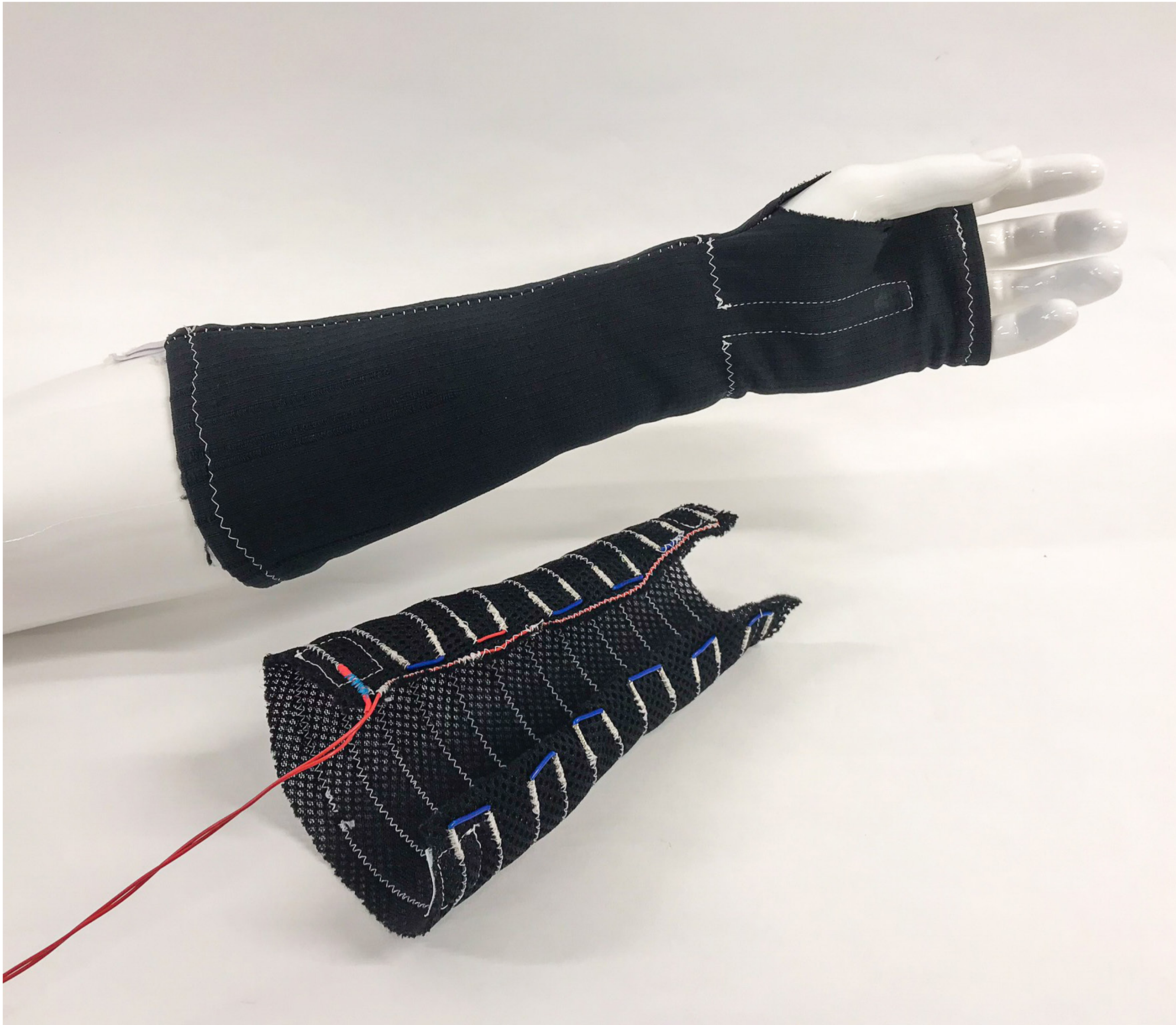
SereniSleeve

Designing Shape Memory Based Wearables for Anxiety Modulation



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> “Anxiety was born in the very same moment as mankind. And since we will never be able to master it, we will have to learn to live with it — just as we have learned to live with storms.”
>
> — Paulo Coelho

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Now I can finally go relax and feed some geese without constantly thinking about getting work done.

