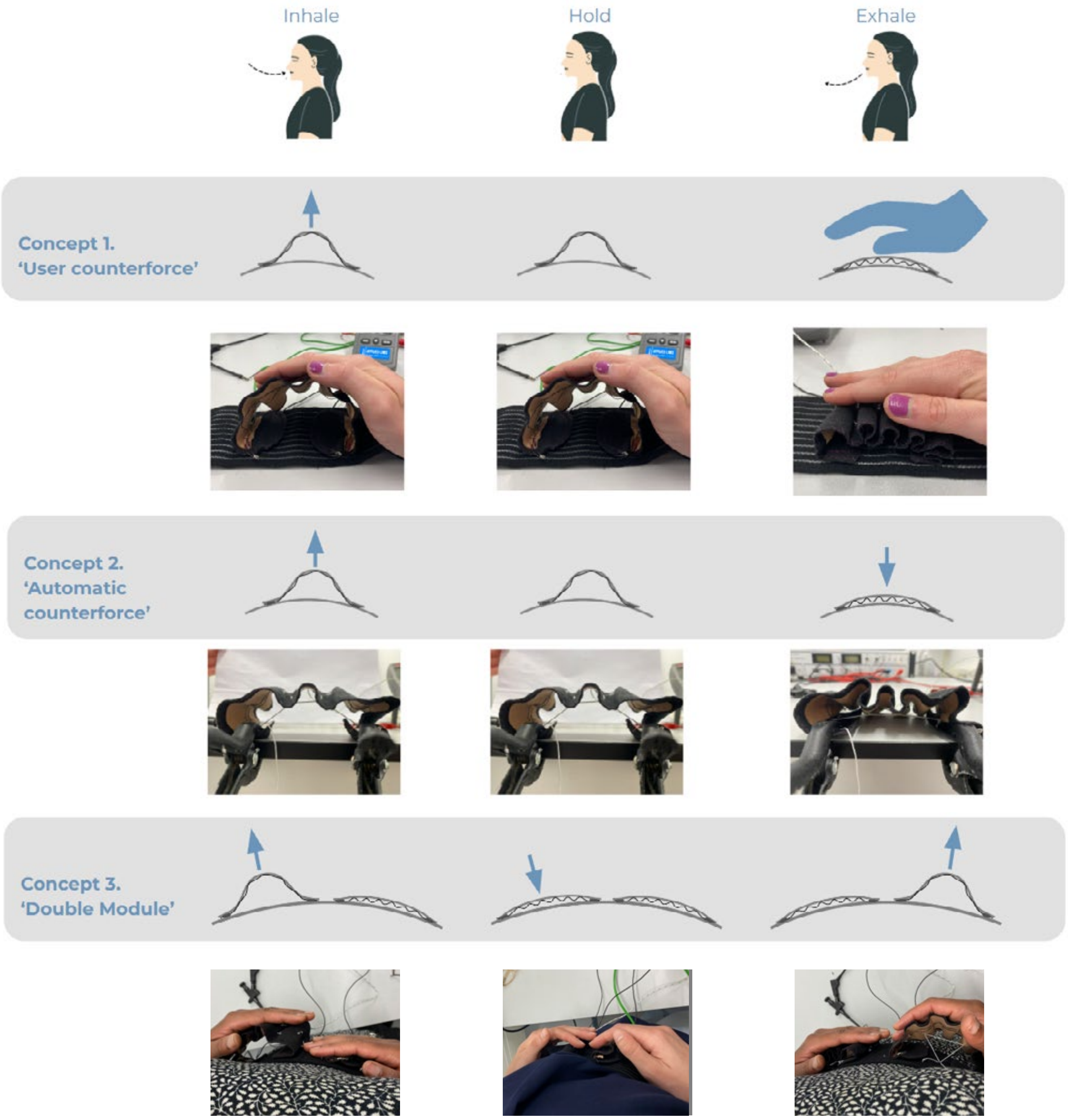


Fig. 80: Visual representation of the three concepts with the expansion and contration movement when inhaling, holding breath, and exhaling.

4.4 User Evaluation

INTRODUCTION

A user study is conducted to validate the functionality and user experience of the three concepts. This study qualitatively and quantitatively assesses two key parameters: the clarity of haptic perception (noticeability of the movement) and the ease of synchronizing the user's breathing rhythm with the design. Additionally, insights are gathered regarding different body placements of the design and its use outside the body ('touchable'). The test is inspired by the 'Experiential Characterization' technique from the Materials Driven Design (MDD) method to analyze non-technical aspects related to performative, sensorial, affective, and interpretive levels.

PARTICIPANTS

Five participants (3 female and 2 male) from diverse ages and backgrounds (all students from TU Delft) are selected for the user test. No prior experience with anxiety conditions is required, yet it is asked at the beginning of the questionnaire.

PROCEDURE

The user study is conducted at the Materials Lab of the Industrial Design faculty of TU Delft. Upon arrival, participants read and sign a consent form. They then complete a questionnaire collecting personal information and gauging their familiarity with anxiety and breathing techniques. Each participant is first introduced to Concept 1, sharing their initial thoughts and impressions before the purpose and functionality of the design are explained. The prototype is then placed around the participant's abdomen, and they follow the expansion and contraction guidance with their breathing. Participants rate the clarity of perception and ease of synchronization and provide general comments. This process is repeated for all three concepts. Subsequently, participants select one concept and discuss potential alternative body placements and out-of-body uses ('touchable'). The final part of the study involves providing general feedback on the entire test, including the mechanism, comfort, usability, location aspects, and suggestions for improvement.

APPARATUS

The study requires three prototypes of the concepts (two modules), two power supplies, connection cables to the SMAs, a timer for the heating-cooling cycles, two thermometers, and headphones for isolating the user.

Fig. 81: Apparatus for the user test: two modules for the three concepts, two power supplies, connection cables, two thermometers, and headphones.

RESULTS

All the user study results are showed in the Appendix 5.

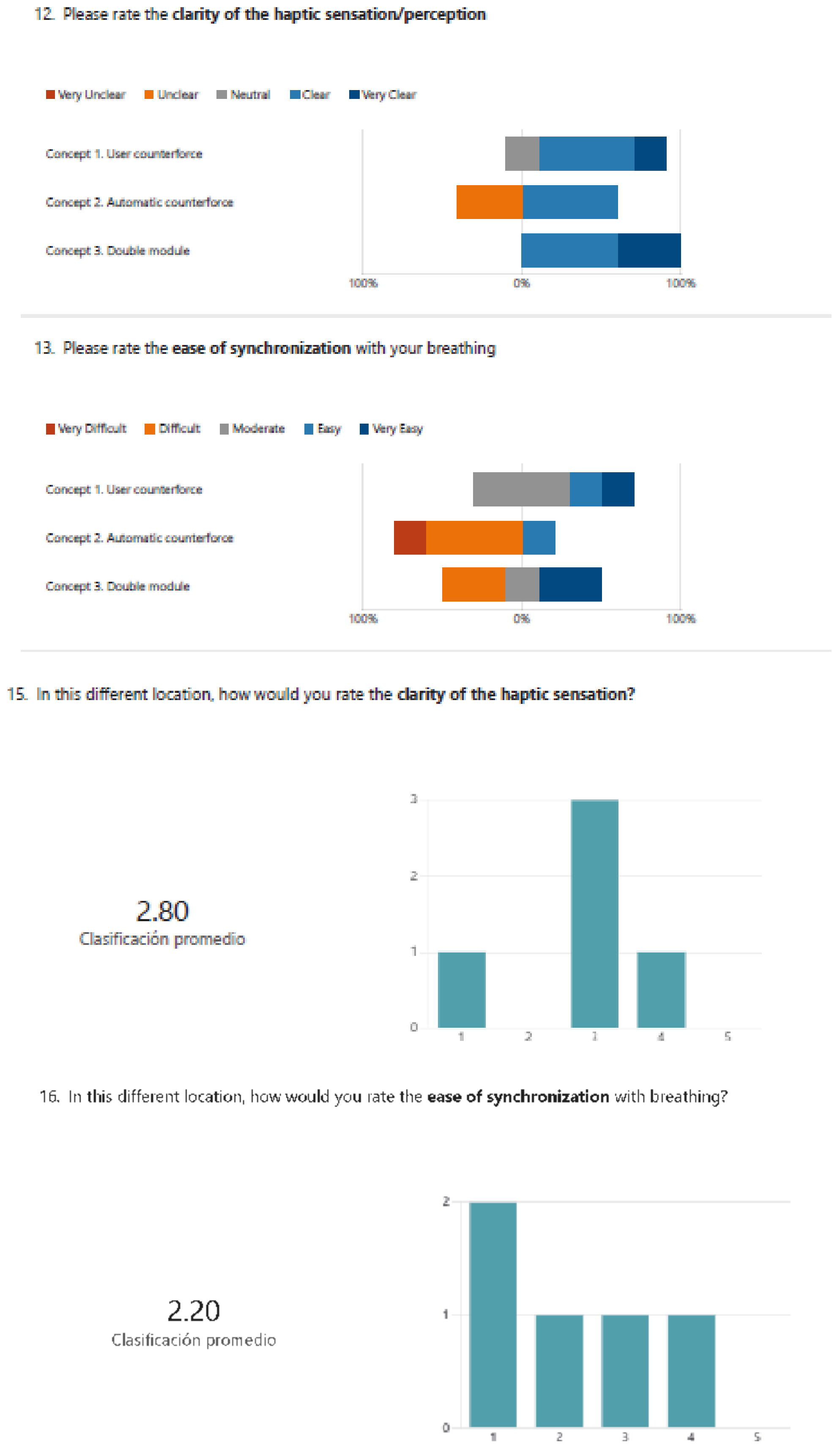


Fig. 82: Visual results of the clarity of perception and ease of synchronization of the three concepts around the abdomen (Questions 12 and 13) and on a different location (Questions 15 and 16).

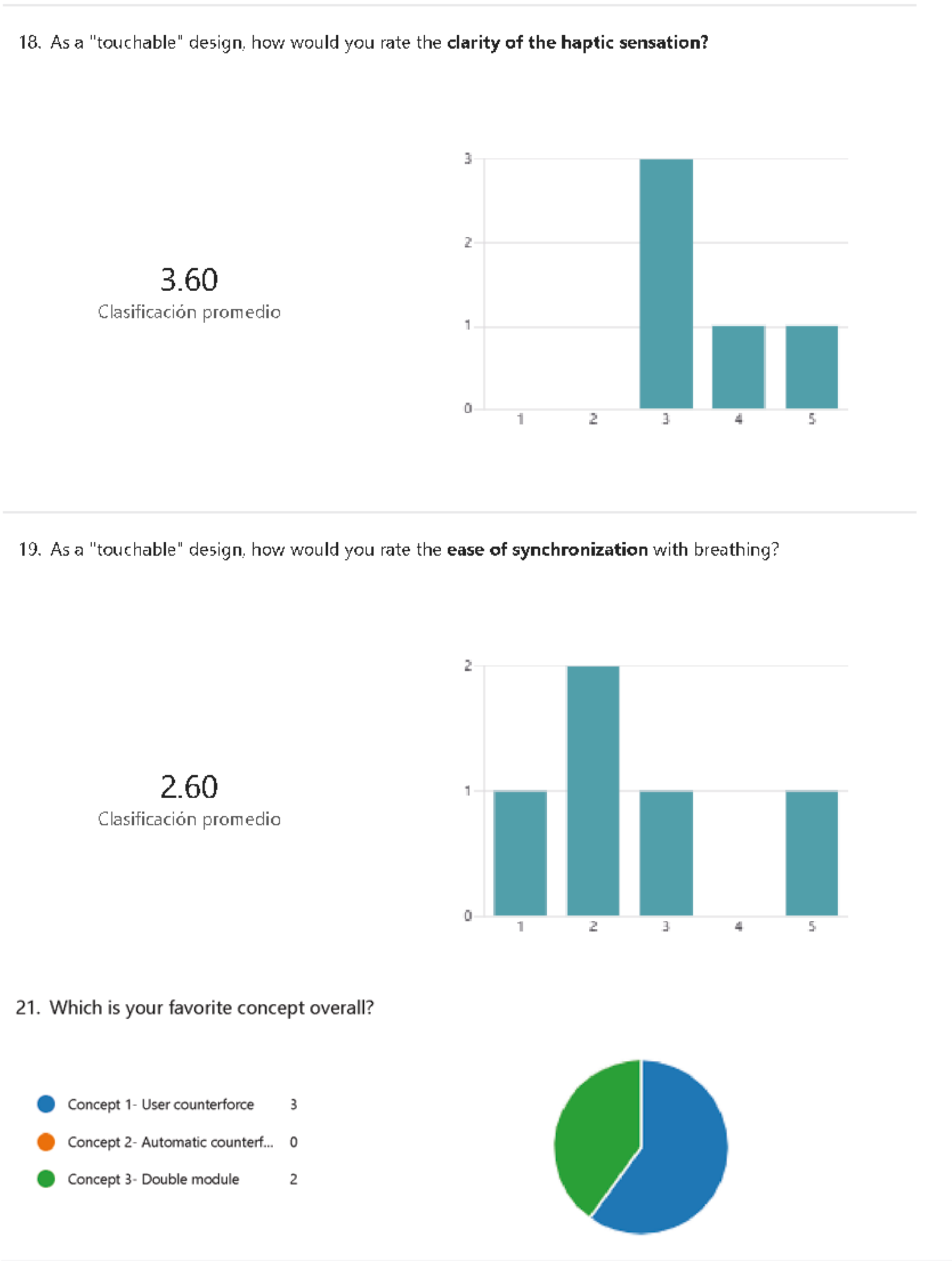
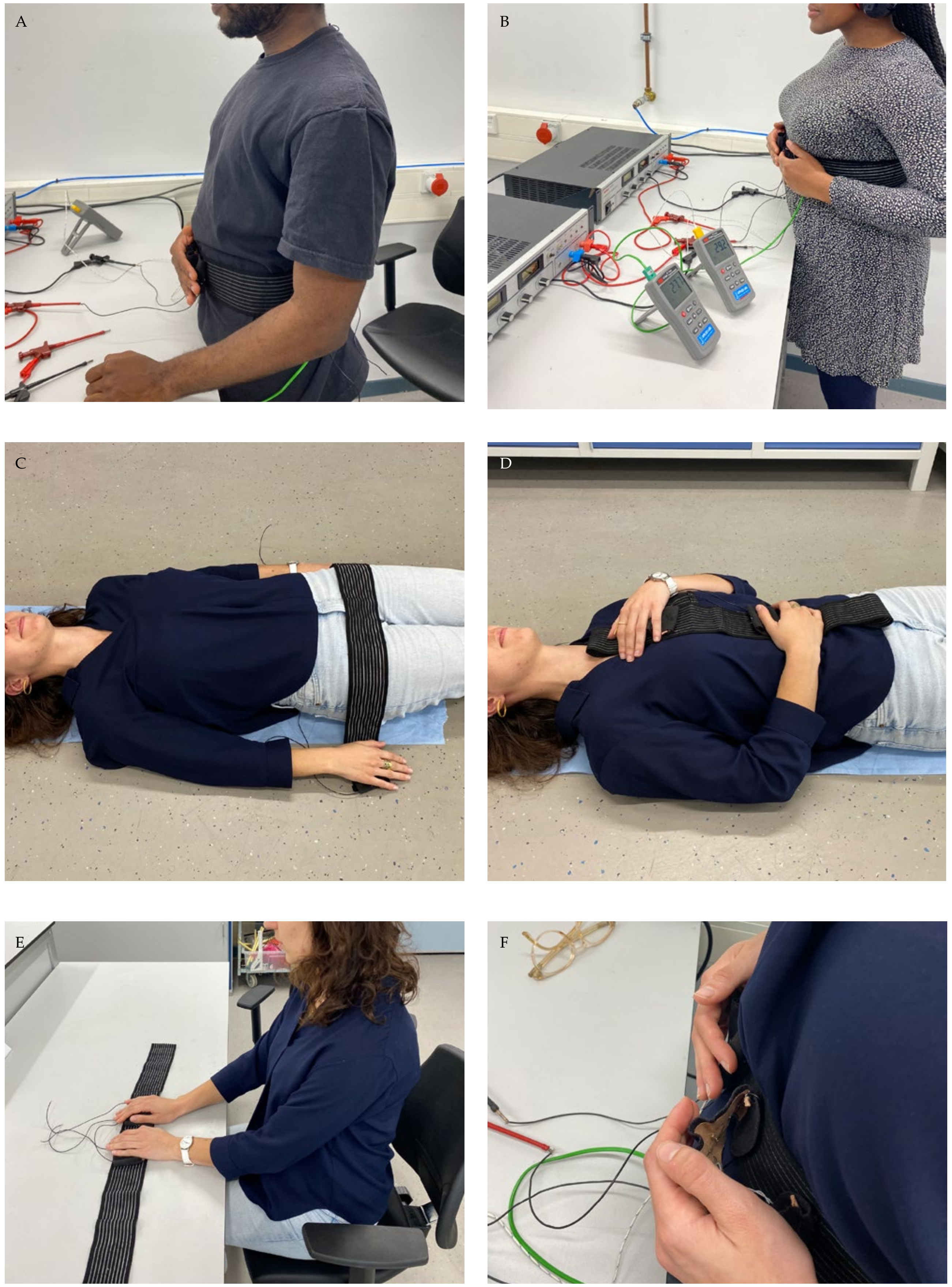


Fig. 83: Visual results of the clarity of perception and ease of synchronization of the three concepts as a 'touchable' design (Questions 18 and 19) and favourite concept (Question 21).



Images from the user study: (A) Concept 1 with one module, (B) Concept 3 with two modules, (C) alternative use of the prototype laying down on the body sides, (D) on the torso, (E) on the table while stting, and (F) zoom to expansion of Concept 3.

DISCUSSION

The results indicate a clear preference for Concept 1, where the user acts as the counterforce for a single module, and Concept 2, consisting of two modules where the user follows the guidance for inhaling (left module) and exhaling (right module).

In terms of haptic movement perception, Concepts 1 and 3 exhibit more noticeable movement, especially during the expansion phase when breathing in. Conversely, Concept 2's movement is more restricted and less clear due to the presence of the elastic counterforce. When it comes to breathing synchronization, Concept 1 scores higher as it is easier to understand and control a single module mimicking natural abdominal movements. However, issues with holding breath-exhalation transitions are noted, as they are perceived as unclear. Users also struggle with Concept 2 due to unclear perception and exhalation timing, as they feel there is too much waiting time for the automatic inward movement.

Concept 3 receives mixed feedback; while some participants find the two modules easier to follow for the two breathing actions, others find the movement unnatural and the feedback too confusing, which distracts them from focusing on relaxation. Participants feel more engaged with Concepts 1 and 3 since their actions are necessary to complete the breathing cycle, preventing passive distraction. Concepts 1 and 2 are highlighted as more intuitive to use than Concept 3, where differing feedback for each hand does not align well with the relaxing purpose.

Regarding design simplicity and potential applications, Concepts 1 and 2 are seen as simpler and more compact, making them suitable for various applications such as wrist placement, use in bed, during yoga/meditation classes, or in stressful scenarios like presentations.

In exploring different body locations and 'touchable' uses, participants agree that while haptic perception remains similar, synchronization becomes more challenging without a direct connection to the abdomen. Nonetheless, the ability to place the design elsewhere increases customization and adaptability, catering to individual user preferences such as sitting, lying down, or practicing yoga.

These results are organized in a table based on the Harris Profile evaluation method, with each concept scored from 1 to 5 on five criteria aspects, prioritizing haptic perception and breathing synchronization.

Regarding non-technical aspects and in line with the experiential characterization of MDD, several insights were interesting to analyze. Participants evaluated the material qualities of the concepts from an experiential perspective both at the beginning and throughout the procedure. They were curious about the irregular shape and wanted to interact with it. The elastic band and surrounding electronics led them to associate the device with medical or fitness/sportive purposes, such as muscle relaxation or blood pressure tools. When the mechanism was activated, participants were surprised by the unexpected natural and slow movement, which effectively mimicked natural breathing. They found the elastic abdominal band comfortable, strong, and adjustable, while the folding material was soft but slightly unstable. Overall, they described the prototypes as a combination of medical and professional mechanisms and a personal, integrated tool, almost as if it were part of the body.

These insights are categorized into four levels of material qualities interpretation:

Requirements	Concept 1. User counterforce	Concept 2. Automatic counterforce	Concept 3. Double module
★ **Clear haptic perception**	●●●●	●●	●●●●
★ **Ease of breathing synchronization**	●●●●	●	●●●
User awareness (engagement)	●●●●●	●	●●●
Intuitiveness	●●●●	●●●●	●●
Versatility (preferences)	●●●●●	●●●●●	●●
	*natural movement *easy to synchronization *struggle with transition *more engagement	*lack of perception when contracting *laziness, passive behaviour	*clear transitions *too much complex feedback *unnatural movement

Fig. 84: Concept evaluation based on main requirements (with a star) and secondary requirements.

Performative level: What does the material make you do?

- Pressing
- Caressing
- Grazing

Sensorial level: How does the material feel?

- Soft
- Rough
- Elastic
- Light
- Strong band but weak folding
- Irregular texture

Affective level: What emotions does the material elicit?

- Surprise
- Curiosity
- Comfort

Interpretive level: What do you associate with the material?

- Professional (medical, sportive)
- Natural
- Calm
- Toy-like
- Strange
- Hand-crafted

Fig. 85: Experiential characterization of the user study categorized into the four MDD levels: performative, sensorial, affective, and interpretive.

4.5. Final Concept Selection

The concept showing the most potential is Concept 1, 'User Counterforce,' with some elements from Concept 3, 'Double Module.' Concept 1 exhibits the highest haptic perception and ease of synchronization. It also opens the possibility of integrating a phase transition indicator from holding to exhaling, enhancing clarity and intuitive use. Concept 1 is preferred for its high engagement, making the user actively part of the process and enhancing the feelings of release. Its single-module composition makes the mechanism easier to follow and aligns well with the natural expansion-contraction movements of abdominal breathing. Additionally, it suggests greater versatility in field applications and body locations.

However, some aspects should be improved, such as using more pastel colors for a relaxed aesthetic, creating a more solid folding structure, automating the heating-cooling cycles with customizable breathing techniques depending on the user's expertise, and designing a more portable and discreet device with non-visible electronics to enhance user-friendliness.

Chapter 5.
Embodiment Design

The concluding chapter refines the final concept into a detailed embodied prototype, enhancing technical and aesthetic aspects while integrating electronic components. Subsequently, the final design undergoes validation both technically and experientially.

5.1 Final iterations

The final design is based on Concept 1, where the user pushes back the module during exhalation. It incorporates suggestions from Concept 3 and user study feedback. Additionally, it features an electronic system with a heart rate (HR) sensor and a breathing mode selection button to enhance automation, portability, customization, and user-friendliness. By combining heartbeat measurement with breathing tactile guidance, the design aims to enhance self-awareness of body-mind conditions, facilitating nervous system regulation. The SMA is shaped through the new re-training method by applying power at 60ºC while fixing the textile module in an expanded state, as previously described. Before the final prototype, some iterations are undertaken to simplify, minimize, and optimize the design.

Fig. 86: Explosion of components of the final protoype: (top-bottom) SMA, kinesiology tape, microfiber textile, and abdominal elastic band.

Fig. 87: Iterations with stitching the SMAs to the kinesiology tape.

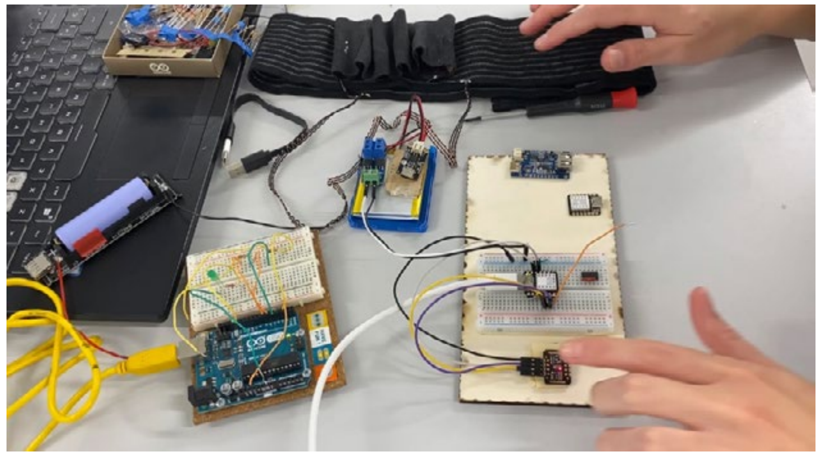


Fig. 88: Iterations with electronics' components.

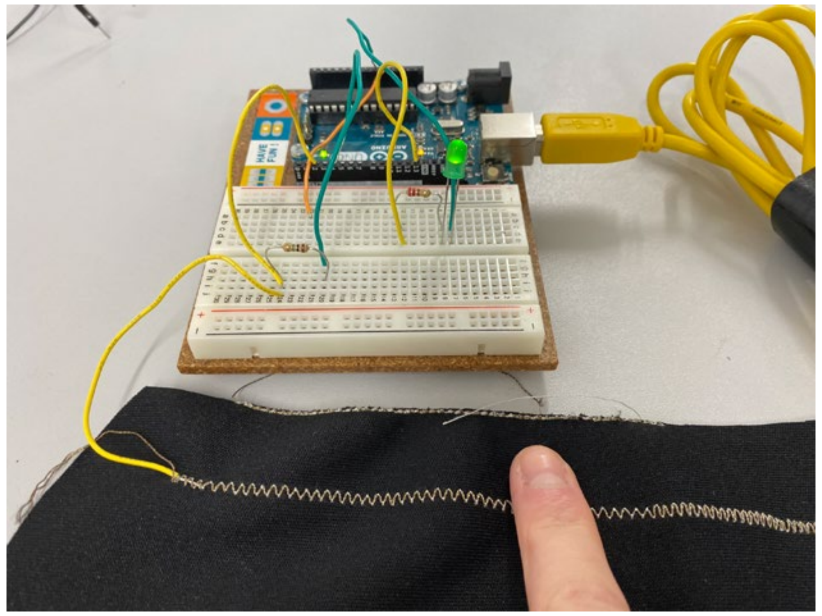


Fig. 89: Iterations with conductive thread as a capacity sensor.