SUMMARY

Anxiety is a natural "fight-or-flight" response that everybody experiences to perceived stress or threat. Even though it is a natural response, some individuals struggle with managing their anxiety levels in a healthy manner. Prolonged exposure to high anxiety states can lead to clinical anxiety disorders that negatively impact the quality of life, thus early interventions to reduce anxiety levels can help prevent the development of clinical level anxiety. Even nonclinical individuals can also suffer from periods of heightened anxiety state, so anyone can benefit from additional guidance with anxiety modulation.

This graduation project aims to create a wearable garment that helps with daily levels of anxiety modulation in a non-clinical setting by providing warmth and pressure sensations typically associated with Deep Touch Pressure (DTP). DTP is a form of tactile sensory input that is provided by holding, stroking, hugging and squeezing, which has been proven to elicit feelings of safety, relaxation, and comfort. Although there are some commercially available DTP wearable products typically in the form of a vest, they are often heavy, uncomfortable, or indiscreet as the DTP sensations are provided by additional weights or inflatables with hand-operated pumps. Since they are difficult to conceal, wearing those commercial DTP vests can attract unwanted attention from nearby strangers and further aggravate anxiousness. Instead, DTP sensations can be applied to the body in a noiseless, lightweight, and discreet manner by utilizing shape memory alloy (SMA) actuators in wearable garments.

The insights that formed the groundwork for this project was gathered through literature review in a wide variety of topics including haptic technology, affect regulation, and SMA. Deeper understanding of the intricate nuances involved with anxiety modulation were gained through self-reflection and introspection as part of the autobiographical design method. Although the insights gathered from introspection are rooted in subjective lived experiences, they can yield universally applicable outcomes based on genuine empathy and firsthand understanding that resonate with a broader range of users who experience similar or related difficulties with anxiety. Moreover, rapid prototyping and iterative processes were utilized to tinker with and learn about designing SMA based actuators for wearable garments. After fabricating several prototype iterations, each exploring different design variables, SereniSleeve was developed.

SereniSleeve is a fingerless glove sleeve that provides warmth and deep pressure sensations to the forearm. It helps users break out of spiraling anxious thoughts by providing on-body haptic sensations that they can focus on, enhancing their grounding techniques. User test participants experienced feelings of calmness, relaxation, and comfort at varying pressure settings. Users can intuitively activate the sleeve by clenching their fists during stressful or anxious situations, triggering one of three preset pressure settings depending on the user applied force. All the electronic components can easily be detached from the double-layered fabric sleeve cover for easy maintenance and washability. Based on the participant feedback, future work and iterations on SereniSleeve could further improve its overall usability and user experience.

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1. INTRODUCTION

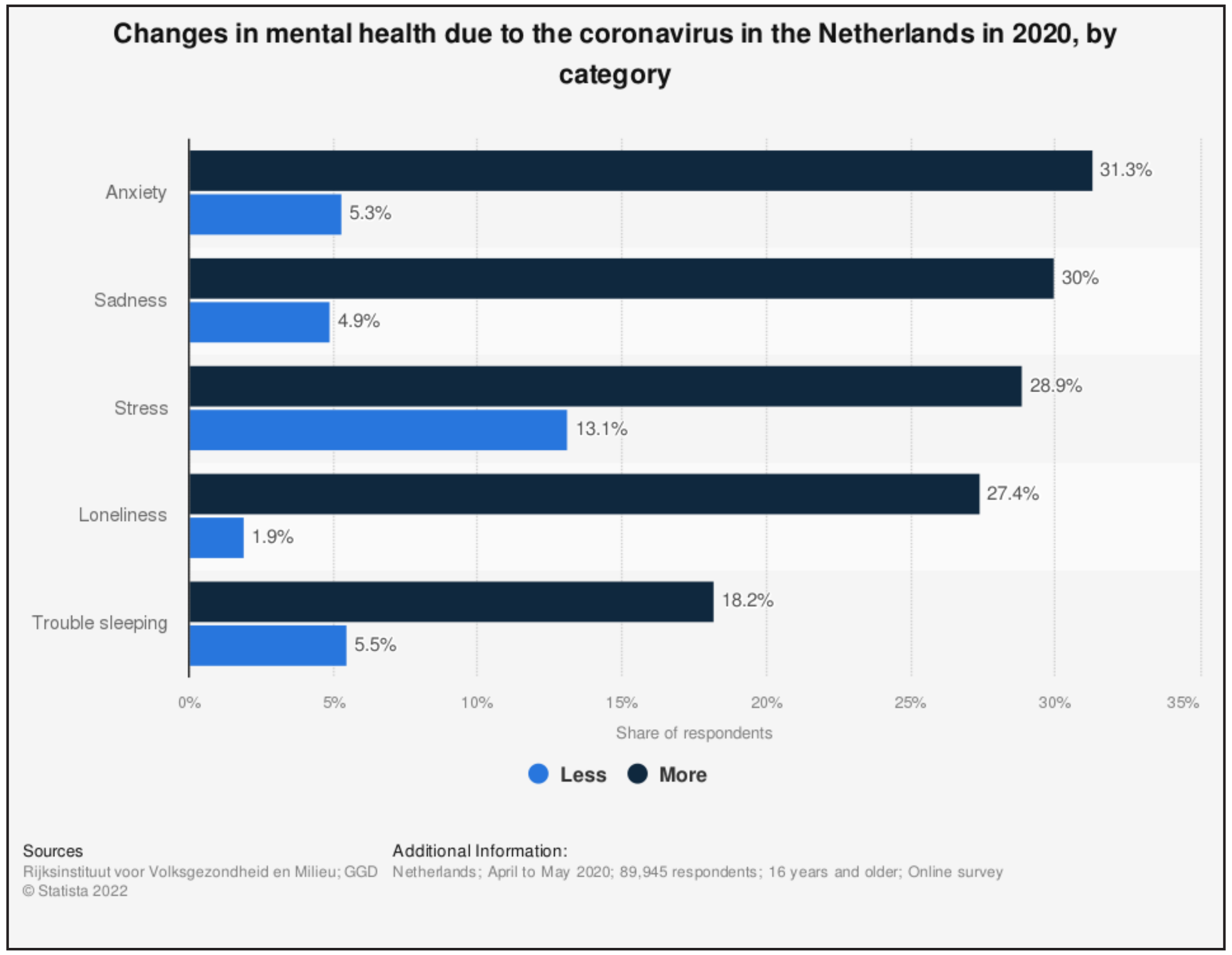
1.1 Project Context

According to an online survey conducted by the Dutch National Institute for Public Health and the Environment in April and May of 2020, approximately 30% of the 89,945 respondents 16 years and older have indicated that they experienced increased anxiety during the COVID-19 pandemic (Figure 1.1). Although the pandemic may have exacerbated anxiety among the Dutch population, it is undeniable that mental health has been a global point of concern globally long before COVID. Even though anxiety is a natural "fight-or-flight" phenomena that everyone experiences to varying degrees (Haynes et al., 2022), many individuals often do not wish to be identified as struggling with mental health due to the associated negative social stigma (Shrivastava et al., 2012).