5.2 Final Prototype Design

TECHNICAL ASPECTS

Several technical improvements have been implemented. First, the automatization of breathing cycles: the heating (inhalation) and cooling (exhalation) cycles are automated using a SEEED XIAO SAMD21 microcontroller. Two modes of breathing techniques are programmed:

- Mode 1, "Beginner 5-5-5," with cycles of 5 seconds for inhalation, 5 seconds for holding breath, and 5 seconds for exhalation.
- Mode 2, "Advanced 4-7-8," with cycles of 4 seconds for inhalation, 7 seconds for holding breath, and 8 seconds for exhalation.

Users can select the mode based on their expertise in breathing techniques and specific needs.

Second, the bulky power supply is replaced with a portable 3.7v lithium battery, which is sufficient to power the device. A flat battery of 1 cm thickness is chosen to minimize space. To power the XIAO (5v) with the battery (3.7v) and to charge it, a SEEED Lipo Rider Plus module is integrated, along with a Grove Mosfet to regulate power and avoid short-circuiting.

Third, the HR pulse sensor: the MAX30102 module measures the user's heartbeat before and after the breathing exercises, providing clearer awareness of self-biomarkers indicating anxiety levels. Ideally, these measurements would be displayed and stored in an app to avoid distracting the user during breathing exercises and to observe the correlation between HR and stress relief. This sensor demonstrates higher reliability and stability in measurements than the pulse sensor from Arduino used in the tinkering at the beginning.

Fourth, conductive threads: to discreetly integrate the electronics into the textile and enhance a friendly appearance, two types of conductive threads are used for connection. One thread covered with insulation connects the electronic system to the SMA and is stitched throughout the abdominal band. It is important to note that for soldering the conductive thread, it first needs to be covered with tack flux (CHIPQUIK SMD4300TF10) to remove the insulation. The other type of conductive thread is stitched directly with the sewing machine and serves as a button to select the preferred mode – one touch activates beginner mode and a 3-second touch activates advanced mode. It works as a capacitive sensor measuring the electromagnetism from the body through the fingertip, replacing larger and heavier electromechanical buttons or switches.

It is key to emphasize the importance of component connections to prevent energy dissipation. By incorporating metal connector tubes between the SMA and the conductive thread and soldering all connection points, there is a significant improvement in power transmission and the overall functioning of the mechanism. Additionally, a phase transition from 'holding breath' to 'exhalation' was tested, as recommended in the user study, using a small expansion indicator. However, this was not sufficiently clear and will need further improvement. An attempt was also made to use one long wire instead of two parallel wires to simplify the wiring. However, as predicted by the equations, it required double the current intensity due to higher resistivity. Therefore, maintaining two wires remains the optimal and more sustainable option.

AESTHETIC ASPECTS

The design is also refined from a non-technical perspective through some aesthetic adjustments. Inspired by Mila Luker's project, the prototype's folding mechanism is improved into a more solid and stable origami structure during expansion and compression by incorporating an origami-like stitching on the textile aligned with the SMA.

All electronic components are housed in a small portable closed storage case (92x55x30mm) covered with a 'textile pocket,' making the design more discreet and user-friendly, with a less 'electronic' appearance, as stated in the user test. The textile color is changed to pastel light grey and white tones, aligning it more with meditation and 'calm' associations, making it less 'aggressive' or 'medical.' To enhance the interaction, the mode selection button made with conductive thread includes a small sponge to make the experience more satisfying and fun when touching the button.

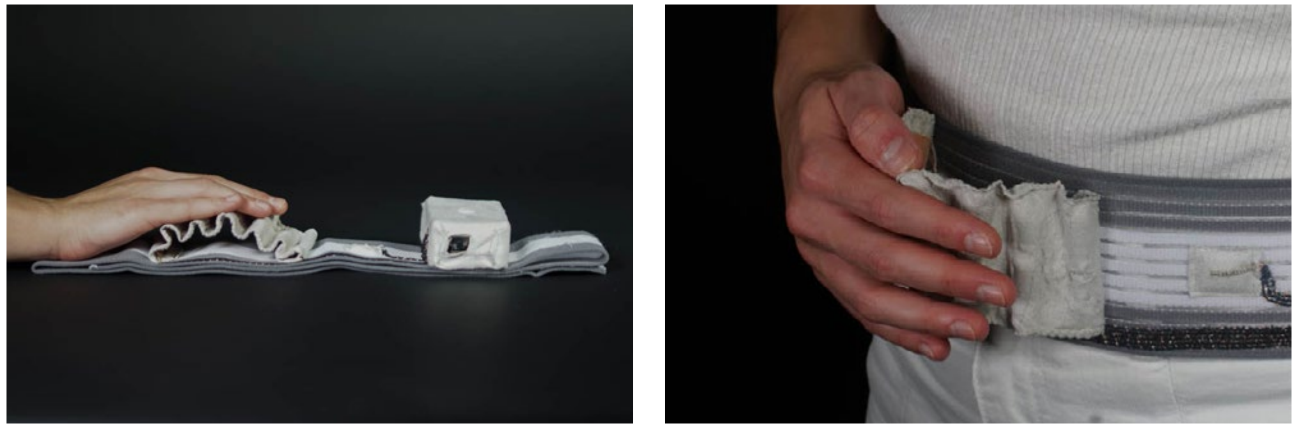
A

B

Fig. 90: Final prototype (A) placed on the abdomen and (B) from top view with components: SMA-textile band, capacity sensor button for mode selection, electronics' housing covered with textile, and conductive thread connecting all components.

A 0s - Beginning (SMA is cooled)

B 0-2.5s: SMA starts heating and expands (inhaling)



C 5-10s: SMA starts cooling and keeps expanded shape (holding breath)

D 10-15s: SMA is cooled and contracts (exhaling)

Fig. 91: Steps of SMA mechanism with Mode 1-Beginner 5-5-5: (A) expanding, (B) keeping expanded shape, and (C) contracting.

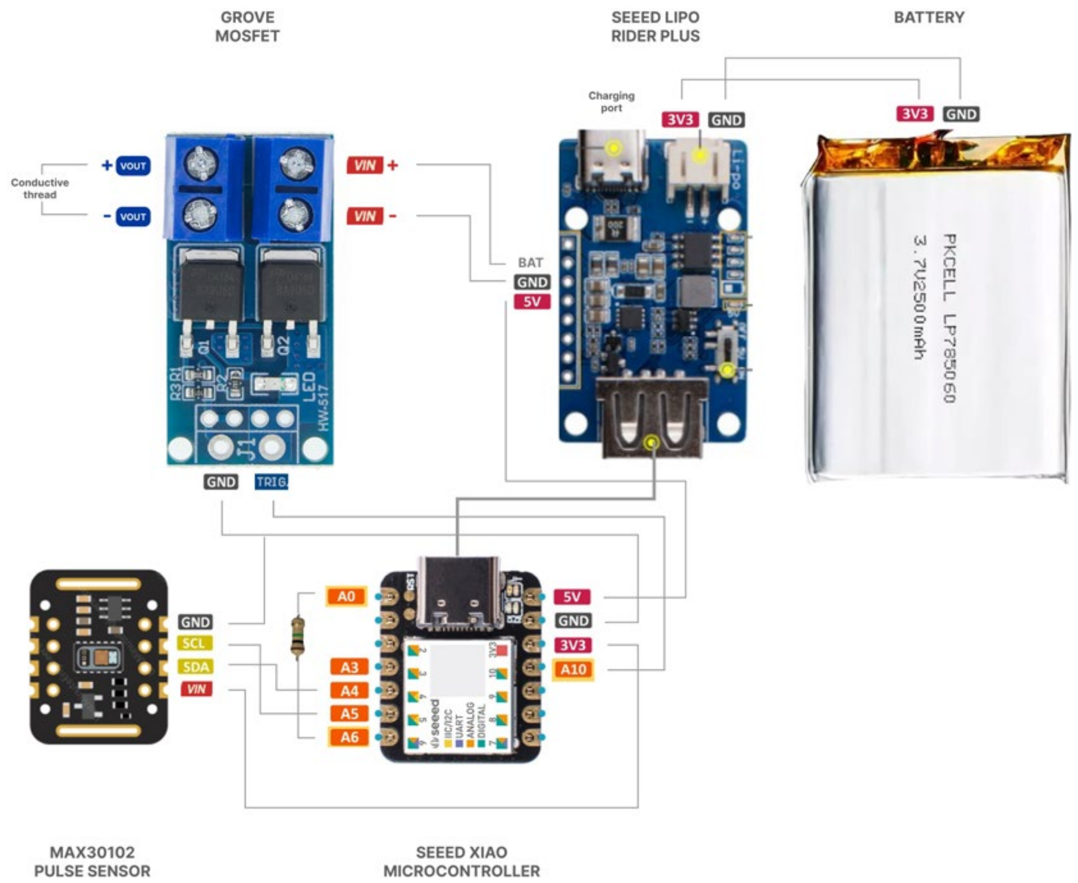


Fig. 92: Electronic circuit of the final prototype composed of a grove mosfet, a SEEED Lipo Rider Plus, a battery, a MAX30102 pulse sensor, and a SEEED XIAO microcontroller.

A B

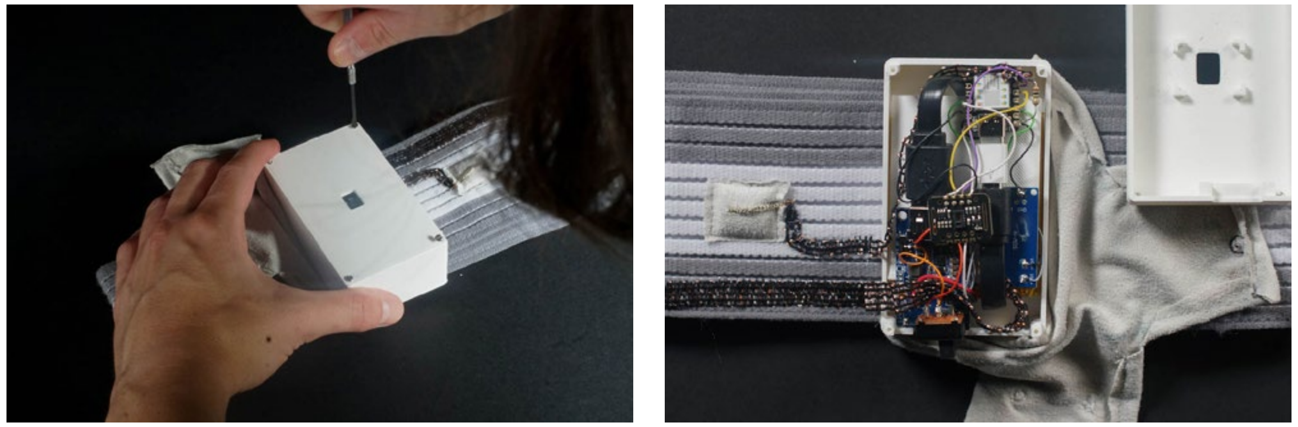


Fig. 93: Images of electronics' housing module: (A) opening casing and (B) components connected through conductive thread.

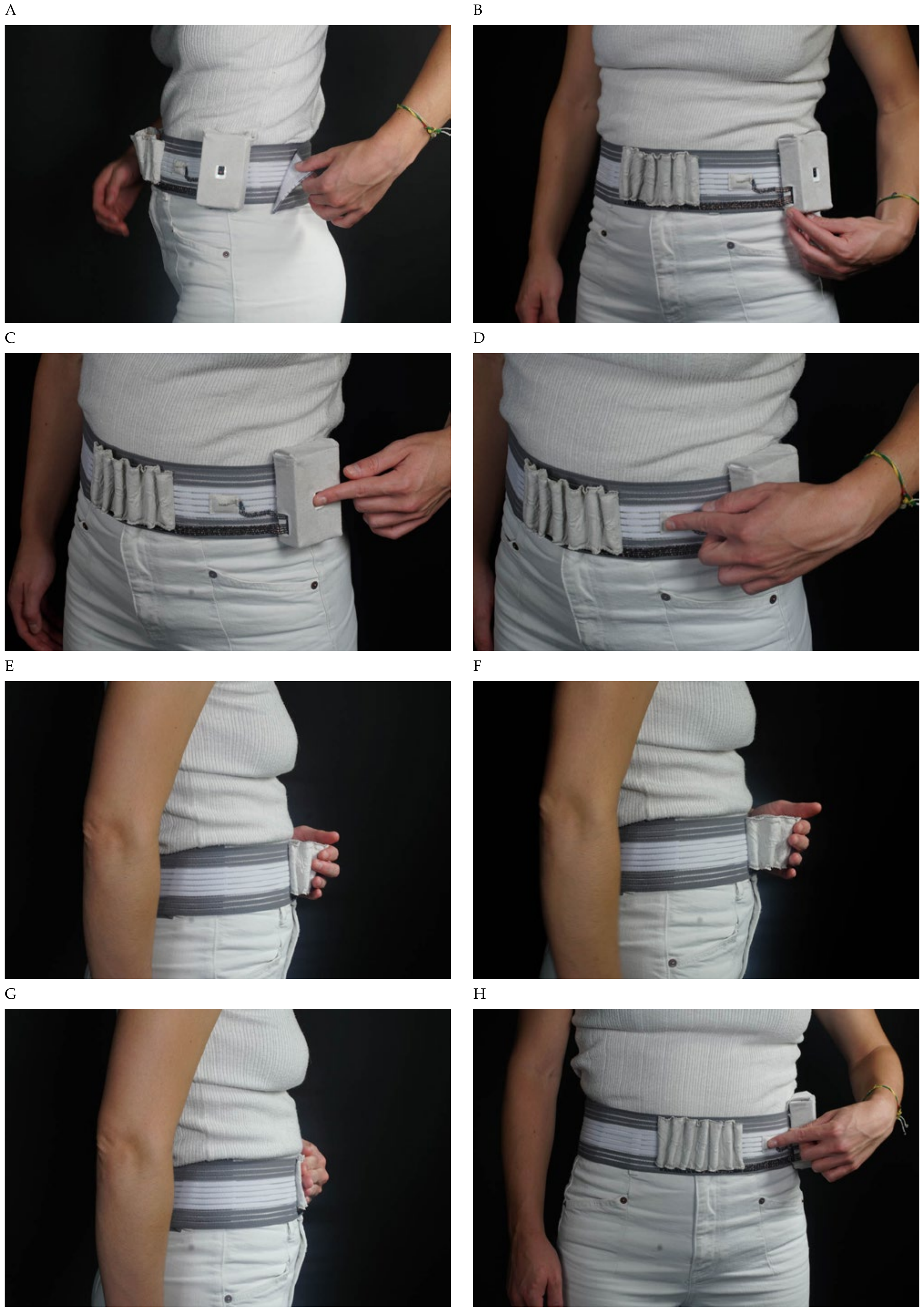


Fig. 94: Steps of the 5-5-5 breathing technique with the final prototype: (A) adjusting abdominal band, (B) switching ON system, (C) measuring HR through fingertip, (D) selecting breathing exercise mode, (E) inhaling, (F) holding breath, (G) exhaling, and (H) measuring HR at the end of exercise.

Fig. 95: Details of final prototype: (A) Capacity sensor button connected to conductive thread and (B) SMA integrated into textile and connected to conductive thread through a metal tube.

5.2 Validation

EXPANSION MECHANISM AND HEART RATE MEASUREMENT

The functionality of the expansion mechanism is validated by testing the continuity of module expansion from the abdomen (displacement) when placed on the body. The experiment involves measuring the expansion after 5 seconds of heating (inhalation) over 10 consecutive cycles. The cycles are automated using the electronic system, lasting a total of 2.5 minutes as recommended for breathing exercises. Each cycle is measured three times, and the standard deviation is calculated. Additionally, the heartbeat is measured after 15 seconds using the integrated pulse sensor for 10 iterations.

The test results indicate consistent expansion (53mm on average) over the cycles, except for the initial ones, which are affected by residual stresses that hinder deformation. Furthermore, the heartbeat results show a clear and stable signal (82.2 bpm on average) , with measurement starting at 5-7 seconds and stabilizing around 10-15 seconds.

HR measurement

```
IR=118089, BPM=88.24, Avg BPM=77
Capacitive Sensor Value: 11
IR=118235, BPM=79.05, Avg BPM=78
Capacitive Sensor Value: 9
IR=118018, BPM=85.84, Avg BPM=82
Capacitive Sensor Value: 7
IR=118280, BPM=88.24, Avg BPM=82
Capacitive Sensor Value: 13
IR=118382, BPM=79.05, Avg BPM=82
Capacitive Sensor Value: 23
IR=400, BPM=300.00, Avg BPM=82 No finger?
Capacitive Sensor Value: 30
IR=396, BPM=300.00, Avg BPM=82 No finger?
Capacitive Sensor Value: 20
IR=394, BPM=300.00, Avg BPM=82 No finger?
Capacitive Sensor Value: 10022
IR=387, BPM=300.00, Avg BPM=82 No finger?
Capacitive Sensor Value: 79274
IR=402, BPM=300.00, Avg BPM=82 No finger?
Capacitive Sensor Value: 41825
IR=365, BPM=300.00, Avg BPM=82 No finger?
Mode 1 selected.
Heating 1 out of 5 seconds
```

BPM stored when finger not detected

Capacity sensor detects one touch through the finger after 3 seconds

One touch activates Mode 1 and mechanism is activated

Fig. 96: Results displayed on the program's screen:Pulse sensor measuring HR and capacity sensor measuring skin electromagnetism to activate the mechanism.

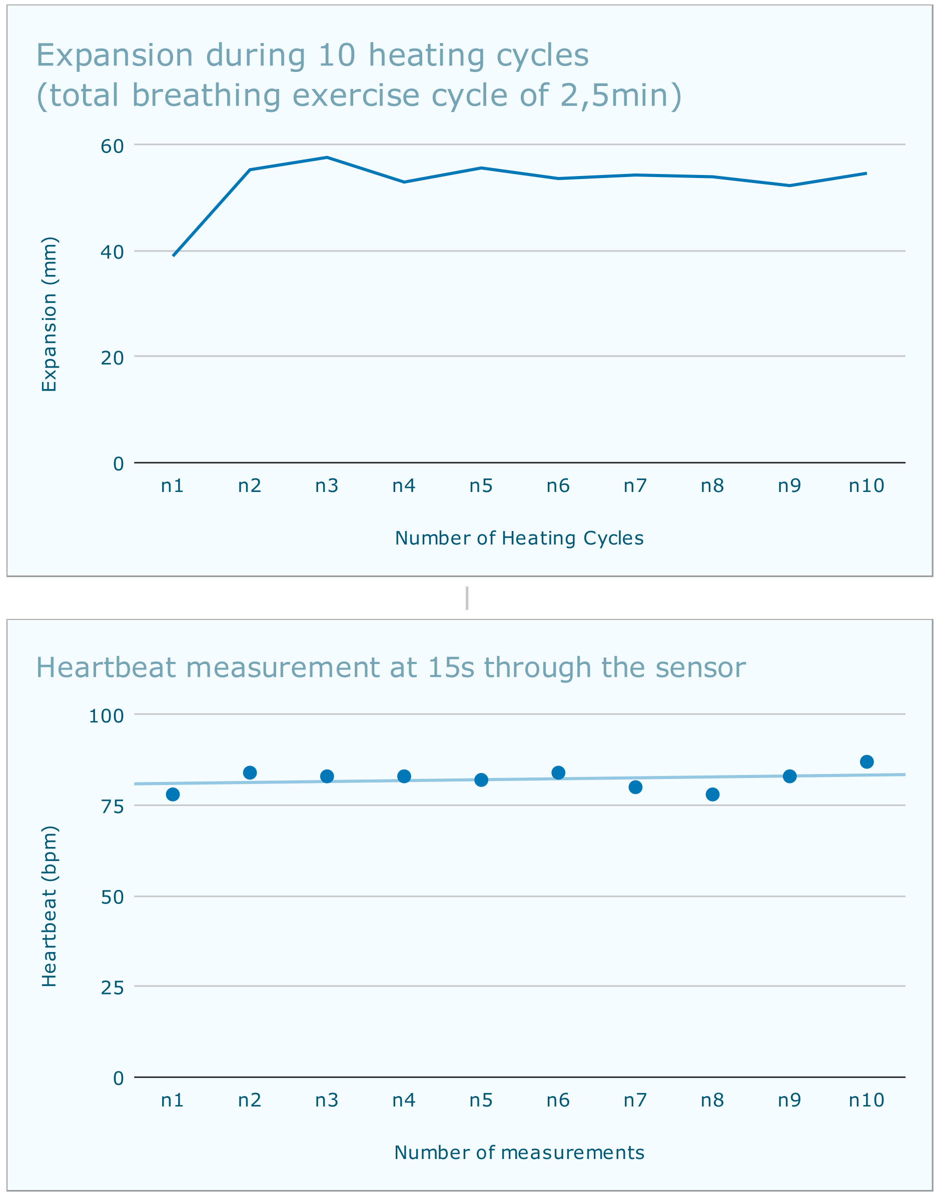


Fig. 97: Diagram results of expansion and HR during 10 heating cycles.

USER EXPERIENCE

The final prototype is evaluated experientially using the method of auto-ethnography based on self-reflection. The design effectively synchronizes breathing and guides the user throughout the exercise, contributing to soothing and stress-relieving sensations. The expansion mechanism clearly signals the start of inhalation, with a slight warmth during inhalation (felt through the hand close to the band), indicating when to begin breathing in. However, the transition from holding breath to exhalation remains slighly confusing and requires further improvement for clearer indication. In the initial cycle, the movements are not highly noticeable but help the user become accustomed to the haptics and understand the expansion principle.

The softness of the material provides a soothing touch, and the elastic abdominal band encourages maintaining a straight posture and focusing on the area, reminding of yoga postures. As the expanding module is currently unstable -and therefore slightly distracting during the breathing exercise-, it could be improved with a stiffer material or a fixed folding structure for enhanced intuitiveness. Additionally, the force required to push back the band increases slightly with each cycle, aiding in a slower pushback and extended exhalation.

Regarding the electronics' housing, it does not interfere with the haptic guidance, but if both hands are used, one on top of the other, it slightly limits the ability to push back completely. For left-handed individuals, touching the housing might interfere with the perception of expansion and contraction, affecting the overall soothing experience. A flatter housing or a different location might be beneficial, although housing on the side is convenient for lying down or leaning back in a chair.

When measuring HR through the fingertip, arm movement is manageable, and the conductive thread button provides a satisfying, soft, and 'spongy' texture, making it easy to locate without looking.

PART III.
CONCLUSIONS

Contributions and limitations

This project has revealed new insights into the potential of integrating stress regulation, smart wearables for health, and shape-morphing materials. There is a significant gap in existing solutions that effectively combine body monitoring and haptic feedback for anxiety relief. Current solutions often rely on noisy, bulky, and non-discreet pneumatic or mechanical systems, or they apply shape-morphing materials mainly for sports or fashion rather than for conscious breathing techniques. This gap leaves individuals with anxiety unaware of their physiological and psychological conditions and disengaged from improving or preparing for anxious episodes in daily life, addressing Research Question 1.1.

The project highlights the advantages of shape-morphing materials and smart textile technology for health applications due to their noiseless, lightweight, discreet, non-invasive, and stretchable nature, as well as their favorable power-to-weight ratio compared to electromechanical motors. These attributes facilitate the integration of these materials into textile-based wearable devices for everyday use, offering an improved alternative to conventional treatments. Additionally, the project emphasizes the importance of a research methodology that combines theoretical and empirical exploration, as seen with the MDD method, to gain a deep technical and experiential understanding of the materials.

MATERIAL: SMA, textile and electronics

The experimental studies revealed that Shape Memory Alloys (SMAs) with a 0.5mm diameter reduce response time by a factor of ten compared to a 1mm diameter at an electric current of 3A and require half the current for initial shape change (1.5A for 0.5mm and 3A for 1mm). The 0.5mm SMA cooled faster, facilitating manual deformation during cooling. However, applying load during the austenite transformation phase can lead to 'memory loss'; thus, the load must be applied below As=40°C. During the first heating cycle, most samples exhibited higher recovery times and lower displacement due to residual stresses impeding deformation. Among zigzag, loop, and spring shapes, springs offer a 10 times faster response, with higher displacement, yet are more difficult to integrate into textiles. Zigzag and loop shapes present greater potential for slow, organic movement due to their wider range of response times (As-Af), with zigzag being the easiest to shape and integrate into textiles at a higher deformed strain (above 100% of initial shape). This aligns with RQ 1.2's focus on enhancing user perception through the accurate simulation of the breathing rhythm system.

In terms of textile substrates, reducing the number of stitches between SMA and textile and positioning a single stitch laterally to the zigzag wire allowed greater wire mobility and halved response time (from 20 to 10s) at equivalent displacement. The wire peaks, critical bending points, should be left freer, while proper fixation of wire ends is necessary to ensure full textile movement. Larger zigzag sizes required more power and exhibited less shape stability but achieved higher deformed strain. Adding thermal insulation reduced displacement by 20%, though load remained around 1.3N. Thinner textile layers reduced response time by a few seconds. Adding a second parallel wire required slightly more current (from 2A to 3A) but doubled the load and increased displacement by 10%, while reducing response time tenfold. The elasticity property of the textile also contributed to the expansion-contraction movement of the prototype for simulating the breathing rhythm system.

Regarding electronics and sensors, the power source can be connected to the SMA through a Grove MOSFET power regulator to prevent overheating. The microcontroller successfully automated breathing exercises of 5-5-5s and 4-7-8s. While the pulse sensor measured heartbeats with a noise cancelling program, the signal still remained unstable. Conductive thread simplified, lightened, and reduced the size of electronic components, acting as 'connecting cables' and capacitive sensors for system activation and breathing technique selection. Integrating all electronic components into a single discreet housing improved durability and 'non-dangerous' appearance, and a low-energy battery enhanced portability and discreetness.

The overall design integrates the three elements in a single portable wearable and ensures a correct expansion mechanism (above 90% of shape recovery). By attaching only the sides of the SMA module it can easily move outwards and through the conductive threats along the elastic abdominal band it can be connected to the electronics housing in a discreet manner. The microfiber properties of the module textile brings softness to the user and elasticity for free expansion movement. With the selected elastic and 'breathable' abdominal band is easy to adjust to body and allows ventilation of skin sweat. And with the kinesiology tape it prevents a skin contact above 50º. This alignes with the Research Questions 1.1 and 1.2.

MANUFACTURING PROCESS

A significant discovery was the new re-training method for SMA. After standard training (heating to annealing temperature and fast cooling in water), SMA can be re-trained to the same or a different shape by manually fixing it to a structure, applying power to raise its temperature above Af (70-80ºC), and maintaining the shape during cooling until below As (40ºC). This SME method, repeatable and reliable –shape recovery above 90%– even with the wire integrated into the textile, offers a promising approach for easy and fast shape training, requiring less effort, time, and energy.

It is important to note that SMA behavior can differ from literature due to specific technical properties, supplier composition, and manufacturing processes. For instance, Flexmet recommended training NiTiCu SMA wire at lower time and temperature (15 minutes at 500ºC) instead of the typical 40 minutes at 550ºC to achieve full shape recovery,

New insights indicate that users prefer active involvement in haptic breathing guidance to maintain focus and feel a stronger personal connection to the device. The module's slow, organic expansion-contraction movements on the abdomen are closely aligned with natural diaphragmatic breathing, facilitating easy synchronization and enhancing the user's sense of calm. The combined movement and slight warmth from the SMA through the textile create a 'hugging'-like and soothing experience. While the haptic feedback effectively engages users throughout the breathing exercises, clarity in phase transitions requires improvement. The softness and pastel color of the textile provide a skin-like sensation, enhancing the product's 'familiarity.' Its elasticity and adjustability are key for fitting the body, making the user feel 'secured' and focused. Users perceive the prototype as having both 'medical' and 'personal' qualities, making it a promising solution for anxiety relief and other applications such as yoga, meditation, and sleep (Research Question 2.1).

The prototype's simplicity and portability enable versatile use in various locations and body postures, such as on the knees while sitting, on the bed while lying down, or on the wrist while walking. It can also be used as a 'touchable' device, for instance, by placing it on the floor during a yoga class. The curiosity and playful reactions from users suggest a positive overall experience with the design, both initially and over time (Research Question 2.2).

Recomendations

The results of this project suggest several recommendations for further exploration in the application of smart textiles within the mental health sector and their interaction with users to enhance well-being. A major challenge with Shape Memory Alloys (SMAs) lies in accurately predicting their behavior to achieve complete shape recovery. Consequently, it is essential to collaborate closely with suppliers to deeply understand the material's properties and limitations. For instance, the Flexmet supplier recommended training the SMA for 15 minutes at 500ºC, although it remains unclear what the maximum temperature—beyond the austenite finish (Af) temperature—it can tolerate before experiencing 'memory loss'. This knowledge is crucial as it directly impacts shape recovery and temporal changes.

Further research is recommended to explore the newly developed re-training method to determine its efficacy with other SMA wires besides NiTiCu from Flexmet. Investigating how the austenite and martensite transformations are affected—preliminary experiments indicate that the As temperature may decrease by a few degrees—and whether key technical parameters (displacement, response time, and load) remain stable throughout the cycles is essential. This method could potentially be applied to other shape memory materials, such as shape memory polymers and gels, which could be integrated into textiles.

In terms of sustainability, energy consumption can be minimized by using textile substrates that allow greater movement. For example, textiles with a more open internal structure that does not restrict SMA movement, integrating wires through knitting techniques instead of stitching, or employing advanced origami structures to enhance the shape-morphing effect. Additionally, to avoid high energy demands and lack of textile integration with thicker wires, exploring the use of thinner wire distributions, such as multiple wires connected with moving pivot joints to facilitate expansion-contraction movements, is recommended.

Improving data monitoring is also crucial. Replacing the pulse sensor with more stable and accurate heart rate measuring sensors, such as ECG technology, or using conductive threads as capacitive pulse sensors to convert electromechanical skin signals into heartbeats, could be beneficial. Collecting multiple HR measurements and displaying them in a user-friendly app would allow easy access for users and mental health professionals, leading to more accurate and effective diagnoses.

Experiential results suggest that clearer guidance in phase transitions during breathing exercises could enhance the interaction between the user and the wearable, thereby improving breathing synchronization. Incorporating additional haptics, vibrations, or even color-changing effects for transitioning indicators could ensure discreet, non-intrusive interaction. Additionally, minimizing the visibility and presence of electronic components, such as by integrating them into a PCB, is recommended to avoid the 'non-relaxing' associations with electronics. Enhancing the customization of breathing exercise patterns by allowing users to adjust haptic intensity and speed, as well as incorporating more complex breathing techniques, would also be beneficial.

As a wearable design, it currently utilizes sweat 'breathable' textiles, but it should become 'washable' either by disassembling the electronic housing or using waterproof textiles. Feedback from user studies indicates the potential to expand the applications of the prototype beyond stress regulation to include teaching diaphragmatic breathing for sports, children's pedagogy, and meditation practices.

Self-Reflection

My graduation project was driven by a strong motivation to bridge the gap between healthcare and smart materials. My goal was to demonstrate the potential of shape morphing technology in designing innovative alternatives to conventional stress treatments, such as medication. By exploring this cutting-edge technology in textiles, I aimed to reintroduce ancient universal stress-relief techniques, such as conscious breathing, in a modern context. I firmly believe that enabling people with anxiety to better understand their body-mind conditions can empower them to manage anxiety in its early stages. This motivation was rooted in my desire to positively impact mental health and enhance well-being both in the short and long term.

Throughout the project, I faced several challenges that provided valuable learning experiences. The most significant challenge was understanding the properties and behavior of Shape Memory Alloys (SMA) over time. Gaining confidence and predictive capabilities with this material required a substantial investment of time and effort to identify its limitations and translate them into benefits. Although I typically work in a theoretically oriented manner, I am pleased to have achieved my objectives through a simultaneous combination of theory and hands-on experiments. This balanced approach was key to my success, and I highly recommend it to future students. I am proud to have developed a promising method to make this challenging work more effective for future researchers and designers.

Additionally, I acquired interesting knowledge in textiles, particularly conductive textiles. I learned about their potential for replacing traditional electronics, which I can now use in future projects with greater confidence. Noticing a gap in previous related work regarding the inclusion of electronics, automation, and sensors in SMA-textile prototypes, I am happy to have implemented these aspects, achieving a goal I set at the beginning of the project.

Beyond gaining technical expertise, I explored the experiential aspects of the project, which was a new area for me. I learned that integrating user experience into the design process is vital for enhancing wearable devices, as they are directly used by individuals. The user studies and interviews played a key role in shaping my design to ensure it is appealing and practical for everyday use. Moving forward, I can apply this blend of technical and experiential insights in future projects, inspired by the Materials Driven Design (MDD) method.

I was grateful to have mentors who guided me through both the technical and experiential aspects of the thesis, contributing to my personal growth. Overall, I am highly satisfied with my project and the knowledge I have gained from it, as well as from my enthusiastic mentors. While I am uncertain if I will continue in the field of smart materials research, I am confident in my ability to apply a symbiosis of theoretical and empirical development of ideas from both technical and experiential perspectives in future work.

This project has deepened my understanding of the intersection between design, technology, and healthcare, reinforcing my commitment to creating impactful solutions for mental health and well-being. I highly encourage other students and researchers to take risks, face challenges, and create practical solutions,as the discovery of innovative results is profoundly rewarding.. Creativity arises when one takes risks and dedicates significant effort and commitment to the process.

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APPENDIX

1. Consent Form Interviews
2. Consent Form User Study
3. HREC Checklist
4. Interview Template
5. User Study Results
6. Technical Characterization
7. Coding
8. Technical Data Sheets of SMAs
9. Project Brief and Planning

APPENDIX 1.
Consent Form Interviews

Participant ID:

Informed consent to participate in a research study

You are being invited to participate in a research study titled "**Understanding Clinical Stress Treatment Approaches"**. This study is being done by Carlota Muñoz Ruiz from the TU Delft.

The purpose of this research is to gather insights into stress treatment approaches for anxiety used with clinical patients, as well as individuals' coping strategies. It will take you approximately 40 minutes to complete. The data collected will contribute to a Graduation Project focused on enhancing the treatment process for anxiety patients, with a specific emphasis on slow and deep breathing techniques or "breathwork". We are particularly interested in your perspectives on effective techniques and methods for measuring/assessing them, as well as patient reactions from a clinical standpoint. The collected data will be used for the design of various prototypes and their subsequent testing with users, aiding in the identification of design challenges and product requirements.

To the best of our ability, your answers in this study will remain confidential. Upon signing this consent, you will be assigned a unique participant ID number to ensure that all collected data is anonymized. We will further minimize any risks of personal data breach by storing your personally identifiable information in a password-secured electronic format at a secure TU Delft repository. All personal and raw data will be destroyed after the study is completed, and no raw data will be shared with anybody outside the research team at any time.

Your participation in this study is entirely voluntary, and you can withdraw at any time without having to give a reason and without adverse consequences. You are free to omit any questions, and your data can be removed by August 15th once the project is concluded.

If you have questions about the study or the procedures, please feel free to contact the corresponding researcher Carlota Muñoz Ruiz (c.munozruiz@student.tudelft.nl), or the responsible researcher Sepideh Ghodrat (s.Ghodrat@tudelft.nl) at any time.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [/ /2024], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves in-person/online interviews which will be audio-recorded. The recordings will be transcribed and destroyed immediately after the interview to minimize personal data collection.	☐	☐
4. I understand that I will not be compensated for my participation	☐	☐
5. I understand that the study will end on August 15th	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the risk of psychological discomfort due to past memories with patients. I understand that this risk will be mitigated in the following ways: • I will be free to omit any questions. • I will be able to withdraw from the interview at any point without having to give a reason and without adverse consequences.	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [name, e-mail address] and associated personally identifiable research data (PIRD) [audio recordings/photos of the interview] with the potential risk of my identity being revealed	☐	☐
8. I understand that some of this PIRD is considered as sensitive data within GDPR legislation, specifically health-related data.	☐	☐
9. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach: • Upon signing this consent, I will be assigned a unique participant ID number, under which all information I provide during the study will be stored; • My personally identifiable information will be stored in a password-secured electronic format at a secure TU Delft repository; • Audio recording • Photos	☐	☐
10. I understand that personal information collected about me that can identify me, such as name and e-mail address, will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed after the study is completed (August 15th).	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
12. I understand that after the research study the de-identified information I provide will be used for designing prototypes to obtain insights for a Master's Graduation Project at TU Delft.	☐	☐
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
14. I give permission for the de-identified health-related data that I provide to be archived in a secure TU Delft repository, so it can be used for future research and learning.	☐	☐
15. I understand that access to this repository is restricted only to the corresponding researchers.	☐	☐

Signatures

_________________________ _________________________ _________

Name of participant [printed] Signature Date

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

CARLOTA MUÑOZ RUIZ 16/05/2024

_________________________ _________________________ _________

Researcher name [printed] Signature Date

Study contact details for further information: the researcher Carlota Muñoz Ruiz (c.munozruiz@student.tudelft.nl) and the responsible researcher Sepideh Ghodrat (s.Ghodrat@tudelft.nl).

APPENDIX 2.

Consent Form User Study

Participant ID:

Informed consent to participate in a research study

You are being invited to participate in a research study titled "**Understanding Haptic Perception and 'Conscious Breathing' Synchronization of SMA Textile-Based Prototypes"**. This study is being done by Carlota Muñoz Ruiz from the TU Delft.

The purpose of this research is to gather insights into the guidance of 'Conscious Breathing' related to haptic perception and user synchronization using Shape Morphing Materials (SMA) textile-based prototypes. *'Conscious Breathing' is a type of breathing technique commonly used in therapy and meditation focused on slow and deep respiration in the diaphragm. It aims to relax the Nervous System and, therefore, reduce stress by enhancing the connection between mind and body*. The data collected will contribute to a Graduation Project focused on enhancing the self-awareness and self-management of anxiety via 'Conscious Breathing' techniques with SMA technology. The insights will be used for an experiential characterization of the design and to identify design challenges and requirements for improvement.

The test will take you approximately 40 minutes. It will be divided into a brief questionnaire about user familiarity with anxiety and breathing techniques and, second, a test comparing haptic perception and self-breathing synchronization with different physical prototypes.

To the best of our ability, your answers in this study will remain confidential. Upon signing this consent, you will be assigned a unique participant ID number to ensure that all collected data is anonymized. We will further minimize any risks of personal data breach by storing your personally identifiable information in a password-secured electronic format at a secure TU Delft repository. All personal and raw data will be destroyed after the study is completed, and no raw data will be shared with anybody outside the research team at any time. **Your participation in this study is entirely voluntary, and you can withdraw at any time without having to give a reason and without adverse consequences. You are free to omit any questions, and your data can be removed by August 15th once the project is concluded.** If you have questions about the study or the procedures, please feel free to contact the corresponding researcher Carlota Muñoz Ruiz (c.munozruiz@student.tudelft.nl), or the responsible researcher Sepideh Ghodrat (s.Ghodrat@tudelft.nl) at any time.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [/ /2024], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves audio recordings. The recordings will be transcribed and destroyed immediately after the test to minimize personal data collection.	☐	☐
4. I understand that I will not be compensated for my participation	☐	☐
5. I understand that the study will end on August 15th	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the risk of psychological discomfort due to past personal memories. I understand that this risk will be mitigated in the following ways: • I will be free to omit any questions. • I will be able to withdraw from the study at any point without having to give a reason and without adverse consequences.	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [name, e-mail address] and associated personally identifiable research data (PIRD) [audio recordings/photos] with the potential risk of my identity being revealed	☐	☐
8. I understand that some of this PIRD is considered as sensitive data within GDPR legislation, specifically health-related data.	☐	☐
9. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach: • Upon signing this consent, I will be assigned a unique participant ID number, under which all information I provide during the study will be stored; • My personally identifiable information will be stored in a password-secured electronic format at a secure TU Delft repository; • Audio recording • Photos	☐	☐
10. I understand that personal information collected about me that can identify me, such as name and e-mail address, will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed after the study is completed (August 15th).	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide will be used for designing prototypes to obtain insights for a Master's Graduation Project at TU Delft.	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
14. I give permission for the de-identified health-related data that I provide to be archived in a secure TU Delft repository, so it can be used for future research and learning.	☐	☐
15. I understand that access to this repository is restricted only to the corresponding researchers.	☐	☐

Signatures

_______________________ _______________________ ________

Name of participant [printed] Signature Date

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

CARLOTA MUÑOZ RUIZ

_______________________ ________________ ________

Researcher name [printed] Signature Date

Study contact details for further information: the researcher Carlota Muñoz Ruiz (c.munozruiz@student.tudelft.nl) and the responsible researcher Sepideh Ghodrat (s.Ghodrat@tudelft.nl).

APPENDIX 3.

HREC Checklist

Delft University of Technology
HUMAN RESEARCH ETHICS
CHECKLIST FOR HUMAN RESEARCH
(Version January 2022)

IMPORTANT NOTES ON PREPARING THIS CHECKLIST

1. An HREC application should be submitted for every research study that involves human participants (as Research Subjects) carried out by TU Delft researchers
2. Your HREC application should be submitted and approved **before** potential participants are approached to take part in your study
3. All submissions from Master's Students for their research thesis need approval from the relevant Responsible Researcher
4. The Responsible Researcher must indicate their approval of the completeness and quality of the submission by signing and dating this form OR by providing approval to the corresponding researcher via email (included as a PDF with the full HREC submission)
5. There are various aspects of human research compliance which fall outside of the remit of the HREC, but which must be in place to obtain HREC approval. These often require input from internal or external experts such as Faculty Data Stewards, Faculty HSE advisors, the TU Delft Privacy Team or external Medical research partners.
6. You can find detailed guidance on completing your HREC application here
7. Please note that incomplete submissions (whether in terms of documentation or the information provided therein) will be returned for completion **prior to any assessment**
8. If you have any feedback on any aspect of the HREC approval tools and/or process you can leave your comments here

I. Applicant Information

PROJECT TITLE:	Shape Morphing-Haptic Wearable for Regulating the Nervous System via Breathwork
Research period: *Over what period of time will this specific part of the research take place*	02.2024-08.2024
Faculty:	Industrial Design Engineering
Department:	Emerging Materials
Type of the research project: *(Bachelor's, Master's, DreamTeam, PhD, PostDoc, Senior Researcher, Organisational etc.)*	Master's Graduation Project
Funder of research: *(EU, NWO, TUD, other – in which case please elaborate)*	TUD
Name of Corresponding Researcher: *(If different from the Responsible Researcher)*	Carlota Muñoz Ruiz
E-mail Corresponding Researcher: *(If different from the Responsible Researcher)*	[redacted]
Position of Corresponding Researcher: *(Masters, DreamTeam, PhD, PostDoc, Assistant/ Associate/ Full Professor)*	Master's student (Integrated Product Design)
Name of Responsible Researcher: ***Note:** all student work must have a named Responsible Researcher to approve, sign and submit this application*	Sepideh Ghodrat
E-mail of Responsible Researcher: *Please ensure that an institutional email address (**no Gmail, Yahoo, etc.**) is used for all project documentation/ communications including Informed Consent materials*	s.ghodrat@tudelft.nl
Position of Responsible Researcher : *(PhD, PostDoc, Associate/ Assistant/ Full Professor)*	Assistant Professor / Project Chair

II. Research Overview

***NOTE:** You can find more guidance on completing this checklist here*

a) Please summarise your research very briefly (100-200 words)
What are you looking into, who is involved, how many participants there will be, how they will be recruited and what are they expected to do?

Add your text here – (please avoid jargon and abbreviations)

The purpose of this study is to understand the stress-related treatment and its different techniques for anxiety, particularly 'Conscious Breathing'. Therefore, it would be analyzed the viewpoint of mental health experts -via interviews- and of people with and without anxiety disorders -via user test of tactile haptics-. The aim is to gather valuable insights for identifying design opportunities in the wearable prototype.

The research will consist of two parts: first, semi-structured face-to-face/online interviews with mental health experts (approximately 40 minutes); second, a user test using physical prototypes with people experiencing (or not) chronic stress or anxiety. It will be tested their tactile haptic perception and self-synchronization to evaluate the ideas. This second phase will last around 40 min and each patient will fill out an individual questionnaire about her/his experience related to anxiety treatment.

A total of approximately 5 participants will be recruited for each phase through networking, email, and WhatsApp.

b) **If your application is an additional project** related to an existing approved HREC submission, please provide a brief explanation including the existing relevant HREC submission number/s.

Add your text here – (please avoid jargon and abbrevations)

N/A

c) **If your application is a simple extension of, or amendment to,** an existing approved HREC submission, you can simply submit an HREC Amendment Form as a submission through LabServant.

III. Risk Assessment and Mitigation Plan

NOTE: You can find more guidance on completing this checklist here

Please complete the following table in full for all points to which your answer is "yes". Bear in mind that the vast majority of projects involving human participants as Research Subjects also involve the collection of **Personally Identifiable Information (PII)** and/or **Personally Identifiable Research Data (PIRD)** which may pose potential risks to participants as detailed in Section G: Data Processing and Privacy below.

To ensure alighment between your risk assessment, data management and what you agree with your Research Subjects you can use the last two columns in the table below to refer to specific points in your Data Management Plan (DMP) and Informed Consent Form (ICF) – **but this is not compulsory**.

It's worth noting that **you're much more likely to need to resubmit your application if you neglect to identify potential risks**, than if you identify a potential risk and demonstrate how you will mitigate it. If necessary, the HREC will always work with you and colleagues in the Privacy Team and Data Management Services to see how, if at all possible, your research can be conducted.