It is believed that being in an anxious state for prolonged periods of time is one of the possible factors that could lead to clinical anxiety disorders (Rosen & Schulkin, 1998); therefore, anyone can benefit from having additional help with anxiety modulation through the use of products. To help reduce anxiety, some individuals utilize deep touch pressure (DTP) in the form of weighted blankets or compression vests (Duvall et al., 2016). DTP is a form of tactile sensory input that is provided by holding, stroking, hugging and squeezing, which has been increasingly utilized in "acute mental healthcare settings for crisis intervention, preparatory purposes… as it gives subjects the feelings of safety, relaxation, and comfort" (Chen et al., 2013).

Many of the current commercially available wearable DTP garments are in the form of weighted or inflatable compression vests. Weighted or non-adjustable compression vests must be periodically taken off as the user can acclimate to the pressure and experience reduced effectiveness of DTP (Duvall et al., 2016). Because of the bulkiness or the need for manual operation, commercial wearable DTP garments are difficult to conceal which can attract unwanted attention from nearby strangers. Since the main users of such products are people who struggle with anxiety, getting unwanted attention can further aggravate anxiousness due to potential negative scrutiny from others (Schneier & Goldmark, 2015). Conversely, there are various research projects utilizing shape memory alloys (SMA) to address the aforementioned downsides of existing wearable DTP garments because SMA actuators can be noiseless, lightweight, and low profile for discretion. However, these research tend to stop at the technological exploration level rather than being fully integrated into an actual product.

The goal of this graduation project is to develop a wearable garment that helps reduce daily anxiety levels and elicit a sense of calmness in a non-clinical setting. By utilizing SMA actuators, the final prototype should be able to create warmth and pressure sensations typically associated with DTP while remaining discreet and comfortable for daily use. To design a successful prototype, it is crucial to delve into diverse research areas and topics, including haptic technology, affect regulation, and wearable devices (Figure 1.2).



Sources
Rijksinstituut voor Volksgezondheid en Milieu; GGD
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Additional Information:
Netherlands; April to May 2020; 89,945 respondents; 16 years and older; Online survey

FIGURE 1.1 : CHANGES IN MENTAL HEALTH DUE TO THE COVID-19 PANDEMIC IN THE NETHERLANDS 2020, BY CATEGORY; (STEWART, 2021)

1.2 Research Approach

A. Research Questions

The graduation project revolves around two primary themes: user experience and technology. Based on the two themes, the following questions were used as a roadmap for the overall research trajectory:

USER EXPERIENCE THEMED QUESTIONS:

RQ 1.1 - What kinds of DTP or related tactile sensations are useful for decreasing anxiety at what intensity, frequency, and locations?

RQ 1.2 - What kinds of wearable forms, such as belt/strap, vest, and bracelet, are best suited for discretion and comfort?

TECHNOLOGY THEMED QUESTIONS:

RQ 2.1 - What leads to the technological disjunction between research and commercially available wearable DTP products?

RQ 2.2 - Which SMA configurations can create the DTP or related tactile sensations useful for anxiety modulation and best suited for wearables?