			If YES please complete the Risk Assessment and Mitigation Plan columns below.		*Please provide the relevant reference #*	
ISSUE	**Yes**	**No**	**RISK ASSESSMENT – what risks could arise?** *Please ensure that you list ALL of the actual risks that could potentially arise – do not simply state whether you consider any such risks are important!*	**MITIGATION PLAN – what mitigating steps will you take?** *Please ensure that you summarise what actual mitigation measures you will take for each potential risk identified – do not simply state that you will e.g. comply with regulations.*	**DMP**	**ICF**
A: Partners and collaboration						
1. Will the research be carried out in collaboration with additional organisational partners such as: • One or more collaborating research and/or commercial organisations • Either a research, or a work experience internship provider[1] *[1] If yes, please include the graduation agreement in this application*		X				
2. Is this research dependent on a Data Transfer or Processing Agreement with a collaborating partner or third party supplier? *If yes please provide a copy of the signed DTA/DPA*		X				
3. Has this research been approved by another (external) research ethics committee (e.g.: HREC and/or MREC/METC)? *If yes, please provide a copy of the approval (if possible) and summarise any key points in your Risk Management section below*		X				
B: Location						
4. Will the research take place in a country or countries, other than the Netherlands, within the EU?	X		Some professionals from Spain will be interviewed and test results could be biased due to demographics.	State in the final thesis report the potential biases that could arise due to recruitment methods.		
5. Will the research take place in a country or countries outside the EU?		X				
6. Will the research take place in a place/region or of higher risk – including known dangerous locations (in any country) or locations with non-democratic regimes?		X				
C: Participants						
7. Will the study involve participants who **may** be vulnerable and possibly (legally) unable to give informed consent? (e.g., children below the legal age for giving consent, people with learning difficulties, people living in care or nursing homes,).		X				
8. Will the study involve participants who **may** be vulnerable under specific circumstances and in specific contexts, such as victims and witnesses of violence, including domestic violence; sex workers; members of minority groups, refugees, irregular migrants or dissidents?		X				
9. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children, own students or employees of either TU Delft and/or a collaborating partner organisation)? *It is essential that you safeguard against possible adverse consequences of this situation (such as allowing a student's failure to participate to your satisfaction to affect your evaluation of their coursework).*		X				
10. Is there a high possibility of re-identification for your participants? (e.g., do they have a very specialist job of which there are only a small number in a given country, are they members of a small community, or employees from a partner company collaborating in the research? Or are they one of only a handful of (expert) participants in the study?		X				
D: Recruiting Participants						
11. Will your participants be recruited through your own, professional, channels such as conference attendance lists, or through specific network/s such as self-help groups	X		1. Test results could be biased due to personal ties with the researcher. 2. Test results could be biased due to recruitment being done in similar demographics (experts mainly from Spain and patients mainly from IDE faculty).	1. Before user testing, reassure participants that honesty is the most important in responses. 2. State in the final thesis report the potential biases that could arise due to recruitment methods.		
12. Will the participants be recruited or accessed in the longer term by a (legal or customary) gatekeeper? (e.g., an adult professional working with children; a community leader or family member who has this customary role – within or outside the EU; the data producer of a long-term cohort study)		X				
13. Will you be recruiting your participants through a crowd-sourcing service and/or involve a third party data-gathering service, such as a survey platform?		X				
14. Will you be offering any financial, or other, remuneration to participants, and might this induce or bias participation?		X				
E: Subject Matter *Research related to medical questions/health may require special attention. See also the website of the CCMO before contacting the HREC.*						
15. Will your research involve any of the following: • Medical research and/or clinical trials • Invasive sampling and/or medical imaging • Medical and *In Vitro Diagnostic Medical* Devices Research	X		1. Questions could involve personal experiences with anxiety and coping mechanisms which may lead to personal mental-health invasion. 2. The user test could produce some slight physical discomfort from the warmth sensation	1. Questions will be as generic as possible without entering into too much personal detail. The participants will remain anonymous in the research and they are allowed to not answer. 2. The prototype has heat insulation layers and the temperature will remain under 50C (controlled by Arduino/manually). The prototypes have been tested repeatedly on the Researcher and the wearable prototype can be easily taken off by the participant.		Opening Statement, B-6
16. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants? *If yes see here to determine whether medical ethical approval is required*		X				
17. Will blood or tissue samples be obtained from participants? *If yes see here to determine whether medical ethical approval is required*		X				
18. Does the study risk causing psychological stress or anxiety beyond that normally encountered by the participants in their life outside research?		X				
19. Will the study involve discussion of personal sensitive data which could put participants at increased legal, financial, reputational, security or other risk? (e.g., financial data, location data, data relating to children or other vulnerable groups) *Definitions of sensitive personal data, and special cases are provided on the TUD Privacy Team website.*		X				
20. Will the study involve disclosing commercially or professionally sensitive, or confidential information? (e.g., relating to decision-making processes or business strategies which might, for example, be of interest to competitors)		X				
21. Has your study been identified by the TU Delft Privacy Team as requiring a Data Processing Impact Assessment (DPIA)? *If yes please attach the advice/ approval from the Privacy Team to this application*		X				
22. Does your research investigate causes or areas of conflict? *If yes please confirm that your fieldwork has been discussed with the appropriate safety/security advisors and approved by your Department/Faculty.*		X				
23. Does your research involve observing illegal activities or data processed or provided by authorities responsible for preventing, investigating, detecting or prosecuting criminal offences *If so please confirm that your work has been discussed with the appropriate legal advisors and approved by your Department/Faculty.*		X				
F: Research Methods						
24. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		X				
25. Will the study involve actively deceiving the participants? (For example, will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		X				
26. Is pain or more than mild discomfort likely to result from the study? And/or could your research activity cause an accident involving (non-) participants?		X				
27. Will the experiment involve the use of devices that are not 'CE' certified? *Only, if 'yes': continue with the following questions:*		X				
• Was the device built in-house?						
• Was it inspected by a safety expert at TU Delft? *If yes, please provide a signed device report*						
• If it was not built in-house and not CE-certified, was it inspected by some other, qualified authority in safety and approved? *If yes, please provide records of the inspection*						
28. Will your research involve face-to-face encounters with your participants and if so how will you assess and address Covid considerations?	X		Covid could be spread from the researcher to the participants or vice versa.	1. Offer to conduct interviews in-person or online (Zoom) 2. Offer to wear a mask during face-to-face encounters based on participant's preference. Reschedule if researcher has covid symptoms 3. Few days prior to the face-to-face encounters, check in with participants via digital communication and ask if they have any covid symptoms. If so, reschedule.		
29. Will your research involve **either:** a) "big data", combined datasets, new data-gathering or new data-merging techniques which might lead to re-identification of your participants **and/or** b) artificial intelligence or algorithm training where, for example biased datasets could lead to biased outcomes?		X				
G: Data Processing and Privacy						
30. Will the research involve collecting, processing and/or storing any directly identifiable PII (Personally Identifiable Information) including name or email address that will be used for administrative purposes only? (eg: obtaining Informed Consent or disbursing remuneration)	X		The names and contact information of the participants will be collected for administrative purposes only via an online questionnaire and informed consent form	1. Use a questionnaire platform that allows anonymity. 2. Personal information is only to be kept in the project storage drive accessible by Carlota Muñoz Ruiz, and the information will be deleted once the project is done 3. Assign a unique ID participant number and only refer participants with this number when recording the research data	IV-8A IV-16	Opening Statement, B-9
31. Will the research involve collecting, processing and/or storing any directly or indirectly identifiable PIRD (Personally Identifiable Research Data) including videos, pictures, IP address, gender, age etc and **what other Personal Research Data** (including personal or professional views) will you be collecting?	X		Demographic information such as age and gender of participants will be collected. Interviews will be audio-recorded for observation and transcription purposes. Pictures may be taken. Information regarding personal and professional experiences with anxiety will be also collected.	1. Participants will be informed that the gathered data will be anonymized. Data will be deleted if consent is withdrawn later. 2. Only anonymized photos (crop or blur faces, blur tattoos) will be added to the TUD Project Storage drive that is accessible to the research team. During the duration of the project, the raw data of photos of participants would be stored in the project drive only accessible by Carlota Muñoz Ruiz. 3. Audio recordings will be transcribed, and confidential or private information within the audio transcription will be deleted. 4. Once the project is over, the original photos and audio recordings will be deleted from the project drive.	I-3 IV-18 IV-25	Opening Statement, A-3,B-9, Section C
32. Will this research involve collecting data from the internet, social media and/or publicly available datasets which have been originally contributed by human participants		X				
33. Will your research findings be published in one or more forms in the public domain, as e.g., Masters thesis, journal publication, conference presentation or wider public dissemination?	X		The research is to be published in the TU Delft Repository in compliance with TU Delft graduation requirements. This poses the risk of identification of research study participants.	1. All study participants will be asked for their written consent for taking part in the study and for data processing before the start of the interview. 2. Only the processed and anonymized data will be published in Carlota Muñoz Ruiz's masters thesis to report the findings and for the assessment of the quality of the research.	IV-9	Opening Statement, A-3, B-9, Section C & D
34. Will your research data be archived for re-use and/or teaching in an open, private or semi-open archive?	X		As mentioned above, this research is to be published in the TU Delft Repository which can be reused for teaching purposes.	Refer to above	^	^

H: More on Informed Consent and Data Management

NOTE: You can find guidance and templates for preparing your Informed Consent materials) here

Your research involves human participants as Research Subjects if you are recruiting them or actively involving or influencing, manipulating or directing them in any way in your research activities. This means you must seek informed consent and agree/ implement appropriate safeguards regardless of whether you are collecting any PIRD.

Where you are also collecting PIRD, and using Informed Consent as the legal basis for your research, you need to also make sure that your IC materials are clear on any related risks and the mitigating measures you will take – including through responsible data management.

Got a comment on this checklist or the HREC process? You can leave your comments here

IV. Signature/s

Please note that by signing this checklist list as the sole, or Responsible, researcher you are providing approval of the completeness and quality of the submission, as well as confirming alignment between GDPR, Data Management and Informed Consent requirements.

Name of Corresponding Researcher (if different from the Responsible Researcher) (print)

Signature of Corresponding Researcher:

Name of Responsible Researcher (print)

Signature (or upload consent by mail) Responsible Researcher:

V. Completing your HREC application

Please use the following list to check that you have provided all relevant documentation

Required:

- **Always:** This completed HREC checklist
- **Always:** A data management plan (reviewed, where necessary, by a data-steward)
- **Usually:** A complete Informed Consent form (including Participant Information) and/or Opening Statement (for online consent)

Please also attach any of the following, if relevant to your research:

Document or approval	Contact/s
Full Research Ethics Application	After the assessment of your initial application **HREC will let you know if and when you need to submit additional information**
Signed, valid Device Report	Your Faculty HSE advisor
Ethics approval from an external Medical Committee	TU Delft Policy Advisor, Medical (Devices) Research
Ethics approval from an external Research Ethics Committee	Please append, if possible, with your submission
Approved Data Transfer or Data Processing Agreement	Your Faculty Data Steward and/or TU Delft Privacy Team
Approved Graduation Agreement	Your Master's thesis supervisor
Data Processing Impact Assessment (DPIA)	TU Delft Privacy Team
Other specific requirement	Please reference/explain in your checklist and append with your submission

APPENDIX 4.
Interview Template

Understanding Clinical Stress Treatment Approaches

Thank you for participating in this interview. Your insights will contribute to understanding stress treatment approaches used with clinical patients and individuals' coping strategies for anxiety. The focus is on exploring treatment effectiveness, clinical and non-clinical coping techniques, and stress indicator measurement.

* Indica que la pregunta es obligatoria

1. **Name** *

1. Professional Background

2. Can you provide a brief overview of your professional background and experience in treating patients with high/chronic stress, including anxiety, insomnia, panic attacks, and PTSD? *

2. Treatment Approaches for Stress

3. a. What treatment modalities do you commonly use for patients with high/chronic stress, including anxiety, insomnia, panic attacks, and PTSD? Why these ones? *

4. b. How do you adapt them to meet the unique needs and preferences of each patient? *

5. c. How do you assess the effectiveness of these treatments? What typical frequency do you recommend for meaningful impact? *

3. Measurement of Stress Indicators

6. a. How do you measure stress indicators in patients? (Select all that apply) *

Selecciona todos los que correspondan.

- [ ] Physiologically
- [ ] Psychologically

7. Please briefly specify the measurements here: *

8. b. How do you interpret the results to inform treatment plans? *

Selecciona todos los que correspondan.

- [ ] Quantitatively
- [ ] Qualitatively

9. Please specify the interpretation here: *

4. Managing Strategies for Anxiety

10. a. In your experience, what strategies do individuals commonly use to manage anxiety? (Select all that apply) *

Selecciona todos los que correspondan.

- [ ] Therapy
- [ ] Meditation/ Mindfulness practices
- [ ] "Breathwork" (Conscious breathing exercises)
- [ ] Mobile apps (Please specify below)
- [ ] Smartwatches or other external devices (Please specify below)
- [ ] Other (Please specify below)
- [ ] None
- [ ] Otro: ____________

11. Please, specify the strategies they use here:

12. b. How effective are these strategies in your observation?

Marca solo un óvalo.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very effective

13. c. Are there specific techniques or interventions that you recommend to your patients for effectively managing anxiety? How do you advise patients on integrating them into their daily routines?

____
____
____
____
____

5. Attitudes Toward Professional Help

14. a. Do you think people seek professional help for their anxiety? *

Marca solo un óvalo.

◯ Yes
◯ No

15. If no, what are the reasons? (Select all that apply) *

Selecciona todos los que correspondan.

☐ Cost
☐ Stigma
☐ Lack of awareness about available resources
☐ Preference for self-management
☐ Otro: ______________________

6. Conclusion

16. Thank you for taking the time to complete this survey and for sharing your expertise. Your insights will contribute to our understanding of stress management techniques. *
If you have any additional comments or suggestions, please feel free to share.
Additionally, if you would like to receive the results of this survey, please provide your email address (optional).

____
____
____
____
____

APPENDIX 5.
User Study Results

Understanding Conscious Breathing Guidance of SMA Textile-Based Design

5 Respuestas | 92:05 Tiempo medio para finalizar | Activo Estado

1. ID number

5 Respuestas

Respuestas más recientes
"UT5"
"UT4"
"UT3"

2. Name

5 Respuestas

Respuestas más recientes

3. Age

5 Respuestas

Respuestas más recientes
"27"
"25"
"27"

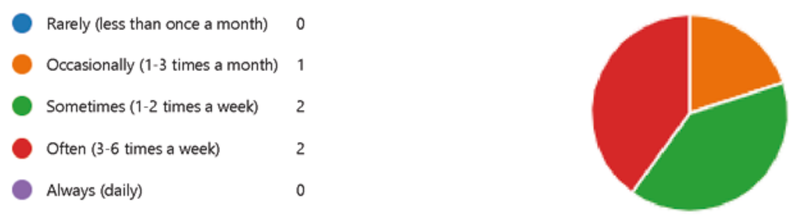
4. Gender

Male	2
Female	3
Non-binary	0
Prefer not to say	0

5. Have you ever experienced anxiety or chronic stress?

Yes	5
No	0

6. If yes, how often?



7. **Are you familiar with any breathing techniques for stress relief** (e.g., diaphragmatic breathing)**?**

8. If yes, which breathing techniques have you tried?

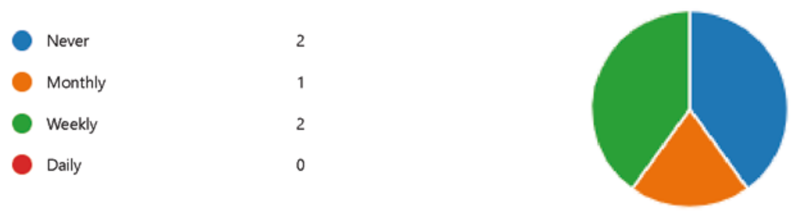
3
Respuestas

Respuestas más recientes

"diaphragm breathing, yoga (nose exercise)"

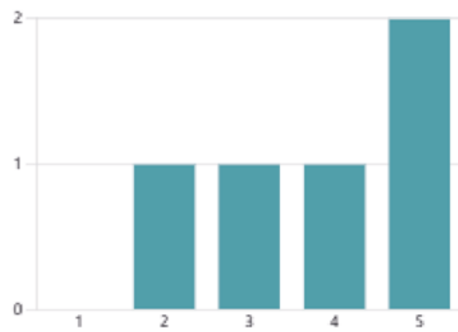
"Deep breathing/conscious breathing"

9. **How often do you practice (these) breathing techniques?**



10. On a scale of 1 to 5, **how effective** do you find these techniques **for managing your anxiety or stress?**

3.80
Clasificación promedio



11. Explore the prototype for a few minutes.
"What are your first thoughts or feelings when handling this prototype?" (Texture, weight...)

5
Respuestas

Its soft

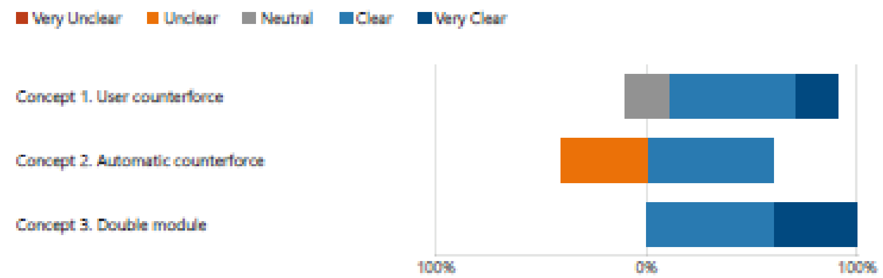
Medical, because it reminds me of the blood pressure tool. Also, sports/fitness because reminds me of the adjustable hot and cold compress band you put in the freezer/microwave for muscle-releasing. Strong structure as for medical purpose. On the contrary, the ripple doesnt remind me of anything, feels like something to be explored or explained. Like for playing. Doesnt seem that is for the arm. Its very soft and feels almost like an animal sort of hide.

The folding doesn't seem well constructed or structured (stable), especially with the pointing out things from the inside

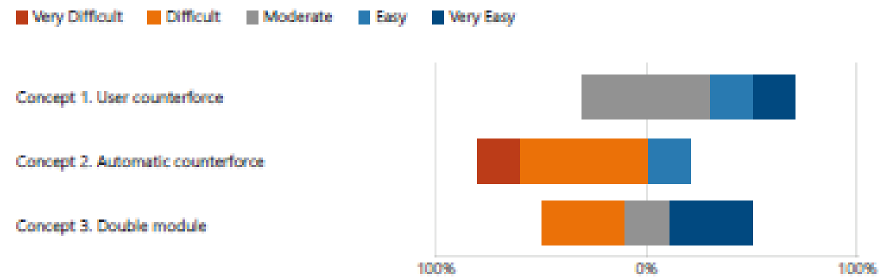
Assuming it's placed around the waist, not sure if it would be comfortable wearing it throughout the day. I like the material. I won't like if people see ruffles under my shirt.

A bit unsafe because of the cables around, nice and soft texture, color is strong

12. Please rate the **clarity of the haptic sensation/perception**



13. Please rate the **ease of synchronization** with your breathing



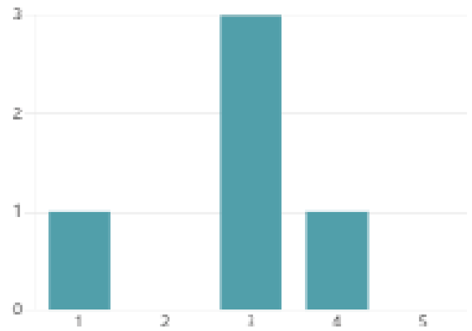
14. **Comments** Are there any specific sensations or aspects of the prototype that you particularly like or dislike?

5
Respuestas

Better C2 than C1, because I can focus more on the breath instead of on the counting and pushing back. The counting of hold breath was a bit less than 5s. However, since in C1 I can control it, its more clear the timing For C1 Im not sure how much force to apply and maybe its too much that the module can not move and I dont feel it expanding again. Clear perception and timing of breathing in, but confusing/mixed holding time and breathing out time. Need some extra guidance on time to breath out. With C1 and C2 I struggle more because I use both of my hands and may be too resistant. C3 is more clear if ideally both concepts were automatically pulled back. With the headphones I could avoid the click button in my guidance. C2 Sometimes I dont perceive is coming back with hand
I first also wanted to watch it to learn and understand the mechanism. Then I can evaluate the haptic nature and the feeling. C1 gives a very clear indication of when to start breathing and is very nice to the touch. Very easy to follow. Since I push it back in all the way it starts flat from the bottom so its more clear. C2 was hard to synchronize with holding the breath because I was not able to perceive clearly when the counterforce was moving towards my body. Harder to follow and feel because it was not going all the way back. It made me hold the breath too long. C3 is the best-guided experience and makes the user feel engaged throughout the breathing sequence which feels comforting psychologically. *If I dont do anything, just passively there, I become lazy. With C1 I have to prompt myself to push it back, same as the breathing so its good.
C1: breath in expansion is clear but diminishes with cycles bc i dont know when to bring it back and how much force to push in and how much distance from body. The timing to push back is unclear. However, the expansion movement feels very good. Maybe because I dont push too much the effect diminishes and its not that obvious. C2 breath in clear, breath out unclear and makes me a bit confused or stress about when to start breathing out. But its also good to be passive if I have the signal correclty of transitions. In C1 I could control it better so i know when to do it. And also C1 im more in touch with the device than C2. C3 is interesting, clear and is somehow easy to synchronize. Yet, the movement is less natural/ intuitive, a bit confusing left and right I have to focus onn the movement. Too many different movements that I mess it up and loose the focus of breathing. C1 C2 were more obvious about the movement, just unsure the time
In the very beginning its starts very slowly and maybe is hard to notice. Just feel something pushing me. Once you see a cycle I thought woah this is very cool! Being a bit distracted in the beginning cause is new, still needed to familiarize myself. Pre-training helps C1: being in partial control of the movement makes me more aware of my breathing i think. A bit unclear the transition timings. So i needed to start counting. C2: contraction made it hard to sync up with the breathing because i was unable to recognize the movement and so i couldnt breath correctly. Loose contact with device when contracting. C3, two of the same input expecting 2 different outcomes was confusing and required thinking which took away from the deep breathing. Is it expanding and I have to breath out? Expansion means in.

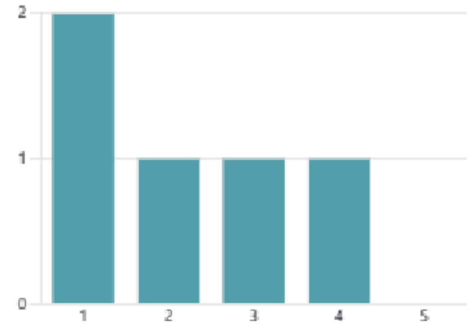
15. In this different location, how would you rate the **clarity of the haptic sensation?**

2.80
Clasificación promedio



16. In this different location, how would you rate the **ease of synchronization** with breathing?

2.20
Clasificación promedio



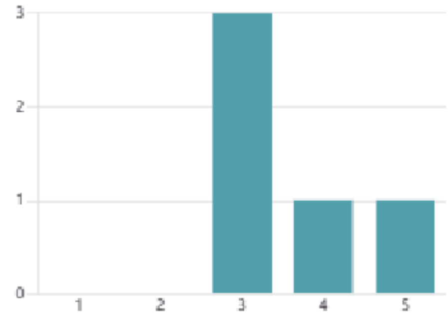
17. Any difference compared to the abdomen location?

5
Respuestas

More comfortable and logical to place it in the abdomen because of the abdominal breathing. Wrist would be weird. Since my favourite is the double module, I need both hands and doesnt make sense to place it on the wrist, maybe it could work on the legs while sitting down or on the sides of my legs while standing up (natural height when leaving relax arms)
If its not on the abdomen, I will be less focused on breathing and I will find it difficult to keep my eyes closed (more visually distracted). Defenitely im gonna look at it if its on my wrist. Its more relieving/relaxing to close my eyes. Its also confusing having to hold something elsewhere while activating my abdomen for breathing. Is more natural to have it in my belly already. Also in the abdomen makes you keep a better posture. Another possible location could be on the chest. The synchronization would be the same.
Abdomen is better. However, standing and holding it is not my most relaxing posture, better in a sitting posture where my arms can rest. Wristband is more portable, good for emergencies/severe scenarios in daily life, out of home (work, transport, streets...). If its out of the abdomen the gesture, the posture is not correlated. Maybe if its on your wrist and you place your hand on your abdomen to indicate the location of breathing could work.
No difference in perception or sync, but it makes more sense on the abdomen because your body is physically reacting to the breathing there, to the part of your body that is actually moving. Wrist design makes me think about something on the go (im out home)
It would be the same clear sensation but it would be more difficult to correlate it with abdominal breathing cause its not located right there. Only people more advanced in breathing techniques could be able to do it correctly if it was on the wrist or elsewhere Maybe if it was in vertical on the torso (lungs+diaphragm) could work, as I sometimes practice to make sure the abdomen is moving.

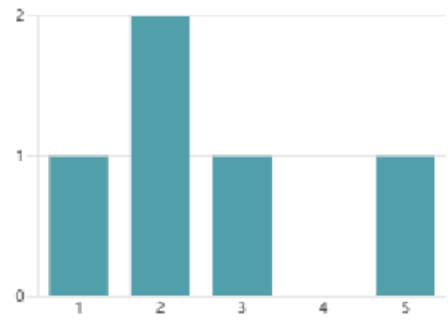
18. As a "touchable" design, how would you rate the **clarity of the haptic sensation?**

3.60
Clasificación promedio



19. As a "touchable" design, how would you rate the **ease of synchronization** with breathing?

2.60
Clasificación promedio

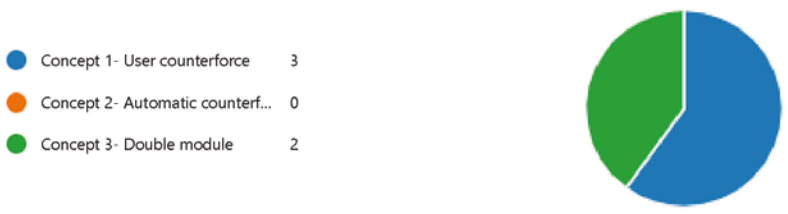


20. Any difference compared to the previous locations?

5
Respuestas

Almost the same perception and synchronization as abdomen. Both comfortable to touch. Only if the hands are oriented in parallel with each other (straight forward), not laterally (no natural). Nice that it can used in multiple locations depending on the user preferences. Touch with hands is nice
Yoga mat, sports ball or block (sports equipment), because when you start the Bikram yoga class, they have the pranayama breathing (standing deep breathing) in the beginning. For example, it could have some kind of cooling effect for the warm Bikram classes (people get dizzy). Or embedded into sports equipment to teach how to breathe during exercises. I think is better if its wearable than something external because its attach to you and feels its "monitoring" you, forcing you to follow as "part of the breathing". It makes you think about the posture if you wear it, keeping your back straight. For example, people with asthma, like me, needs to learn how to breath and posture is important. Or like in yoga. If its located in the middle of your body, it really makes sure that you're aligned and symmetrical
I prefer to interact more with the abdomen because that's the most related to the part to breathing. Elsewhere is more irrelevant to the breathing movement, less obvious/intuitive. I like interacting directly with my stomach. The haptic experience is enhanced. External you don't feel it. Expansion engages more than vibration. Feeling is the key point of this design!
The feedback is the same but it feels less personal because it is detached from the body. the physical element of the device holding you makes it feel like it is more a part of you and not some medical device or something you're using
Good for being more versatile, like on the bed on the sides of your body. But still better on the abdomen.

21. Which is your favorite concept overall?



22. Please briefly explain why.

5
Respuestas

Easier to synchronize the breath, and I can use correctly both of my hands
Holistic, whole breathing guidance from beginning to end
I like a lot feeling more the engagement of C1, after some time you it just goes naturally, yet I missed more time indication
I think the fact that I was in control of a portion of the process made me more aware of my breathing. the contraction elements of all of the other concepts werent strong enough to help me stay in sync. First I thought I like more C2 but reflecting on it, I like more being in control, being part of it really helps. C2 I forget about the exercise. The fact that I have to push it down to restar the process esentially makes me go. The device is helping me to regulate, not helping me to breath
C1 was the only one i was deeply relaxed cause it mimics better the movement of the actual breathing. It was more clear and perceivable than C2 and easier to coordinate than C3 (Im not used to expansion in both breathing in/out). Also since C1 makes you do the pressure, it also prompts the muscles to move along (is key in breathing techniques)

23. **Understanding the mechanism:**

- Could you feel the rhythmic expansion and contraction of the prototype?
- Does the movement pattern remind you of breathing? Why or why not?

5
Respuestas

Yes it reminds me to breathing and the instruction can guide me well. Better with the automatic counterforce for focusing on relaxing. Pretty similar between 5-5-5 and 4-7-8. Even if it needs some adjustements, overall the functionality is very very good and i really perceive it.
The cupping shape it takes is like how it feels when your abdomen is expanding and contracting. And so that made it easy to understand, like the what the movement was asking me to do. Its more fun the up-up movement, I like it more
The feeling of expansion/contraction is key and very intuitive. Still, I struggle a bit holding for 5s
I think the expansion feels like breathing in, feels natural. Although I was not told to be used for breathing, I could discover it because its the only body action that moves like this
Yes, very alike. It reminds me to all these rounded shapes and inflatable movements from meditation products and apps. Not like a sharp linear movement. It has the perfect shape similar to my belly/stomach.

24. **Comfort and Usability:**

- How comfortable is the prototype to hold or wear?
- Do you foresee any issues with using this prototype for an extended period?

5
Respuestas

Very comfortable cause I almost forgot that it was there. For the touchable, if it was integrated in a glove, the person could choose the most comfy posture to relax (e.g. meditation on the knees, on the bed when laying down, or on the chair armrest when sitting). For the future, temperature is fine. Since its a prototype i got a bit hurt with the pointed wire.
Very comfortable. Makes me keep a correct posture and breathing. I was more aware of it. I was a bit careful in not to break the prototype ("the length around was a bit tight).
Yes, because it seems that it could be designed in "privacy" because the people wont like to be seen using it. Is nice because it doesn't need to go through meditation, music.. just easy and fast. Its all integrated so you dont need any other thing, is very low effort.
The physical element of the device holding you makes it feel like it is more a "part of you" and not some medical device or something you're using. If its attach to you feels more personal, like a hugging. Its because of the tightness and material. Maybe I see my arm getting tired after some time in this position The perception and sync feels comfortable because of the material (elastic). It doesnt make me feel restricted.
Yes, very comfy and easy to put on. Maybe make the folding more solid and less loose. In the long term it could be customizable. I think is more focus for beginners in breathing, like people that started with therapy (children or adults).

25. **Location:**
Did the location of the prototype on your body affect your ability to perceive the sensations or synchronize your breathing? How?

5
Respuestas

Abdomen and arms in a straight 90º forward position are the most relaxed ones (not much difference between them). Maybe on the legs could work.
Yes it affects. Placing it on the abdomen helps in keeping a good posture and breathing location.
Engage more if its wearable and is more relevant to abdominal breathing than something external
I think it makes it easier to feel what's going on and like get more things because you're like moving with the part of your body and the actual thing. You are more aware of where to breath in your body Is nice because it seems that you can use it after changing posture, like sitting
Location is key. Works better in the abdomen cause it's related to the breathing there, especially for beginners. On the wrist would be more "everyday use" but would only work for experts. Since its only touch, you dont need headphones for sound and is much more discreet. You can wear it anywhere under your clothes, even during meetings or presentation if its really needed. It could work at home and out because no one sees it (not like a prosthesis for example). Dont mind using both or 1 hand, and wearing it in touch with skin or on top of clothes.

26. **Improvement**:
Based on this experience, how would you improve the design? Any additional comments or suggestions?

5
Respuestas

Both modules automatic and more clear the holding time. It could be implemented, for example, in gloves so its more versatile/adaptable to posture and location individual preferences. Better to use headphones to not heard the button sound of the power ON/OFF (gives a hint for the guidance).
- Feeling more the contracting movement (C2) - Same timing for all phases (automatized?) - Timing hold-breathing out and transition: when to start breathing out exactly? - For training C1 will be the best because the user is more prompt to act proactively about deep breathing. The design tells me when to start and then is like "you do the rest". This could be good for some applications like people treated with anxiety that at some point dont have this device but because the proactive trainning knows more to handle it by himself the rhythm.
- An indication on how to breath slowly and steady because its a long breath, not that easy - Versatile for different body postures (standing, sitting, laying down) - For emergencies/everyday use, like a wristband that works combined with abdomen - More stable and rigid structure - More indications of time and transitions
- Add a little hand strap around the palm to bring the hand with the device during contraction (stay in contact) - If its for a on-the-go purpose, a small hand strap could work (e.g. while walking) - If its on the wrist, it could give some feedback from body (pulse) while breathing - Indication of when each stage is over - Make sure the muscle rests, stays relaxed without affecting the mechanism - Strengthen the movements more, a bit the expansion but much more the contraction, so it just makes it more clear what what's happening.
- It could be connected to a smartwatch or the chestband for cycling that measures heartbeat and can tell you to use it when predicts a heart attack - Color, I would put something more smooth, soft and pastel. Less aggressive. Especially if its for children, make it more friendly (moodborad meditation style) - Longer (the wires) so I can use both hands - Material light, transpirable/breathable both in touch with body (band) and hands (SMA) - Act as another tool in yoga for beginners to learn how to breath

APPENDIX 6.

Technical Characterization

21/03/24

EXPERIMENT 1 — SMA DIAMETER 1MM AND 0.5MM

Objective — **Compare the actuation displacement, temperature, and time of Zigzag SMA wires with diameters 1mm and 0.5mm**

General wire properties		
	Total wire length (mm)	150
	Shape configuration	Zigzag
	Lo (Initial Length first-last peak in mm)	57
	Number of peaks	3
	Pitch (Length consecutive peaks in mm)	28,5
	Height (mm)	15
	Angle of peak (º)	65

Deformed Strain or Deformation	((Ld-Lo)/Lo)*100		How much is deformed from its initial shape
% of Displacement	((Ld-Lh)/Ld)*100		How much is deformed from its deformed shape to the heated shape
Recovery Strain	((Ld-Lh)/(Ld-Lo))*100	(Amount Recovered/ Total Deformation)	How much does it fully recover its initial shape after heating

SAMPLE 1	Diameter (mm)	1
	Actuation Temperature	45-50ºC

TEST 1.1. "Deformation"	**Power**	**2v, 1.5A**
	Lo	57

	L deformed	**Deformed Strain**	**L heated**	**% Displacement**	**Recovery Strain 1mm**	
Deformation 1	60	5%	57	5,0%	100%	
Deformation 2	70	23%	57	18,6%	100%	
Deformation 3	75	32%	57	24,0%	100%	
Deformation 4	80	40%	60	25,0%	87%	Not full Recovery: 3mm of displacement (first recovery had an irregular shape, but the second and third had regular shape)

TEST 1.2. "Power"	**Power of System (V,I)**	**Lo (mm)**	**L deformed (mm)**	**Deformed Strain (Ld-Lo)/Lo**	**L heated (mm)**	**% Displacement (mm)**	**Recovery Strain (Ld-Lh)/(Ld-Lo)**	**Recovery Time (s)**	**Recovery Temperature**
	P1=1.7v, **3A**	60	75	25%	62	17,3%	87%	**10**	30ºC
	P2= 2.2v, **4A**	62	75	21%	64	14,7%	85%	**9**	40ºC
	P3= 2.3v, **5A**	64	75	17%	64	14,7%	100%	**5**	40ºC
	P4= 2.7v, **6A**	64	75	17%	64	14,7%	100%	**3**	50-55ºC
	P5= 3v, **7A**	64	75	17%	64	14,7%	100%	**2**	50-55ºC

SAMPLE 2	Diameter (mm)	0.5
	Actuation Temperature	60ºC

TEST 2.1. "Deformation"	**Power**	**2v, 1.5A**
	Initial Length (mm) Lo	57

	L deformed	**Deformed Strain**	**L heated**	**% Displacement**	**Recovery Strain 0.5mm**	
Deformation 1	60	5%	57	5,0%	100%	
Deformation 2	70	23%	57	18,6%	100%	
Deformation 3	75	32%	57	24,0%	100%	
Deformation 4	80	40%	60	25,0%	87%	Not full Recovery: 3mm of displacement (regular shape)

TEST 2.2. "Power"	**Power of System (V,I)**	**Lo (mm)**	**L deformed (mm)**	**Deformed Strain (Ld-Lo)/Lo**	**L heated (mm)**	**% Displacement (mm)**	**Recovery Strain (Ld-Lh)/(Ld-Lo)**	**Recovery Time (s)**	**Recovery Temperature**
	P1=1.5v, **1.5A**	60	75	25%	62	17,3%	87%	**11**	50ºC
	P2= 2v, **2A**	62	75	21%	64	14,7%	85%	**4**	43ºC
	P3= 3v, **3A**	64	75	17%	64	14,7%	100%	**1**	25ºC

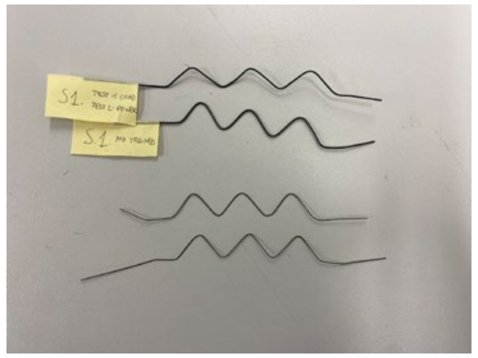
TEST 2.3. "Cycles"		**Lo**	**Ld**	**Lh**	**Heating Time**	**Recovery Strain**
P= 2V, 2A	5s cycles	64	75	75	5s	0%
	10s cycles	64	75	64	10s	100%

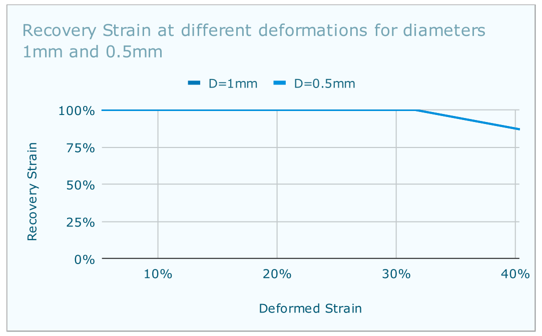
5s cycles	**As**	**Af**
ON (5s)	1s at 23ºC	3s at 32ºC
OFF (5s)	Deformation at 71ºC	
ON (5s)	0s at 60ºC	-
OFF (5s)	Deformation at 110ºC	
ON (5s)	-	-
OFF (5s)	No Deformation	

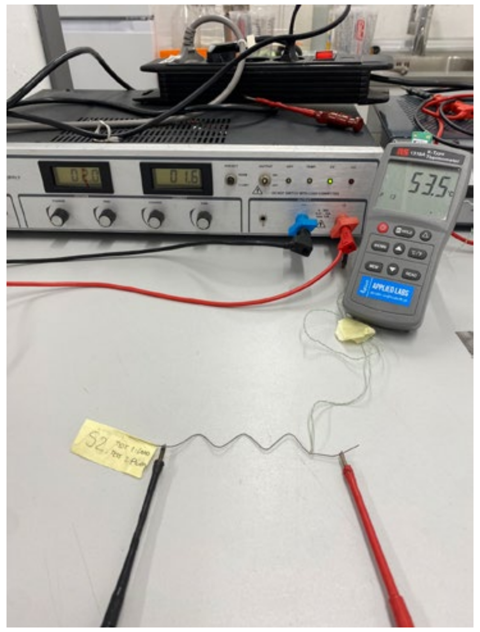
NOT SHAPE RECOVERY!
Due to deformation over Af

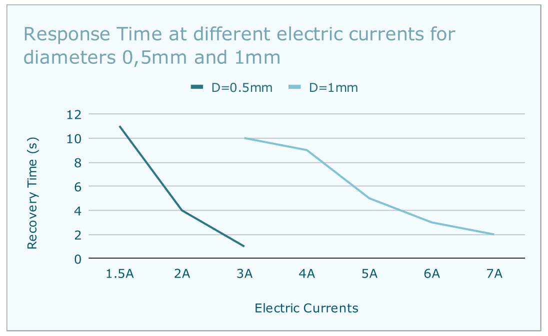
10s cycles	**As (40ºC)**	**Af (44ºC)**
ON (10s)	7s	10s
OFF (10s)	Deformation 6s	
ON (10s)	2s	5s
OFF (10s)	Deformation 10s	
ON (10s)	0s	4s
OFF (10s)	Deformation 10s	
ON (10s)	0s	3s
OFF (10s)	Deformation 12s	
ON (10s)	0s	3s
OFF (10s)	Deformation 12s	

FULL SHAPE RECOVERY
Due to deformation below As

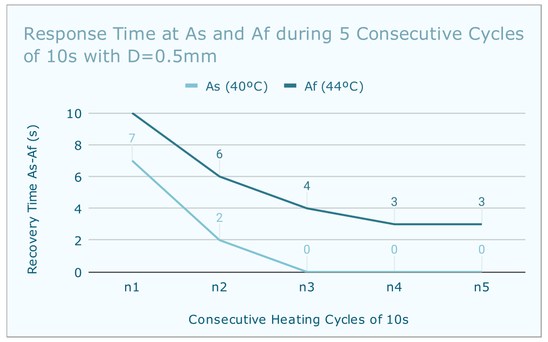








Electric Currents	1.5	2A	3A	4A	5A	6A	7A
D=0.5mm	11	4	1				
D=1mm			10	9	5	3	2



	As (	Af (44ºC)
n1	7	10
n2	2	6
n3	0	4
n4	0	3
n5	0	3

11/04/24

EXPERIMENT 2 SMA Shape Configurations into textile

Objective **Compare performance (Displacement and Time) between different shape configurations of 0.5 SMA**

General wire properties	Total wire length (	150
	Diameter (mm)	0.5
	Actuation Temper	60ºC
	Power	2,3v, 2A

Deformed Strain Deformation	((Ld-Lo)/Lo)*100	
% of Displaceme	((Ld-Lh)/Ld)*100	
Recovery Strain	((Ld-Lh)/(Ld-Lo))*100	(Amount Recovered/ Total Deformation)

Sample 2.1. ZIGZAG

Lo	57	**Deformed Strain**
L deformed	74	29,8%
Nº peaks	3	
Pitch	38mm	
Height	9mm	
Angle of peak	65º	
Stitching pattern	All length zigzag 3L-3W	

Cycles	n1	n2	n3	n4	n5	Average	n6	n7	n8	n9	n10	Average
L heated (mm)	59	59	59	59	59		59	59	59	59	59	59
Displacement (%)	**20,3%**	**20,3%**	**20,3%**	**20,3%**	**20,3%**	**20,3%**	**20,3%**	**20,3%**	**20,3%**	**20,3%**	**20,3%**	20,3%
Recov Strain (%)	**88%**	**88%**	**88%**	**88%**	**88%**		**88%**	**88%**	**88%**	**88%**	**88%**	88%
Zigzag As (s)	1	2	1	1	2	1,5	2	2	1	2	1	1,5
T As (s)	25	26	25	26	27		28	28	24	29	24	26,2
Zigzag Af (s)	8	9	8	8	7	8,1	7	8	9	8	9	8,1
T Af (s)	42	41	40	39	40		39	41	41	40	39	40,2

* Cooling down (40ºC): in 3s it decreases 3ºC

Sample 2.2. SPRING

Lo	35	Deformed Strain
Ld	93	165,7%
Height	6mm	
Stitching pattern	Stitched at both ends	

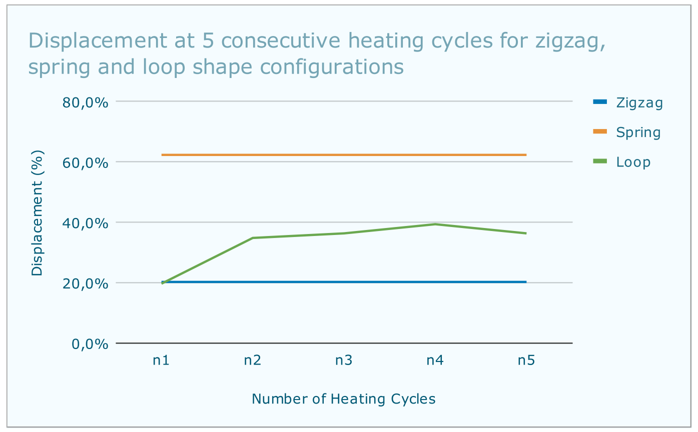
Cycles	n1	n2	n3	n4	n5	Average
L heated (mm)	35	35	35	35	35	-
Displacement (%)	**62,4%**	**62,4%**	**62,4%**	**62,4%**	**62,4%**	**62,4%**
Recov Strain (%)	**100%**	**100%**	**100%**	**100%**	**100%**	
Spring As (s)	0	0	0	0	1	0,2
T As (s)	23	23	23	23	23	23
Spring Af (s)	3	4	4	3	4	3,6
T Af (s)	42	42	42	42	42	42

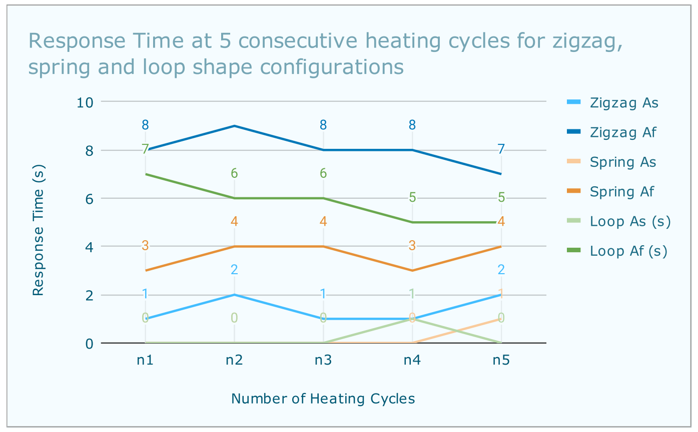
* Too much relief (3D) therefore difficult to seamlessly integrate into textile

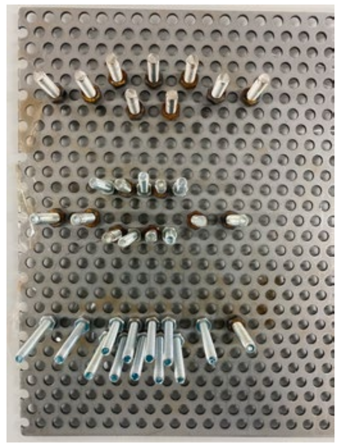
Sample 2.3. LOOP

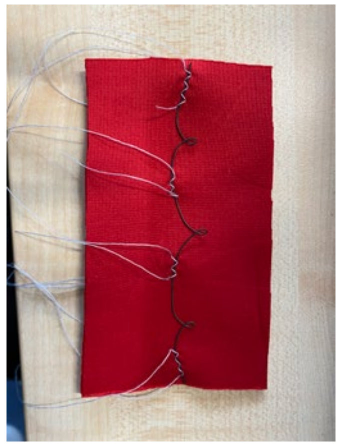
Lo	40	Deformed Strain
Ld	66	65,0%
Nº peaks	3	
Length between p	33mm	
Height	11mm	
Stitching pattern	Stitched between loops (4)	

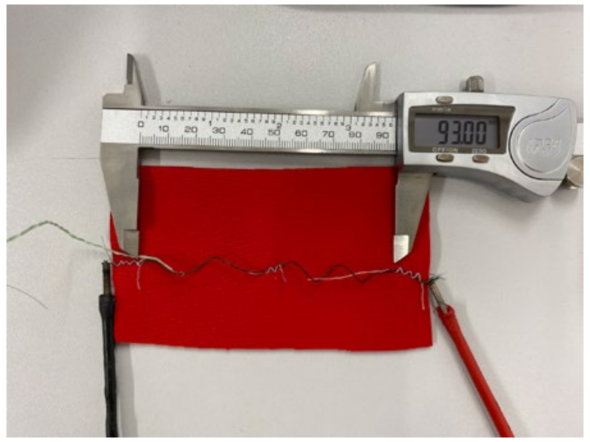
Cycles	n1	n2	n3	n4	n5	Average
L heated (mm)	53	43	42	40	42	
Displacement (%)	**19,7%**	**34,8%**	**36,4%**	**39,4%**	**36,4%**	**33,3%**
Recov Strain (%)	**50%**	**88%**	**92%**	**100%**	**92%**	
Loop As (s)	0	0	0	1	0	0,2
T As (s)	23	23	23	23	23	23
Loop Af (s)	7	6	6	5	5	5,8
T Af (s)	43	43	40	40	40	41,2











12/04/24

EXPERIMENT 3	Stitching pattern
Objective	Compare zigzag shape performance (Displacement and Time) between different stitching patterns on the textile attachment

General wire properties	Total Wire Length	95mm
	Diameter	0.5mm
	Actuation Temperature	60ºC * At 55ºC returns to shape
	Power	2v, 1.5A
	L trained (on the frame)	31mm
	Nº Peaks	3
	Textile type	Neoprene-like
Wire before textile attachment	Lo	38mm
	Height	18mm
Wire after textile attachment	L deformed	78mm
	Height	10mm
	Deformed Strain	105%

Sample 3.1. ALL STITCHED — W3 L3

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average	At P=2.5v, 1,5A	At P=3v, 2A
L heated (mm)	46	48	48	50	51	52	53	54	56	**56**	51,4	55	55
t Af (s)	20	19	15	20	13	20	15	20	18	17	17,7	10	4-5s
Displacement (%)	41,0%	38,5%	38,5%	35,9%	34,6%	33,3%	32,1%	30,8%	28,2%	28,2%	34,1%		
Recovery Strain (%)	80%	75%	75%	70%	68%	65%	63%	60%	55%	55%	67%		

Sample 3.2. STITCHED AT BOTTOM PEAKS — W3 L2 in 4 stitches

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average	At P=3v, 2,4A
L heated (mm)	46	50	52	53	53	53	54	54	55	**55**	52,5	55
t Af (s)	13	18	15	9	10	10	10	10	8	8	11,1	3-4s
Displacement (%)	41,0%	35,9%	33,3%	32,1%	32,1%	32,1%	30,8%	30,8%	29,5%	29,5%	32,7%	
Recovery Strain (%)	80%	70%	65%	63%	63%	63%	60%	60%	58%	58%	64%	

*Irregular shape recoveries due to stitch properties and location (sometimes it doesnt carry all the textile)

Sample 3.3. STITCHED AT ALL PEAKS — W3 L2 in 7 stitches

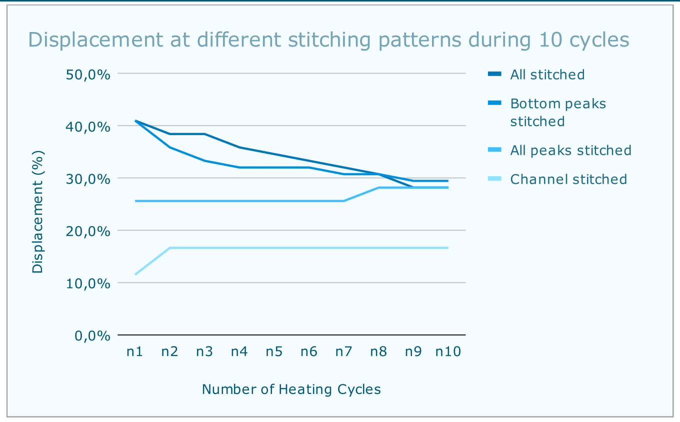
Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average	At P=3v, 2,3A
L heated (mm)	58	58	58	58	58	58	58	56	56	56	57,4	57
t Af (s)	11	14	10	9	9	9	8	10	8	8	9,6	2-3s
Displacement (%)	25,6%	25,6%	25,6%	25,6%	25,6%	25,6%	25,6%	28,2%	28,2%	28,2%	26,4%	
Recovery Strain (%)	50%	50%	50%	50%	50%	50%	50%	55%	55%	55%	52%	

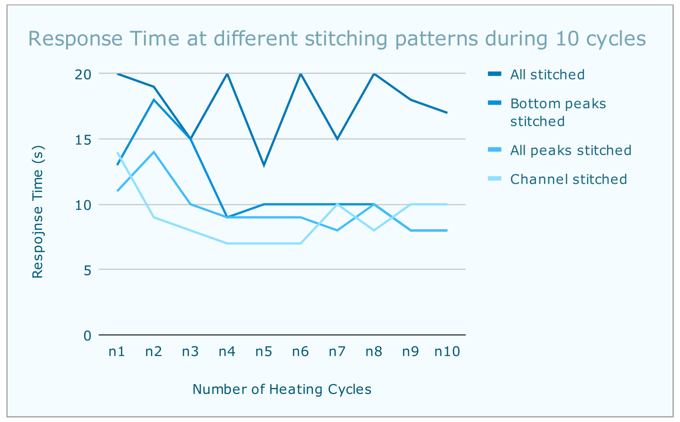
* really fast activation: 1-2s shape recovery and the changes minimally until 55ºC

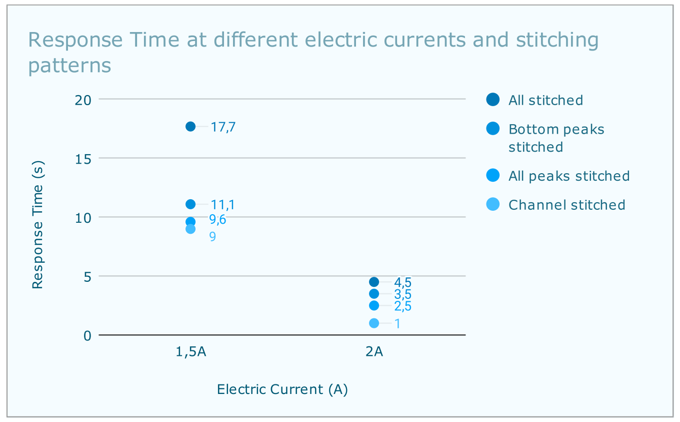
Sample 3.4. STITCHED ALONG A CHANNEL (H=13mm) — 2 stitches in total W3 L3

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average	At P=3v, 2A
L heated (mm)	69	65	65	65	65	65	65	65	65	65	65,4	58
t Af (s)	14	9	8	7	7	7	10	8	10	10	9	1s
Displacement (%)	11,5%	16,7%	16,7%	16,7%	16,7%	16,7%	16,7%	16,7%	16,7%	16,7%	16,2%	
Recovery Strain (%)	23%	33%	33%	33%	33%	33%	33%	33%	33%	33%	32%	

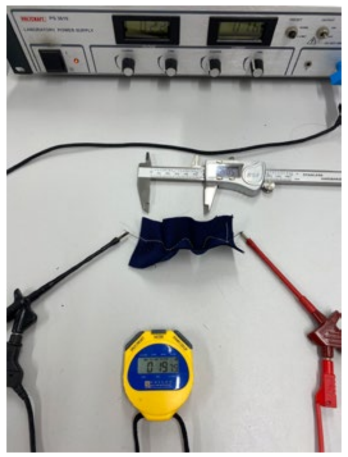
*Difficult to measure precisely.
*Bendin+torsion
*Needs more current P=2.2v, 1,9A

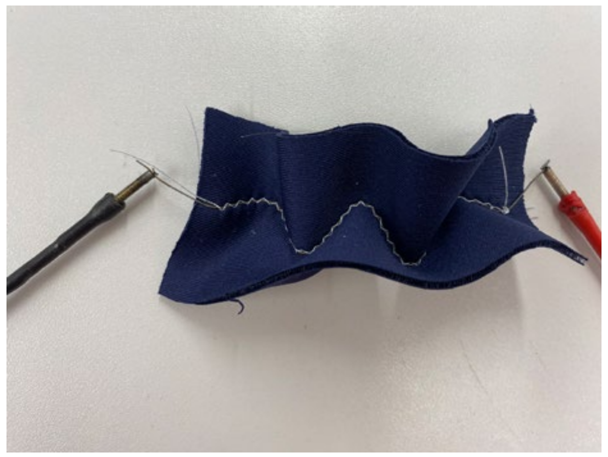


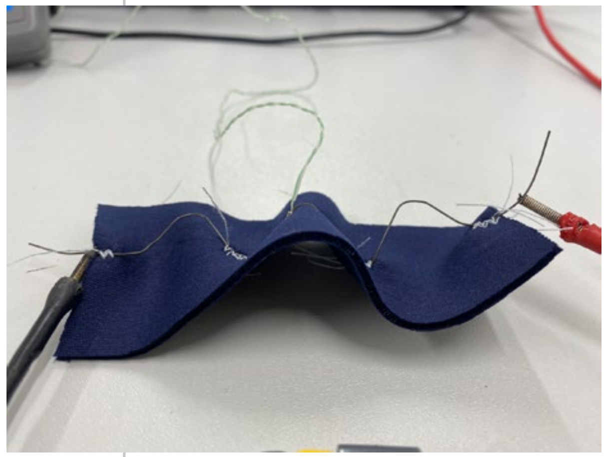


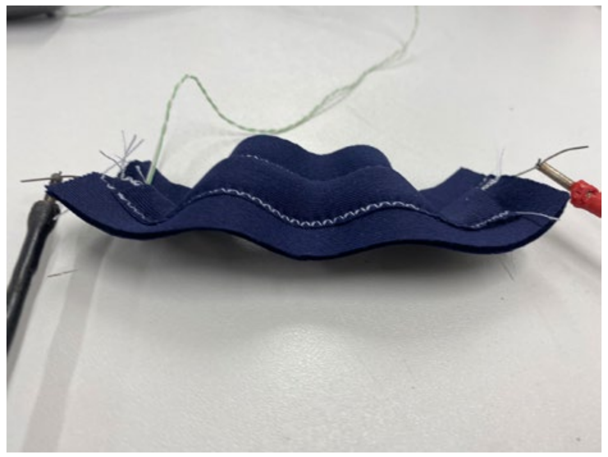


	1,5A	2A
All stitched	17,7	4,5
Bottom peaks :	11,1	3,5
All peaks stitch	9,6	2,5
Channel stitche	9	1









01/05/24

EXPERIMENT 4 — ZIGZAG SIZE INTO TEXTILE

Objective — **Compare performance (Displacement and Time) between different Zigzag sizes into the textile**

General wire properties

Diameter	0.5mm
Actuation Tempera	60ºC
L trained (on the f	31mm
Stitch size	W2 L2

Sample 4.1. BIG SIZE

Total Wire Length	230mm
Nº Peaks	5
Power	3v, 1.8A *First cycle with P=2v, 2.7A and is too low to move

Wire before textile attachment

Lo	60mm
Pitch	15mm
Height	26mm

Wire after textile attachment

L deformed	202mm
Pitch	50mm
Height	10mm
Deformed Strain	237%

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
L heated (mm)	-	150	100	110	116	123	127	131	133	**135**	125
t Af (s)	-	50	25	14	14	12	14	9	11	10	17,7
	*Too low current	*From here on P=3v, 1.8A									
Displacement (%)		25,7%	50,5%	45,5%	42,6%	39,1%	37,1%	35,1%	34,2%	33,2%	38,1%
Recovery Strain (%)		37%	72%	65%	61%	56%	53%	50%	49%	47%	54,2%

*Shape differs more from the trained one
*Needs more force when deforming at cooling down (too stiff)
*Temperature increases extremelly fast, easily reaching 80ºC

Sample 4.2. SMALL SIZE

Total Wire Length	130mm
Nº Peaks	5
Power	2.2v, 1.3A

Wire before textile attachment

Lo	43mm
Pitch	11mm
Height	12mm

Wire after textile attachment

L deformed	90mm
Pitch	24mm
Height	8mm
Deformed Strain	109%

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
L heated (mm)	72	52	53	55	55	56	56	57	62	**62**	58
t Af (s)	29	16	16	16	14	17	14	17	19	20	18
Displacement (%)	20,0%	42,2%	41,1%	38,9%	38,9%	37,8%	37,8%	36,7%	31,1%	31,1%	35,6%
Recovery Strain (%)	38%	81%	79%	74%	74%	72%	72%	70%	60%	60%	68,1%

At P=3.3v, 2,5A

1	**2**	**3**	**4**	**5**	Deformed Strain at double I
60	60	60	60	60	33%
3	3	3	3	3	

*As just when turn on (0s) and Af at 45-50ºC
*More diffcult to shape on the frame

Sample 4.3. MEDIUM SIZE

Total Wire Length	90mm
Nº Peaks	3
Power	2.2v, 1.3A

Wire before textile attachment

Lo	35mm
Pitch	17mm
Height	19mm

Wire after textile attachment

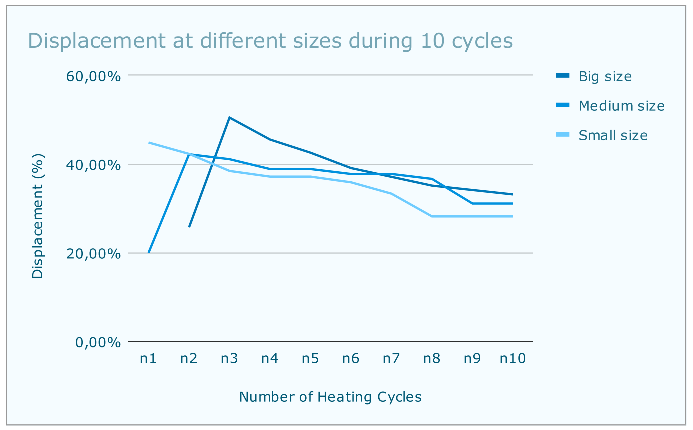
L deformed	78mm
Pitch	39mm
Height	10mm
Deformed Strain	123%

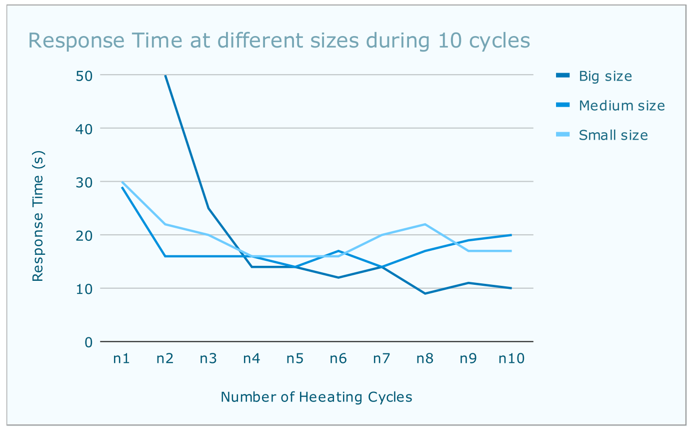
Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
L heated (mm)	43	45	48	49	49	50	52	56	**56**	56	50
t Af (s)	30	22	20	16	16	16	20	22	17	17	20
Displacement (%)	44,9%	42,3%	38,5%	37,2%	37,2%	35,9%	33,3%	28,2%	28,2%	28,2%	35,4%
Recovery Strain (%)	81%	77%	70%	67%	67%	65%	60%	51%	51%	51%	64,2%

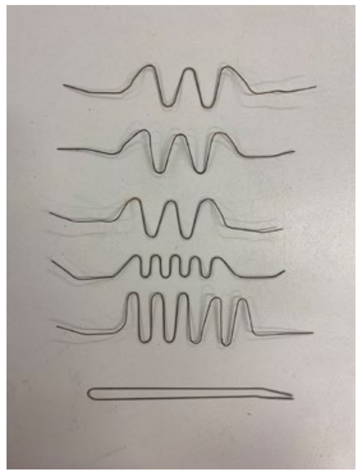
At P=3.3v, 2,5A

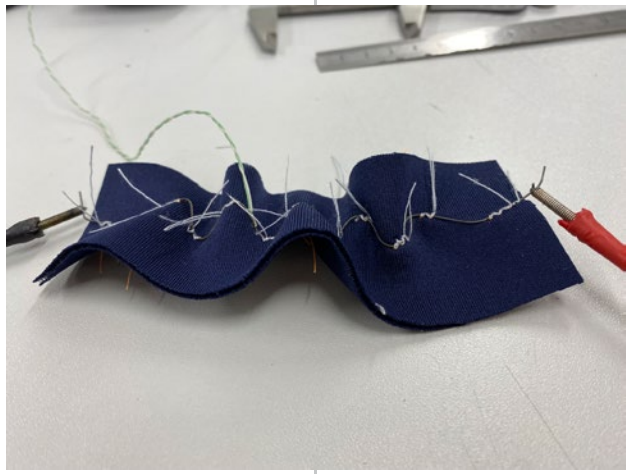
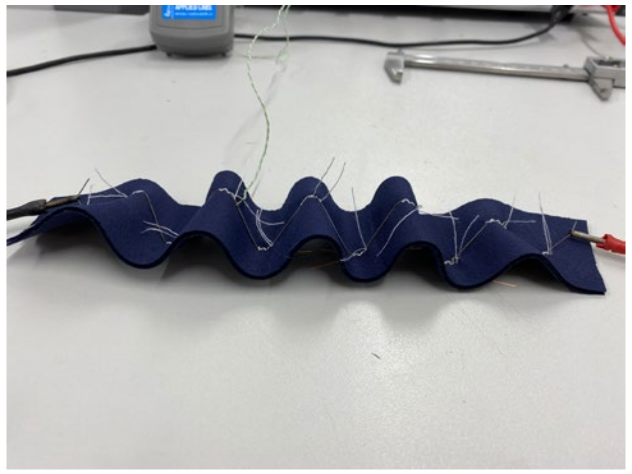
1	**2**	**3**	**4**	**5**	Deformed Strain at double I
53	53	53	54	54	31%
2	3	2	2	3	

*Shape differs the least from the trained one
*Is possible that it takes a bit longer and struggles more to transmit current due to more tight stitches than previously





02/05/24

EXPERIMENT 5 — Loop Vs. Zigzag and Peak Vs. Lateral stitches

Objective — **Compare performance (Displacement and Time) between Loop and Zigzag shape configurations, and between peak or lateral stitching**

General wire properties				
Diameter	0.5mm		Loop total wire length	100mm
Actuation Temperatu	60ºC		Zigzag total wire length	85mm
L trained (on the fra	31mm			
Stitch size	W2 L2			
Nº Peaks	3			
Power	2.3v, 1.4A			

Sample 5.1. Loop shape with peak stitches

Wire before textile		**Wire after textile attachment**	
Lo	34mm	L deformed	68mm
Pitch	17mm	Pitch	23mm
Height	19mm	Height	12mm
		Deformed Strain	**100%**

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
L heated (mm)	33	33	33	34	34	34	36	36	44	**44**	36,1
t Af (s) Loop-peak	33	19	13	17	13	17	13	16	14	14	16,9
Displacement (%)	51,5%	51,5%	51,5%	50,0%	50,0%	50,0%	47,1%	47,1%	35,3%	35,3%	46,9%
Recovery Strain (%)	103%	103%	103%	100%	100%	100%	94%	94%	71%	71%	94%

*Af at 55-70ºC. It increases that fast that easily reaches 100ºC which negatively affects results
*They start really slowly and after first change it moves super fast

Sample 5.2. Zigzag shape with peak stitches
*From Experiment 5

Wire before textile		**Wire after textile attachment**	
Lo	34mm	L deformed	78mm
Pitch	17mm	Pitch	39mm
Height	19mm	Height	10mm
		Deformed Strain	**129%**

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
L heated (mm)	43	43	45	48	49	49	50	52	56	**56**	49,1
t Af (s) Zigzap-peak	31	30	22	20	16	16	16	20	22	17	21
Displacement (%)	44,9%	44,9%	42,3%	38,5%	37,2%	37,2%	35,9%	33,3%	28,2%	28,2%	37,1%
Recovery Strain (%)	80%	80%	75%	68%	66%	66%	64%	59%	50%	50%	66%

*Not moving from As on

Sample 5.3. Loop shape with lateral stitches

Wire before t		**Wire after te attachment**	
Lo	34mm	L deformed	68mm
Pitch	17mm	Pitch	23mm
Height	19mm	Height	12mm
		Deformed Stra	**100%**

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
L heated (mm)	48	50	50	50	50	50	50	50	50	50	49,8
t Af (s) Loop-lateral	17	11	11	11	11	10	10	11	11	11	11,4
Displacement (%)	29,4%	26,5%	26,5%	26,5%	26,5%	26,5%	26,5%	26,5%	26,5%	26,5%	26,8%
Recovery Strain (%)	59%	53%	53%	53%	53%	53%	53%	53%	53%	53%	54%

*More total wire length needed
*Irregular shape recovery on textile

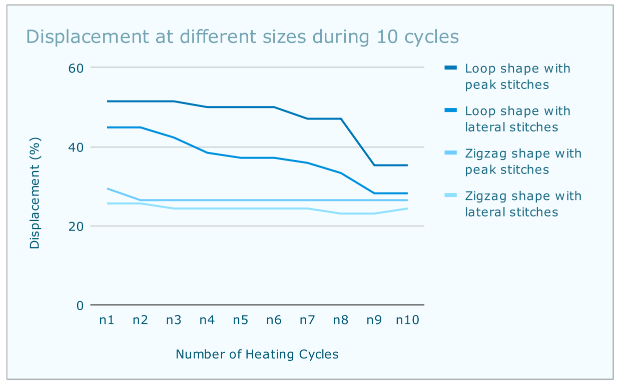
Sample 5.4. Zigzag shape with lateral stitches
*From Experiment 5

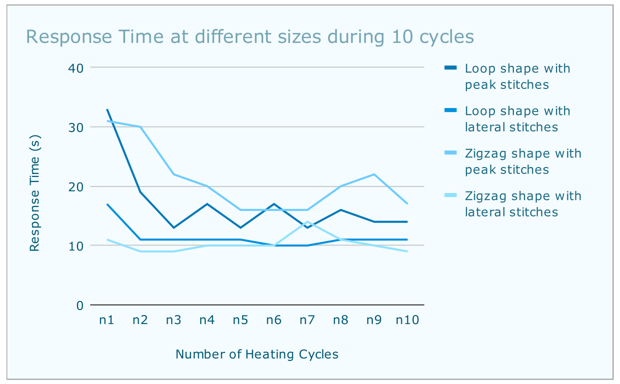
Wire before t		**Wire after te attachment**	
Lo	34mm	L deformed	78mm
Pitch	17mm	Pitch	39mm
Height	19mm	Height	10mm
		Deformed Stra	**129%**

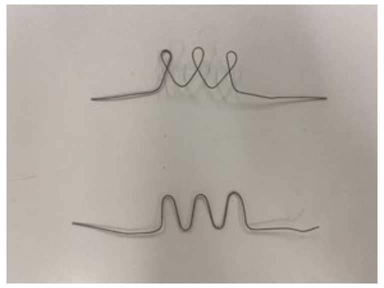
Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
L heated (mm)	58	58	59	59	59	59	59	60	60	**59**	59
t Af (s) Zigzag-lateral	11	9	9	10	10	10	14	11	10	9	10,3
Displacement (%)	25,6%	25,6%	24,4%	24,4%	24,4%	24,4%	24,4%	23,1%	23,1%	24,4%	24,4%
Recovery Strain (%)	45%	45%	43%	43%	43%	43%	43%	41%	41%	43%	43%

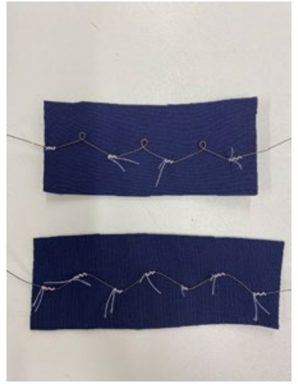
*Easier to return to shape by its own

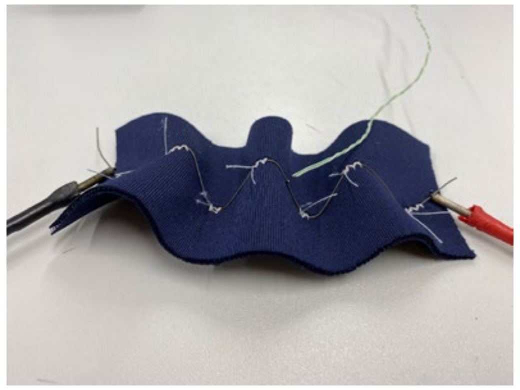
Best option because:
1. Lower heating time
2. Same displacement
3. More deformed strain (129%), which means more occupation on the textile
4. Less wire length needed
5. Easier to shape

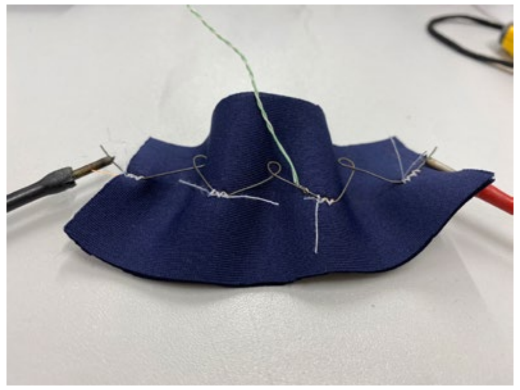


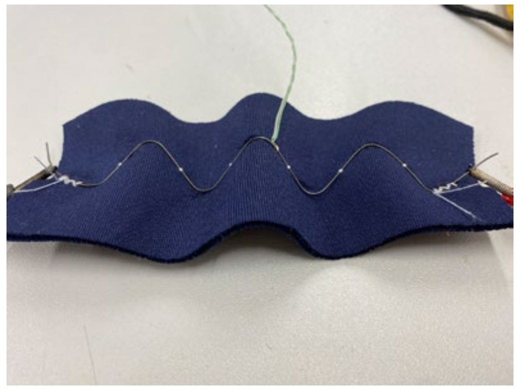


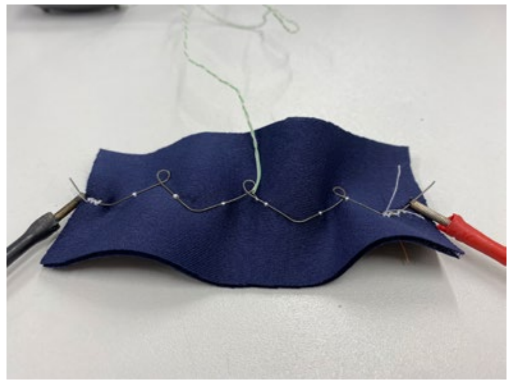












03/05/24

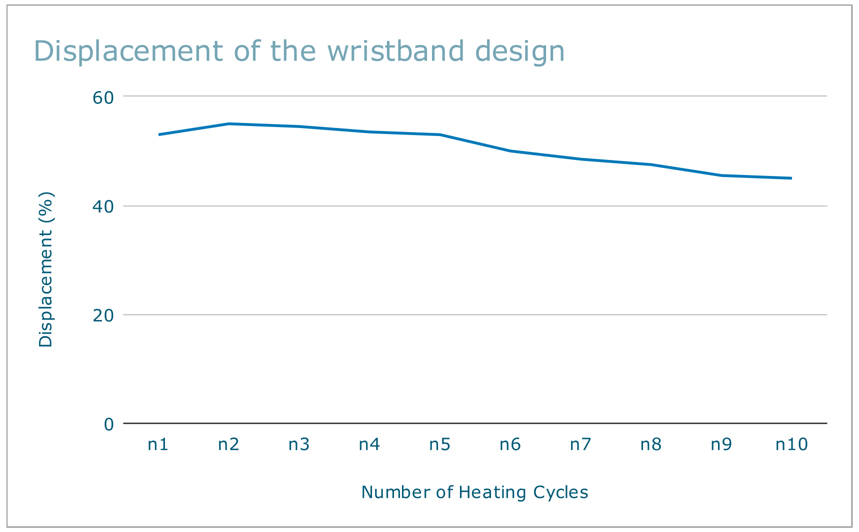
EXPERIMENT 6 Wristband design

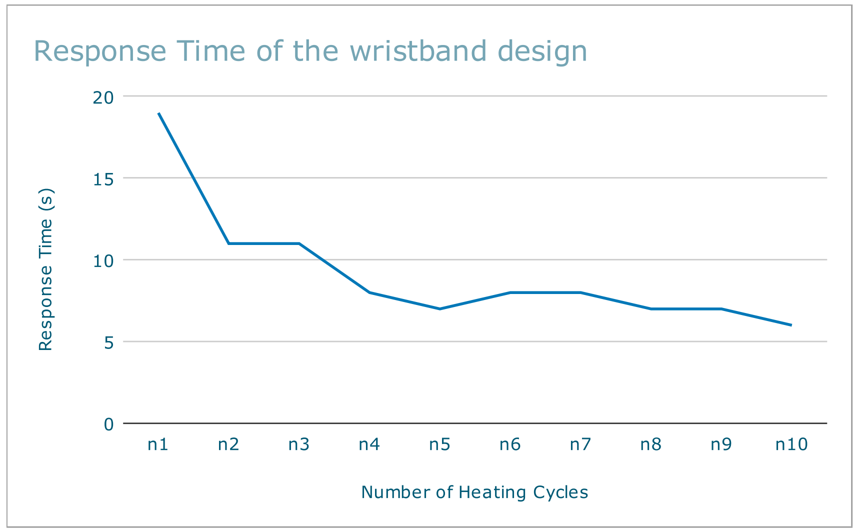
Objective **Understand the performance of a SMA integrated in a textile wristband through squeezing haptics**

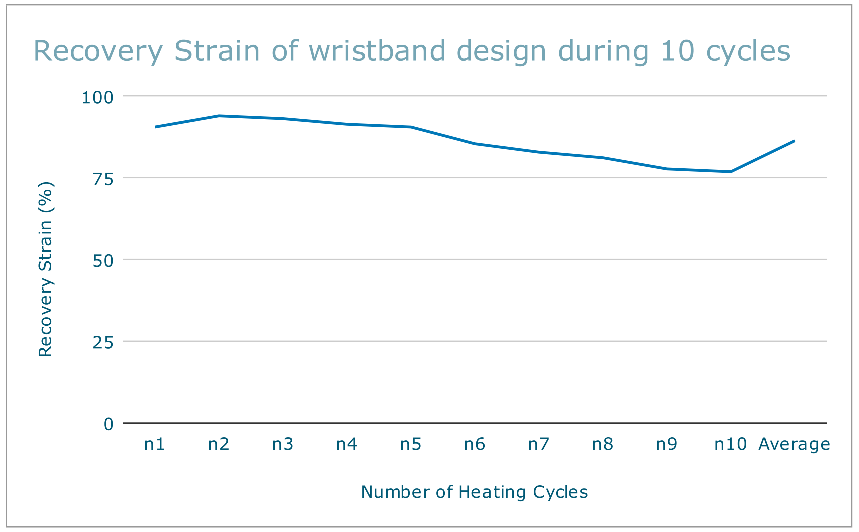
General wire propertie:	Total wire length	300mm	Textile size	280x65mm
	Diameter	0.5mm		
	Actuation Tempera	60ºC		
	Power	3.2v, 1.5A		
	Nº Peaks	6		
	Stitch size	W2 L2		
Wire before textile a	Lo	83mm		
	Pitch	17mm		
	Height	19mm		
Wire after textile att	L deformed	200mm		
	Pitch deformed	40mm		
	Height deformed	12mm		
	Deformed Strain	**141%**		

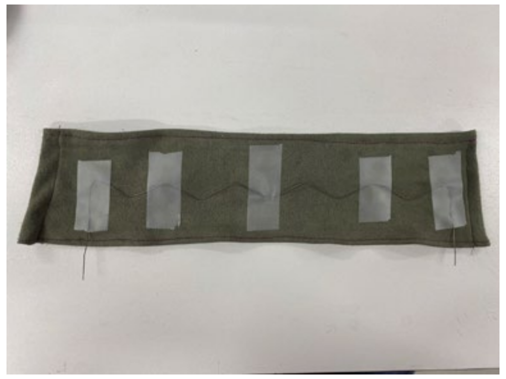
Cycles	**n1**	**n2**	**n3**	**n4**	**n5**	**n6**	**n7**	**n8**	**n9**	**n10**	Average
L heated (mm)	94	90	91	93	94	100	103	105	109	**110**	98,9
t Af (s)	19	11	11	8	7	8	8	7	7	6	9,2
Displacement (%)	53,0%	55,0%	54,5%	53,5%	53,0%	50,0%	48,5%	47,5%	45,5%	45,0%	50,6%
Recovery Strain (%)	91%	94%	93%	91%	91%	85%	83%	81%	78%	77%	86%

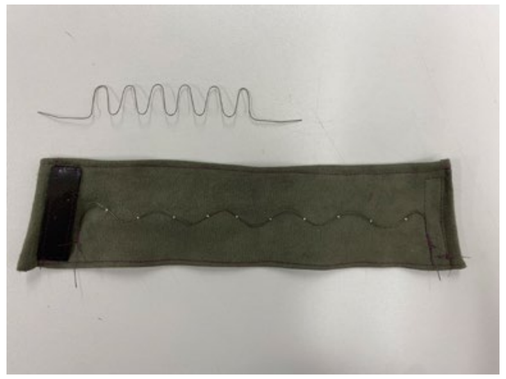
*As=30ºC (in contact with body temp)
*Longer length requires higuer voltage
*After C10, Lheated continue increasing until no recovery and time continues decreasing

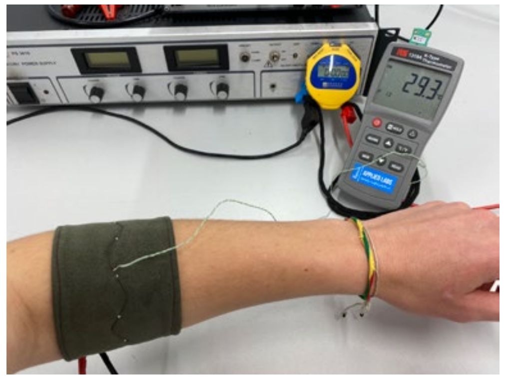












03/05/24

EXPERIMENT 7	Insulation layer load
Objective	**Compare the load/force of SMA integrated into textile with different insulation layers**

General wire properties	Total wire length	300mm	Textile size	280x65mm
	Diameter	0.5mm		
	Actuation Tempera	60ºC		
	Power	3.3v, 2A		
	Nº Peaks	6		
	Stitch size	W2 L2		
Wire before textile attachment	Lo	83mm		
	Pitch	17mm		
	Height	19mm		
Wire after textile attachment	L deformed	185mm		
	Pitch deformed	37mm		
	Height deformed	12mm		
	Peak angle	90º		
	Deformed Strain	**123%**		

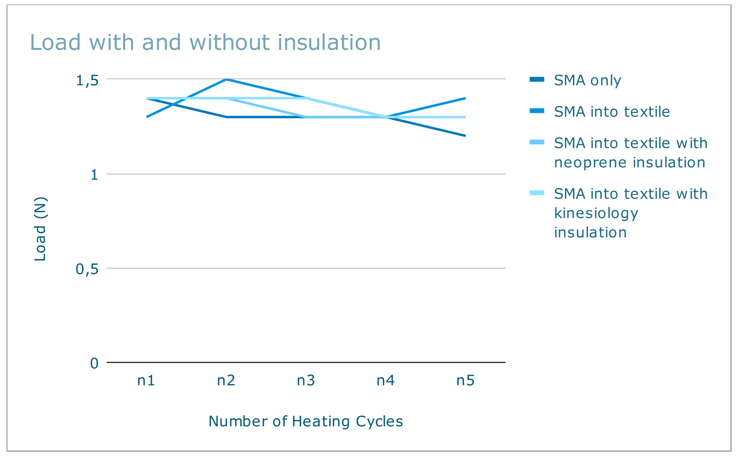
Sample 7.1. SMA only	Ld=205mm					
Cycles	**n1**	**n2**	**n3**	**n4**	**n5**	Average
Load (N)	1,4	1,3	1,3	1,3	1,2	1,30
L heated (mm)	85	90	90	95	100	92,0
t Af (s)	3	3	3	3	3	3,0
Displacement (%)	58,5%	56,1%	56,1%	53,7%	51,2%	55,1%
Recovery Strain (%)	98%	94%	94%	90%	86%	92,6%

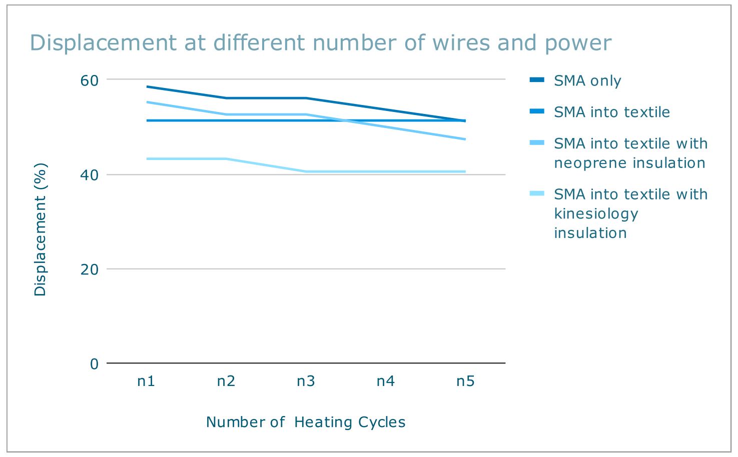
Sample 7.2. SMA into textile	Ld=185mm					
Cycles	**n1**	**n2**	**n3**	**n4**	**n5**	Average
Load (N)	1,3	1,5	1,4	1,3	1,4	1,38
L heated (mm)	90	90	90	90	90	90,0
t Af (s)	3	3	3	2	3	2,8
Displacement (%)	51,4%	51,4%	51,4%	51,4%	51,4%	51,4%
Recovery Strain (%)	93%	93%	93%	93%	93%	93,1%

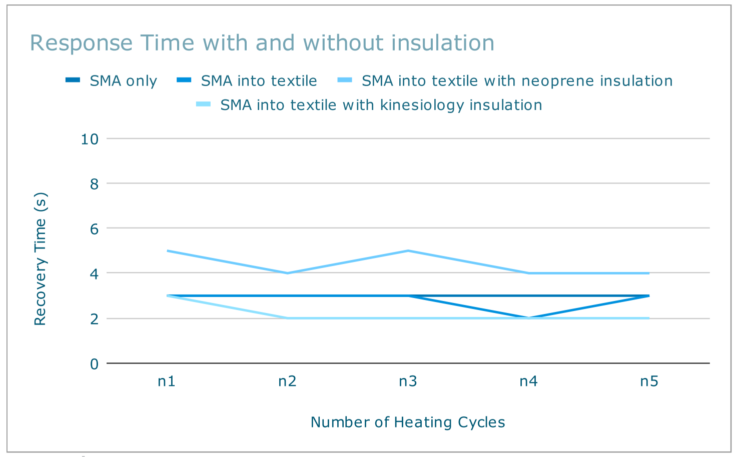
Sample 7.3. SMA into textile with neoprene insulation	Ld=190mm					
Cycles	**n1**	**n2**	**n3**	**n4**	**n5**	Average
Load(N)	1,4	1,4	1,3	1,3	1,3	1,34
L heated (mm)	85	90	90	95	100	92,0
t Af (s)	5	4	5	4	4	4,4
Displacement (%)	55,3%	52,6%	52,6%	50,0%	47,4%	51,6%
Recovery Strain (%)	98%	93%	93%	89%	84%	91,6%

*Only one that requires higher voltage (4v) to reach 2A

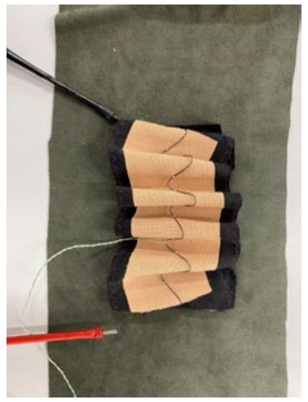
Sample 7.4. SMA into textile with kinesiology insulation	Ld=185mm					
Cycles	**n1**	**n2**	**n3**	**n4**	**n5**	Average
Load (N)	1,4	1,4	1,4	1,3	1,3	1,36
L heated (mm)	105	105	110	110	110	108,0
t Af (s)	3	2	2	2	2	2,2
Displacement (%)	43,2%	43,2%	40,5%	40,5%	40,5%	41,6%
Recovery Strain (%)	78%	78%	74%	74%	74%	75,5%

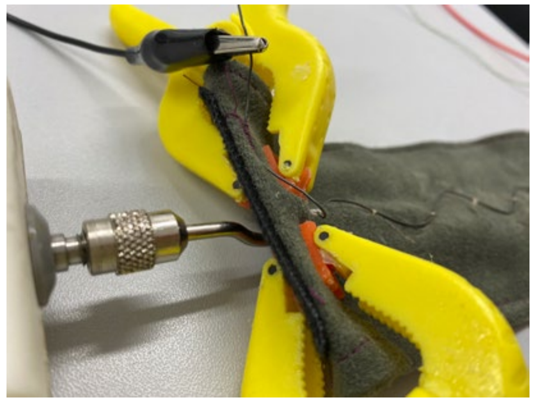








03/05/24

EXPERIMENT 8	Number of wires			
Objective	**Compare the load, displacement and recovery time of 1 SMA wire Vs. 2 wires into textile with kinesiology insulation**			
General wire properties	Total wire length	300mm	Textile size	280x65mm
	Diameter	0.5mm		
	Actuation Temperature	60ºC		
	Power	3.3v, **2A**		
	Nº Peaks	6		
	Stitch size	W2 L2		
Wire before textile attachment	Lo	83mm		
	Pitch	17mm		
	Height	19mm		
Wire after textile attachment	L deformed	185mm		
	Pitch deformed	37mm		
	Height deformed	12mm		
	Peak angle	90º		
	Deformed Strain	**123%**		
	Distance between wires	5mm		

Sample 8.1. One wire P=3.3v, **2A**

Cycles	n1	n2	n3	n4	n5	Average
Load (N)	1,4	1,4	1,3	1,3	1,3	1,34
L heated (mm)	105	105	110	110	110	108,0
t Af (s)	3	2	3	2	2	2,4
Displacement (%)	43,2%	43,2%	40,5%	40,5%	40,5%	41,6%
Recovery Strain (%)	78%	78%	74%	74%	74%	75,5%

Sample 8.2. Two wires P=2.4v,**2A**

Cycles	n1	n2	n3	n4	n5	Average
Load (N)	2,1	2,1	2,1	2,1	2,1	2,1
L heated (mm)	87	90	91	91	90	89,8
t Af (s)	20	20	21	21	20	20,4
Displacement (%)	53,0%	51,4%	50,8%	50,8%	51,4%	51,5%
Recovery Strain (%)	96%	93%	92%	92%	93%	93,3%

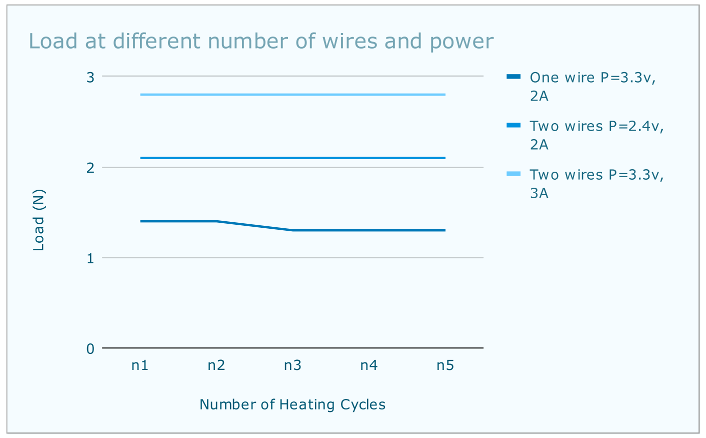
*Less V for the same I.

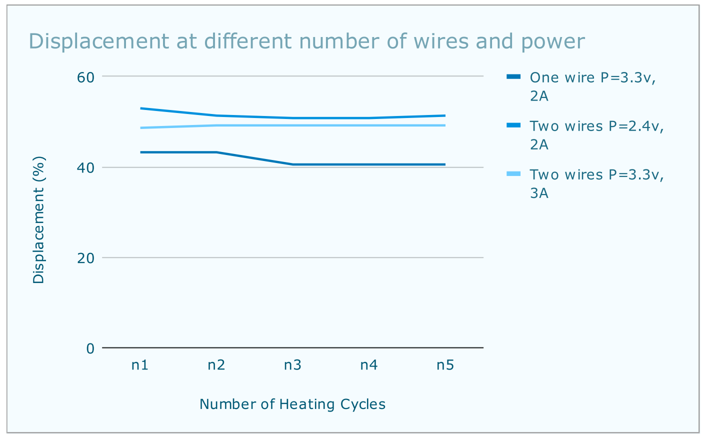
*As=24ºC and Af=35ºC moves super fast, and then slowly until 40ºC

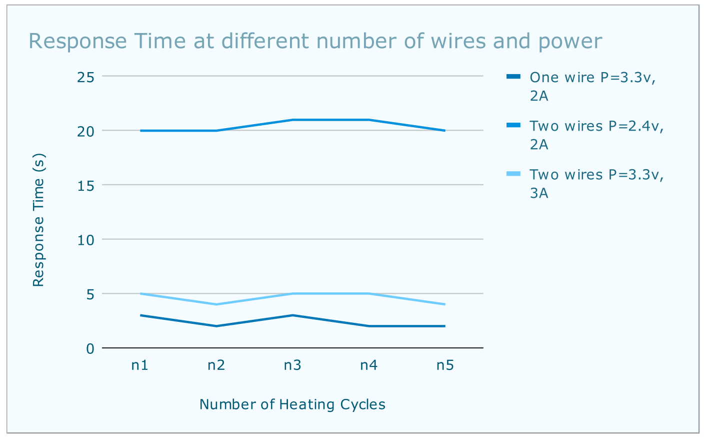
Sample 8.2. Two wires P=3.3v,**3A**

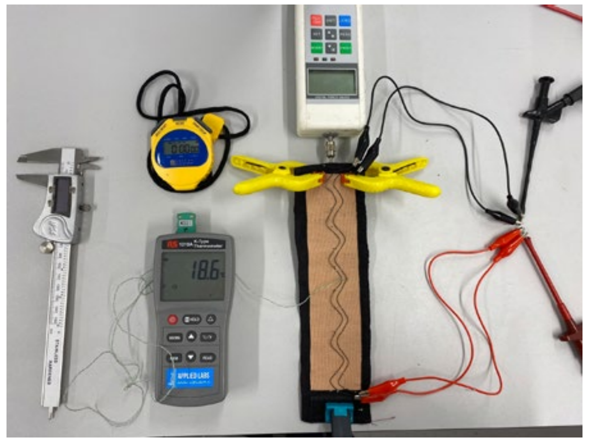
Cycles	n1	n2	n3	n4	n5	Average
Load (N)	2,8	2,8	2,8	2,8	2,8	2,8
L heated (mm)	95	94	94	94	94	94,2
t Af (s)	5	4	5	5	4	5
Displacement (%)	48,6%	49,2%	49,2%	49,2%	49,2%	49,1%
Recovery Strain (%)	88%	89%	89%	89%	89%	89,0%

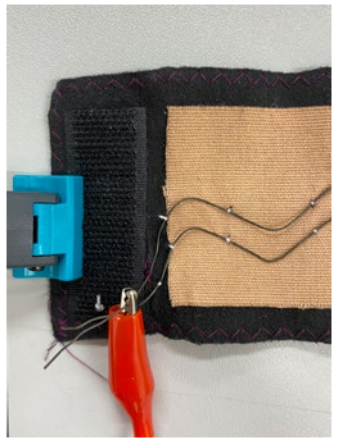
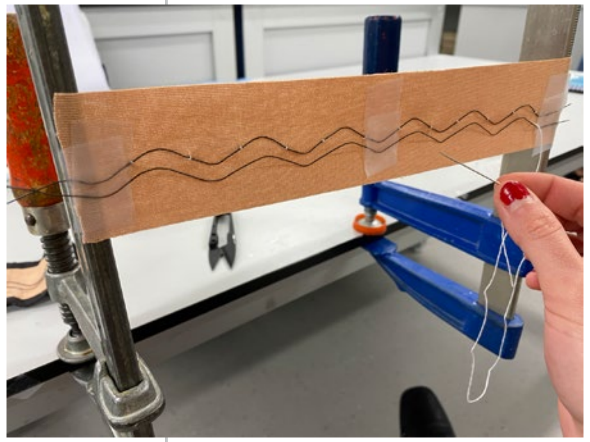
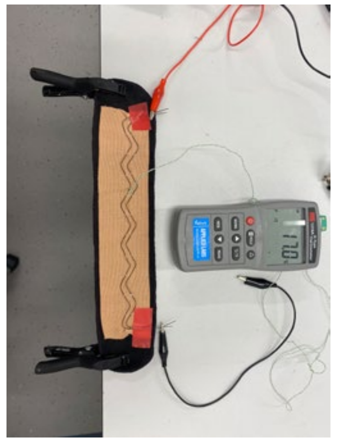
*Af=30ºC









03/05/24

EXPERIMENT 9 — Counterforce

Objective — **Compare the deformed height and recovery time of the design with and without counterforce**

General wire properties	Total wire length	300mm	Textile size	280x65mm
	Diameter	0.5mm	Distance betwe	70mm
	Actuation Tempera	60ºC		
	Power	3v, 3A		
	Nº Peaks	6		
	Stitch size	W2 L2		
Wire before textile attachment	Lo	83mm		
	Pitch	17mm		
	Height	19mm		
Wire after textile attachment	L deformed	185mm		
	Pitch deformed	37mm		
	Height deformed	12mm		
	Peak angle	90º		
	Deformed Strain	**123%**		
	Distance between	5mm		

Sample 9.1. No counterforce

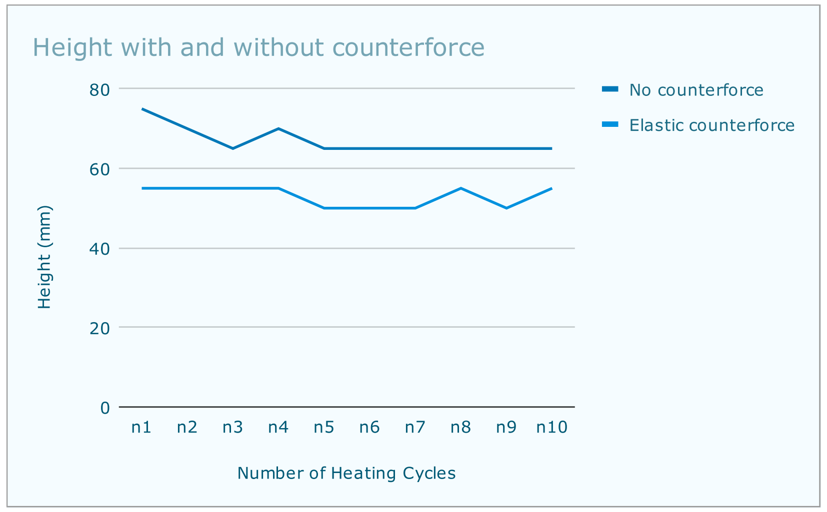
Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
Height (mm)	75	70	65	70	65	65	65	65	65	65	69,0
t Af (s)	6	5	5	4	5	6	5	6	6	6	5,0

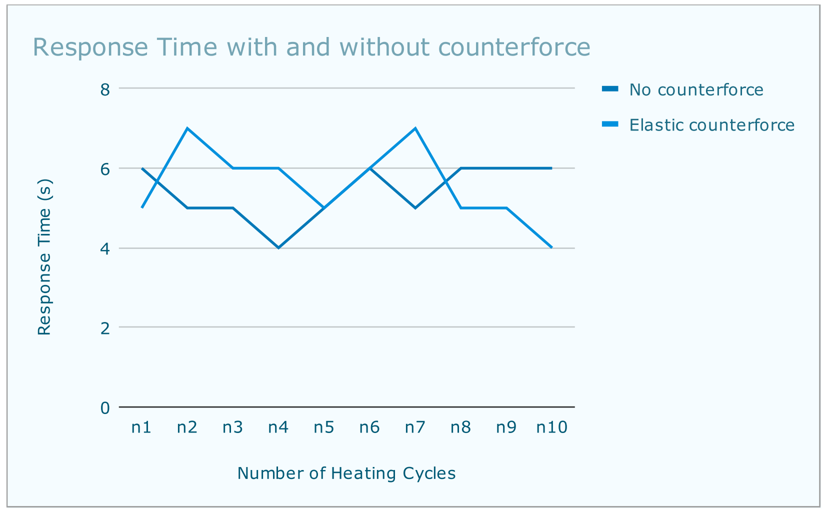
*Af=35-40ºC

Sample 9.2. Elastic Counterforce

Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
Height (mm)	55	55	55	55	50	50,0	50	55	50	55	54,0
t Af (s)	5	7	6	6	5	6,0	7	5	5	4	5,8

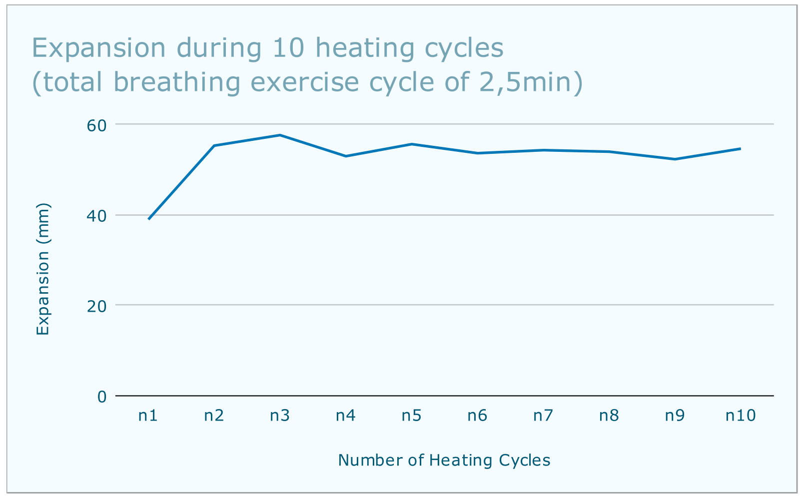
*Af=40-45ºC
*Upon cooling, it start moving faster from 35ºC down





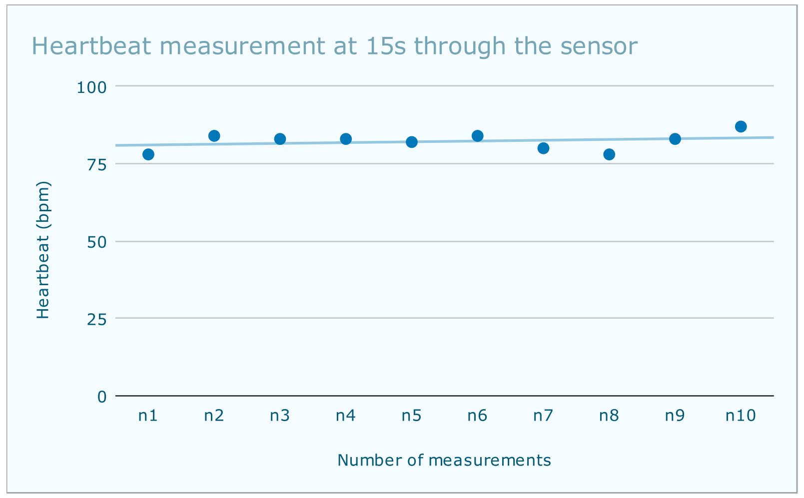
19/07/24

EXPERIMENT 10	Embodiment design			
Objective	**Measure the expansion for consecutive heating-cooling cycles automatized with microcontroller and battery**			
General wire properties	Total wire length	300mm	Textile size	280x65mm
			Distance between attachments to abdominal band	70mm
	Diameter	0.5mm		
	Actuation Temperature	60ºC		
	Power	3,7v, 3A		
	Nº Peaks	6		
	Stitch size	One loop (manual)		
Wire before textile attachment	Lo	83mm		
	Pitch	17mm		
	Height	19mm		
Wire after textile attachment	L deformed	185mm		
	Pitch deformed	37mm		
	Height deformed	12mm		
	Peak angle	90º		
	Deformed Strain	**123%**		
	Distance between wires	5mm		



Cycles	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	Average
Time of Heating Cycles (s)	5	5	5	5	5	5	5	5	5	5	
Heartbeat (bpm)	78	84	83	83	82	84	80	78	83	87	82,2
Expansion Measurement 1 (mm)	30	46	57	56	57	54	56	57	53	55	
Expansion Measurement 2 (mm)	38	60	58	52	55	53	54	51	53	56	
Expansion Measurement 3 (mm)	49	60	58	51	55	54	53	54	51	53	
Expansion (mm)	**39**	**55,33**	**57,67**	**53,00**	**55,67**	**53,67**	**54,33**	**54,00**	**52,33**	**54,67**	53,0
Standard Deviation	9,54	8,08	0,58	2,65	1,15	0,58	1,53	3,00	1,15	1,53	

*Heartbeat starts measuring at 5-7s and stabilize at 10-15s



APPENDIX 7.

Coding

```
#include <Wire.h>
#include <CapacitiveSensor.h>
#include "MAX30105.h"
#include "heartRate.h"

// SMA Wire Control
#define SMAPIN 10
const int MAX = 255;
const float currentAdjustmentFactor = 0.7;
const int pwmValue = MAX * currentAdjustmentFactor;
unsigned long startMillis;
unsigned long currentMillis;
unsigned long heatingDuration;
unsigned long coolingDuration;
unsigned long msecLst;
#define TWO_SEC     1000
int cycleCount = 0;
const int maxCycles = 6;
bool modeSelected = false;

// Capacitive Sensor
const int sendPin = 0;
const int receivePin = 6;
CapacitiveSensor cs_4_2 = CapacitiveSensor(sendPin, receivePin);
const long touchThreshold = 1000;
const int ledThreshold = 1000;
const int numReadings = 10;
int sensorReadings[numReadings];
int sensorIndex = 0;
int total = 0;
const int ledPin1 = 13;
unsigned long lastTouchTime = 0;
unsigned long touchDuration = 0;
bool touchActive = false;

// Pulse Sensor
MAX30105 particleSensor;
const byte RATE_SIZE = 4;
byte rates[RATE_SIZE];
byte rateSpot = 0;
long lastBeat = 0;
float beatsPerMinute;
int beatAvg;

void setup() {
  Serial.begin(115200);

  // Initialize SMA pin
  pinMode(SMAPIN, OUTPUT);
```

```
  // Initialize LED pin
  pinMode(ledPin1, OUTPUT);
  digitalWrite(ledPin1, LOW);

  // Initialize sensor readings array
  for (int i = 0; i < numReadings; i++) {
    sensorReadings[i] = 0;
  }

  // Initialize MAX30105 sensor
  if (!particleSensor.begin(Wire, I2C_SPEED_FAST)) {
    Serial.println("MAX30105 was not found. Please check wiring/power.");
    while (1);
  }
  particleSensor.setup();
  particleSensor.setPulseAmplitudeRed(0x0A);
  particleSensor.setPulseAmplitudeGreen(0);
}

void loop() {
  // Capacitive Sensor Handling
  long sensorValue = cs_4_2.capacitiveSensor(30);
  total = total - sensorReadings[sensorIndex];
  sensorReadings[sensorIndex] = sensorValue;
  total = total + sensorReadings[sensorIndex];
  sensorIndex = (sensorIndex + 1) % numReadings;
  long smoothedSensorValue = total / numReadings;
  unsigned long msec=millis();



  bool touchDetected = (smoothedSensorValue > touchThreshold);

  if (touchDetected) {
    if (!touchActive) {
      touchActive = true;
      lastTouchTime = millis();
    } else {
      touchDuration = millis() - lastTouchTime;
      if (touchDuration >= 3000) {
        if (!modeSelected) {
          heatingDuration = 8000;
          coolingDuration = 11000;
          Serial.println("Mode 2 selected.");
          modeSelected = true;
          startMillis = millis();
          digitalWrite(ledPin1, HIGH);
```



```
        }
      }
    }
  } else {
    if (touchActive) {
      touchActive = false;
      touchDuration = millis() - lastTouchTime;
      if (touchDuration < 3000) {
        if (!modeSelected) {
          heatingDuration = 5000;
          coolingDuration = 10000;
          Serial.println("Mode 1 selected.");
          modeSelected = true;
          startMillis = millis();
          digitalWrite(ledPin1, HIGH);
        }
      }
    }
  }

  if (modeSelected) {
    if (cycleCount < maxCycles) {
      currentMillis = millis();
      if (currentMillis - startMillis <= heatingDuration) {
        analogWrite(SMAPIN, pwmValue);
        int heatingTimePassed = (currentMillis - startMillis) / 1000;
        Serial.print("Heating ");
        Serial.print(heatingTimePassed + 1);
        Serial.print(" out of ");
        Serial.print(heatingDuration / 1000);
        Serial.println(" seconds");
      } else if (currentMillis - startMillis <= heatingDuration +
coolingDuration) {
        analogWrite(SMAPIN, 0);
        int coolingTimePassed = (currentMillis - startMillis -
heatingDuration) / 1000;
        Serial.print("Cooling ");
        Serial.print(coolingTimePassed + 1);
        Serial.print(" out of ");
        Serial.print(coolingDuration / 1000);
        Serial.println(" seconds");
      } else {
        startMillis = millis();
        cycleCount++;
        Serial.print("Cycle ");
        Serial.print(cycleCount);
        Serial.println(" complete.");
      }
    } else {
```

```
      analogWrite(SMAPIN, 0);
      Serial.println("All cycles complete.");
      modeSelected = false;
      cycleCount = 0;
      digitalWrite(ledPin1, LOW);
    }

  }

  // Pulse Sensor Handling
  long irValue = particleSensor.getIR();
  if (checkForBeat(irValue)) {
    long delta = millis() - lastBeat;
    lastBeat = millis();
    beatsPerMinute = 60 / (delta / 1000.0);

    if (beatsPerMinute < 255 && beatsPerMinute > 20) {
      rates[rateSpot++] = (byte)beatsPerMinute;
      rateSpot %= RATE_SIZE;
      beatAvg = 0;
      for (byte x = 0; x < RATE_SIZE; x++)
        beatAvg += rates[x];
      beatAvg /= RATE_SIZE;
    }

  }

  if ( (msec - msecLst) > TWO_SEC)  {
    msecLst = msec;
    Serial.print("Capacitive Sensor Value: ");
    Serial.println(smoothedSensorValue);
    Serial.print("IR=");
    Serial.print(irValue);
    Serial.print(", BPM=");
    Serial.print(beatsPerMinute);
    Serial.print(", Avg BPM=");
    Serial.print(beatAvg);

    if (irValue < 50000)
     Serial.print(" No finger?");

    Serial.println();


  }


}
```

APPENDIX 8.
Technical Data Sheets of SMAs

Find more information at nanografi.com

nanografi

Contact us at sales@nanografi.com

NANOGRAFI NANOTECHNOLOGY

Inspection Certificate

PRODUCT PROPERTIES

Product Name	Nitinol Wire
Furnace No	5-2104
Ingot No	20210425-1
Batch No	20210425-1-2
Condition	Wire
Thickness	1.0mm
AF Temperature	45-50°C

MECHANICAL PROPERTIES

Tensile Strength	1250 Mpa	Yield Strength	245 Mpa
Elongation	21%	Bend Test α>130	Qualified
Dimensional Inspection	Qualified	Visual Inspection	Qualified
Ultrasonic Inspection	A		

CHEMICAL COMPOSITION

Ti	Balance	Ni	55.59%
Co	0.002	Cu	0.002
Cr	0.001	Fe	0.014
Nb	0.004	C	0.035
H	< 0.001	O	0.042
N	0.001		

Materials Date Sheet

NiTiCu Wires

Features:

- Ternary NiTiCu Alloys for actuators
- Narrow Hysteresis.

1.Chemical Composition

Ni (Nominal)	Cu (Nominal)	≤						Ti
		C	Co	H	Fe	Nb	N+O	
55wt%	5	0.05	0.05	0.015	0.050	0.025	0.050	Bal

2.Transformation Transformation(Per ASTM F2004)

Fully Annealed Condition (830℃_20min_WQ)	
Af	60℃±5℃
As-Ms	≤ 5 ℃

3. Sizes

Diameter,(mm)	Size Variation,(mm)
> 0.10 to0.50 inclusive	±0.005
> 0.50 to1.0 inclusive	±0.008
> 1.0 to7.0 inclusive	±0.010

4. Mechanical Properties

Tensile strength(N/mm^2)	Elongation(%)
≥300Mpa in Martensite	≥25 in Martensite
≥550Mpa in Austenite	≥10 in Austenite

5. Physical Properties

Melting Point	Density	Electrical Resistivity		Thermal Expansion Coefficient	
		In Martensite	In Austenite	In Martensite	In Austenite
1250℃	$6.50 g/cm^3$	$80*10^{-8}\Omega m$	$90*10^{-8}\Omega m$	$6.6*10^{-6}/℃$	$11*10^{-6}/℃$

Flexmet BV

Rudy Stalmans

APPENDIX 9.

Project Brief and Planning

Personal Project Brief – IDE Master Graduation Project

Name student Carlota Muñoz Ruiz **Student number**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Shape Morphing Wearable for Nervous System Regulation Through Breathing

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

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The World Health Organization reports that anxiety disorders, the most prevalent mental health issues, affect around 4% of the global population, yet only a quarter of those affected receive treatment. This is mainly due to limited awareness of anxiety as a treatable condition and insufficient development in mental health solutions. Current treatments primarily target acute anxiety episodes, like panic attacks, with medication or therapy. Some individuals also use external devices or apps for self-regulation through relaxation exercises. However, these solutions mainly focus on curing rather than preventing anxiety in its early stages or may not be seamlessly integrated into daily life, resulting in underutilization.
According to mental health experts, anxiety commonly arises from unaddressed stress levels accumulated over time. "Individuals with anxiety require reliable methods to ground themselves and regain control, whether through therapy, technological aids, or mindfulness practices like meditation." Breathing techniques, or "Breathwork," are highlighted as one of the most effective treatments for reducing stress levels. They regulate the Central Nervous System (CNS), improving blood oxygenation, circulation, and brain function, which has a beneficial impact on health status, such as wellness, emotion regulation, and the regulation of stress-related disorders such as anxiety, depression, insomnia, burnout, or PTSD.
Hence, there's potential to enhance treatments by integrating Shape Morphing technologies, such as Shape Memory Alloys (SMA). The project aims to create a smart textile wearable for the torso that detects heightened respiration rates, indicating anxiety, via a sensor. It then utilizes SMA actuators to mimic breathing through haptics and make user synchronize with it for regulating the nervous system and reducing the risk of panic attacks. The wearable, featuring comfortable knitwear, integrates the sensor with conductive yarn knitting and the SMA sewn into the textile. It targets non-clinical individuals managing daily anxiety episodes and facilitates self-awareness of it. Understanding user needs and emotions, as well as professionals' clinical treatment, is crucial for selecting appropriate textiles and designing the SMA mechanism for a soothing user experience.
TU Delft Stakeholders: Sepideh Ghodrat (Chair), with interests in Shape Morphing Design and user-wearable interaction; Stefano Parisi (mentor), with focus on Materials Experience and Material-Driven Design to promote well-being; and the Emerging Materials Lab, offering resources and expertise for technical prototype exploration and feasibility.

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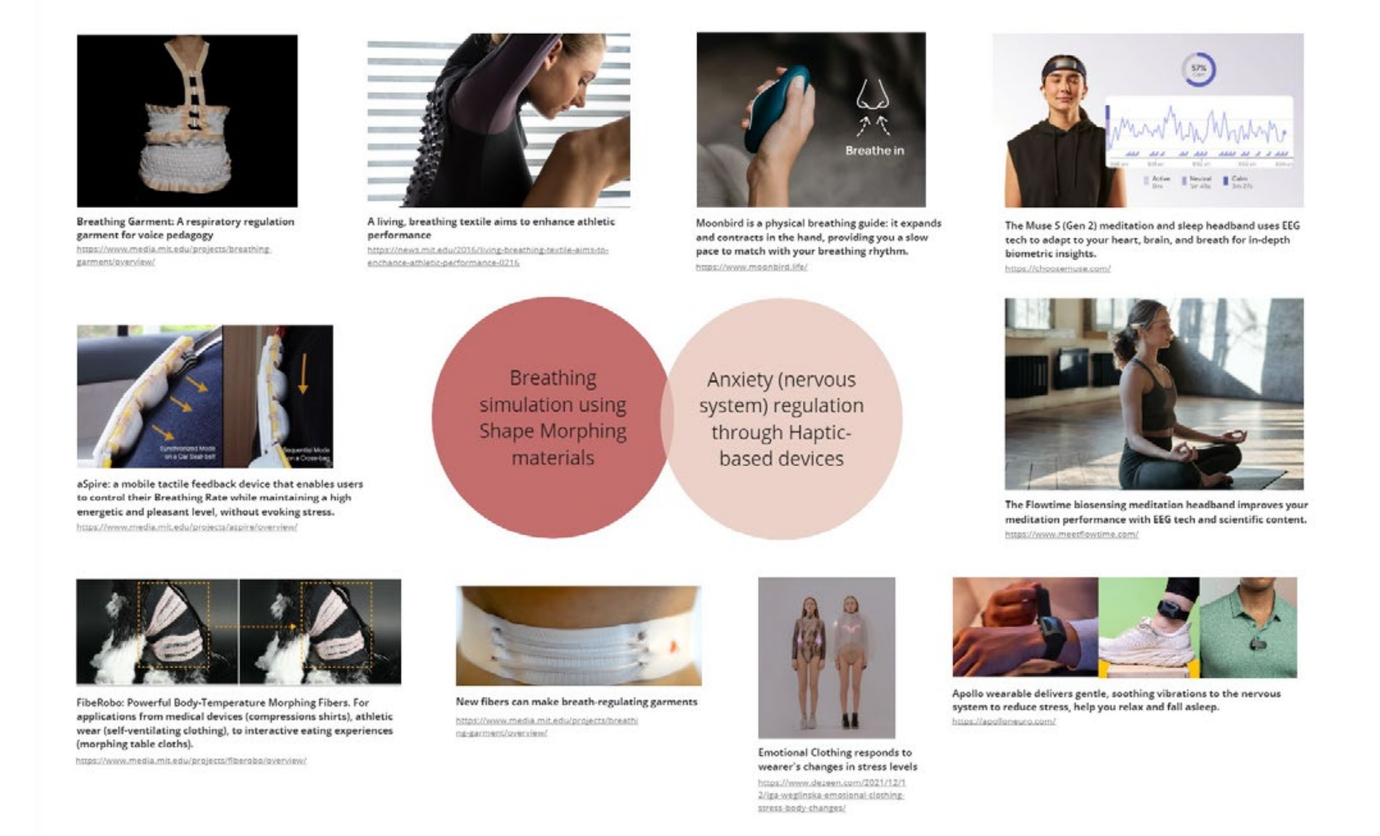


image / figure 1 Benchmarking of anxiety (nervous system) regulation, breathwork, Shape Morphing materials and Haptics

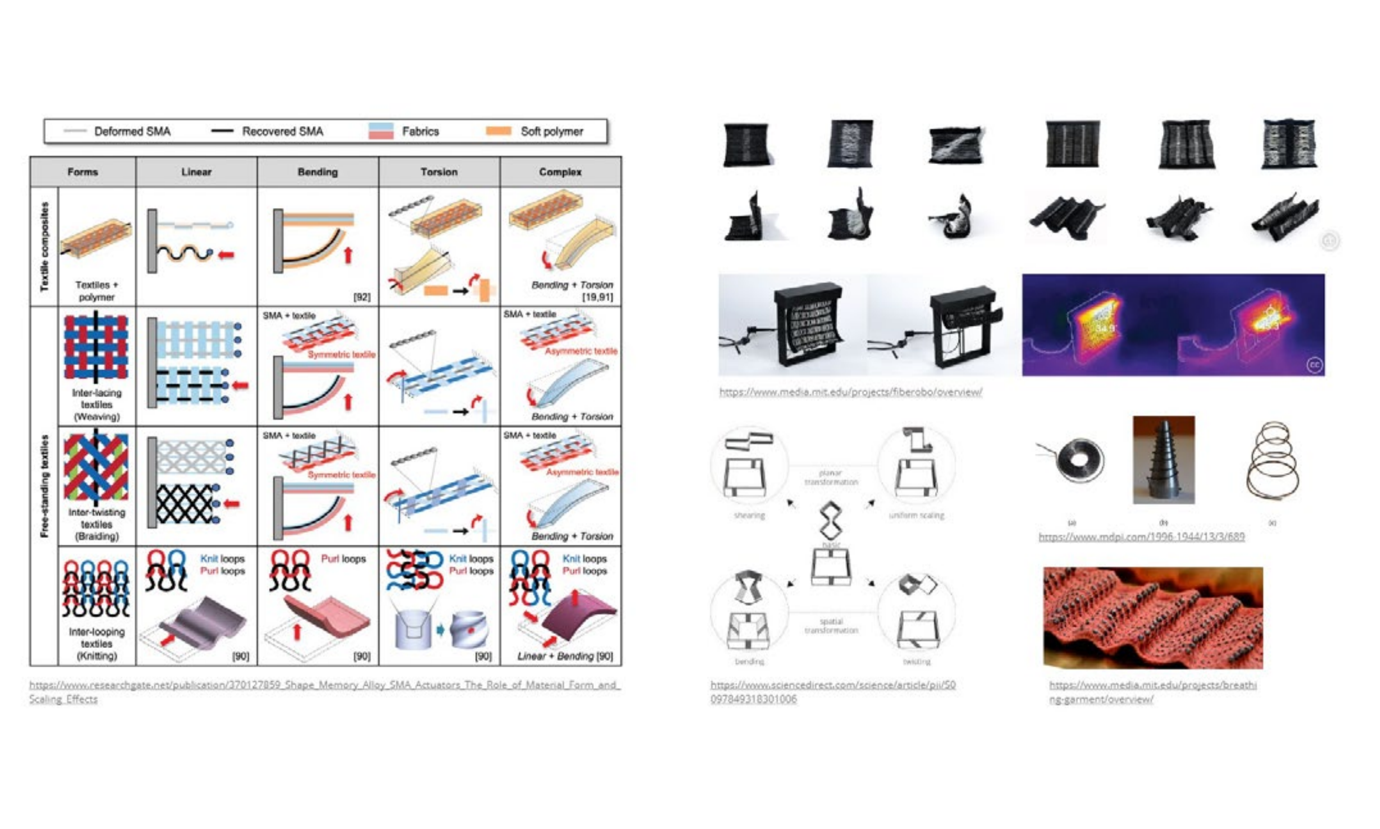


image / figure 2 Configurations of Shape Morphing materials integrated into textiles.

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

Based on the introduction, the Research Questions can be divided into two main themes:

Theme 1: Utilizing Shape Morphing-based technology for Nervous System regulation
RQ 1.1: Which current treatments for regulating the nervous system (e.g. anxiety) incorporate Shape Morphing-based technologies? What are the knowledge gaps between medical treatment and design-focused solutions?
RQ 1.2: How can Shape Memory Alloys (SMA) integrated into textiles accurately simulate the breathing system or "breathwork"? What intensity, location, and mechanism enhance user perception?

Theme 2: Exploring User-Smart wearable interaction (HCI)
RQ 2.1: How can a smart wearable enhance user's awareness of anxiety in order to regulate their Nervous System?
RQ 2.2: How can materials enhance the seamless integration of the wearable into daily life to enhance well-being while avoiding intrusiveness?

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)
As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design and develop a prototype of a smart knitwear wearable integrating Shape Morphing materials (SMA) and breathing rate sensors to regulate the Nervous System and acute daily anxiety episodes in non-clinical patients through haptic breathwork.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The focus is to enhance anxiety awareness by regulating the Nervous System with breathing techniques (breathwork). It main focuses on non-clinical patients suffering from acute anxiety episodes (e.g. panic attacks when sleeping). It increases the effectiveness and minimal intrusion into daily life. Ideally, the project outcome will entail a prototype that:
- Accurately replicates the breathing system through SMA-haptics, and potentially tracks the user's respiration rate via sensors. This will be facilitated by three elements: active elements (SMA actuators), passive elements (textile), and controlled elements (sensors).
- Seamlessly integrates into knitwear to deliver a comfortable and soothing user experience.
To achieve this, extensive research is necessary in areas such as anxiety and nervous system regulation, integration of electronics into materials/textiles, Shape Morphing Materials (especially SMA), and smart wearables-user interaction. Throughout the design process, Materials-Driven Design Methods, such as technical characterization of temporal behavior and experiential characterization with user studies, including prototyping and interviews, are pivotal. This holistic approach aims to validate both the functionality of the mechanism and the comfort of the user experience, identify limitations, and pinpoint areas for improvement.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	29 feb 2024
Mid-term evaluation	26 abr 2024
Green light meeting	21 jun 2024
Graduation ceremony	30 jul 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

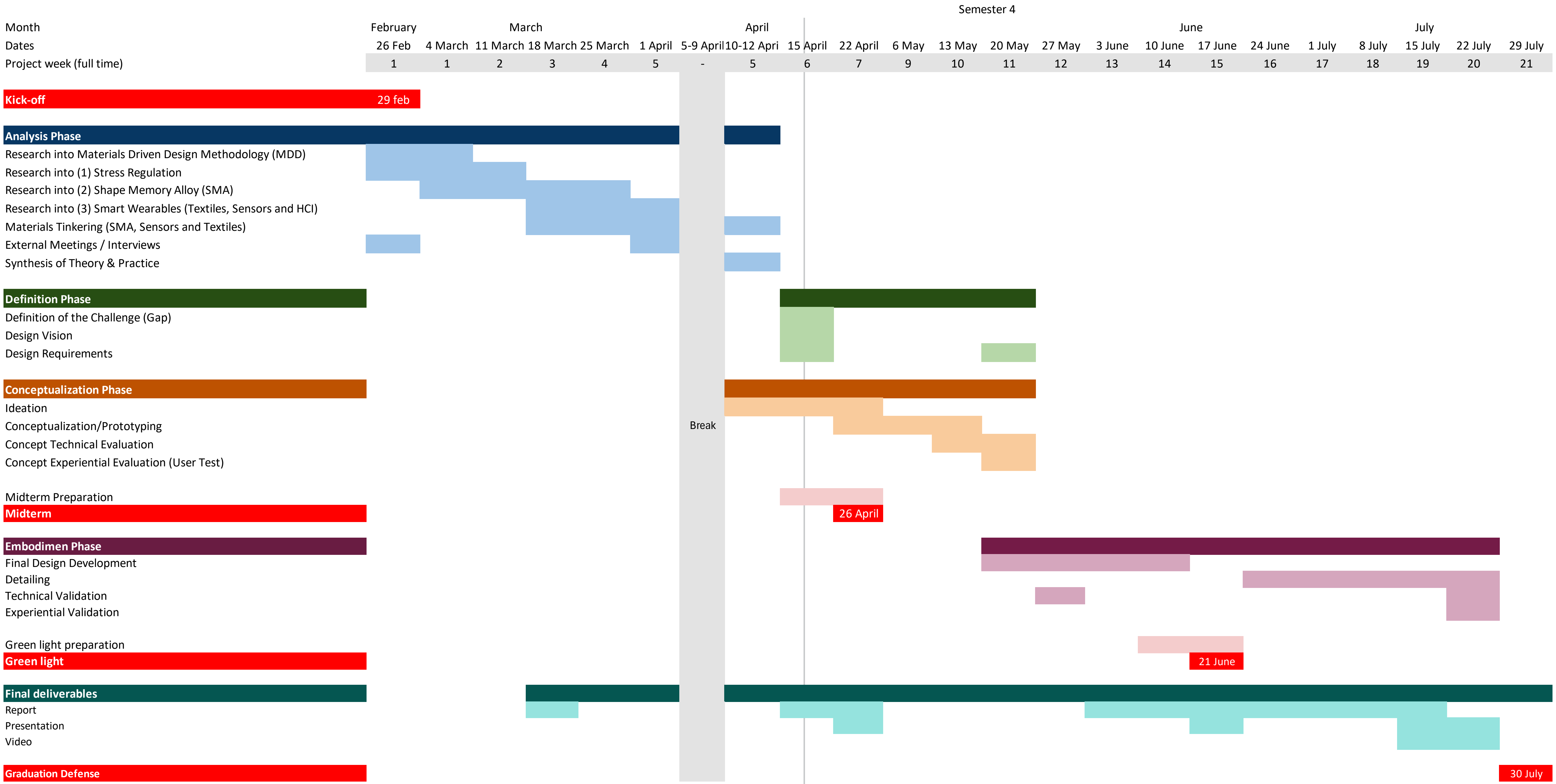
Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

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

Graduation Project Motivation:
Two intriguing fields related to design that are experiencing exponential growth in R&D and investment are Healthcare and Smart Materials. I am very interested in demonstrating that design can leverage technology to explore the integration of both, leading to more innovative solutions. Mental health and well-being, in particular, are essential aspects of life that deserve more effective treatment. This can be achieved by benefiting from high-tech such as Shape Morphing Materials, which, due to their adaptability to the environment, present significant opportunities for mental health improvement, especially concerning anxiety. My goal is to showcase this technology can empower users to train self-control without the necessity for medication. The healthcare field demands more practical solutions, as I learnt in my AED project addressing children malnutrition in Kenya.

Personal Learning Ambitions:
Firstly, I am interested in expanding my knowledge in advanced materials, with a specific focus on Smart Materials and textiles, as I see their high potential. I aim to learn the requirements, limitations, and the design process involved in developing prototypes using them. Secondly, I want to immerse myself in the Healthcare sector to make a tangible impact on people's lives. I chose anxiety because nearly all of my friends and family have experienced it, lacking any effective treatment. I seek to identify areas for improvement and, consequently, provide functional and effective solutions. As a very social person, the idea of designing directly for people serves as a significant source of motivation.


Semester 4
Month
February
March
April
June
July
Dates
26 Feb
4 March
11 March
18 March
25 March
1 April
5-9 April
10-12 Apri
15 April
22 April
6 May
13 May
20 May
27 May
3 June
10 June
17 June
24 June
1 July
8 July
15 July
22 July
29 July
Project week (full time)
1
1
2
3
4
5
-
5
6
7
9
10
11
12
13
14
15
16
17
18
19
20
21
Kick-off
29 feb
Analysis Phase
Research into Materials Driven Design Methodology (MDD)
Research into (1) Stress Regulation
Research into (2) Shape Memory Alloy (SMA)
Research into (3) Smart Wearables (Textiles, Sensors and HCI)
Materials Tinkering (SMA, Sensors and Textiles)
External Meetings / Interviews
Synthesis of Theory & Practice
Definition Phase
Definition of the Challenge (Gap)
Design Vision
Design Requirements
Conceptualization Phase
Ideation
Conceptualization/Prototyping
Concept Technical Evaluation
Concept Experiential Evaluation (User Test)
Break
Midterm Preparation
Midterm
26 April
Embodimen Phase
Final Design Development
Detailing
Technical Validation
Experiential Validation
Green light preparation
Green light
21 June
Final deliverables
Report
Presentation
Video
Graduation Defense
30 July