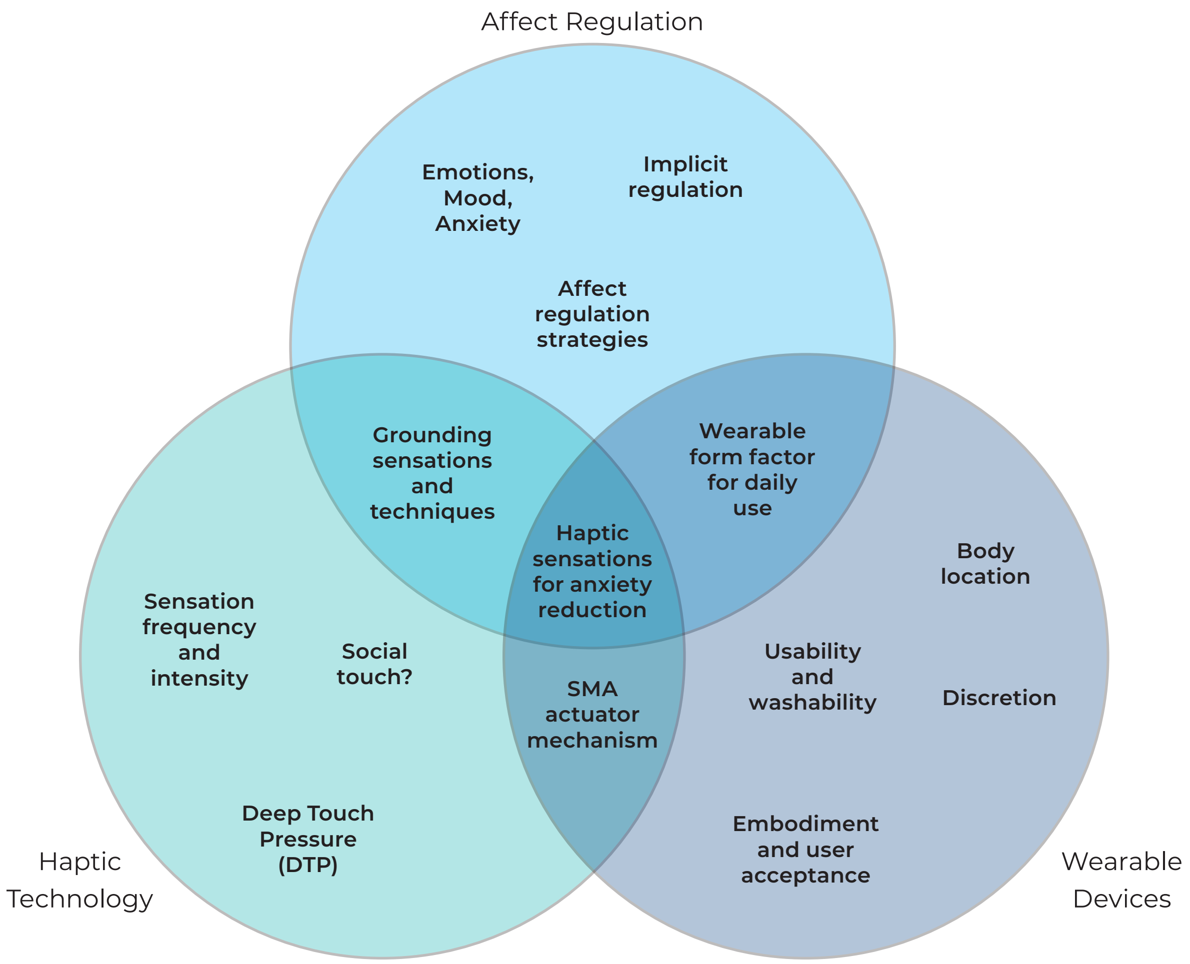


Figure 1.2: Research questions in different areas of interest

B. Autobiographical Design, Rapid Prototyping, Iterative Process

Since mental health is often a stigmatized and sensitive topic, it is difficult to work with user study participants in the timeframe and context of a master thesis. Especially with ethical concerns about increasing participant's awareness of their anxious state, gathering meaningful insights about potential users through interviews and experience sample methods becomes a delicate endeavor. Rather than looking outward for observations, I decided to look inward to gain a deeper understanding of the intricate nuances involved in anxiety modulation through the use of autobiographical design.

In Human-computer interaction (HCI) research, using oneself as a source of insight has been regarded as a questionable approach for a long time. However, as "research foci moved from public/work spheres to private spheres of life", there has been an increasing emphasis on first-person research perspectives since intimate situations, like wearable technologies, where long-term investigation became necessary (Desjardins & Ball, 2018). At its core, autobiographical design requires self-reflection and introspection to investigate subjective or lived experiences for insight and knowledge generation (Xue & Desmet, 2019). Even if the insights are gathered from personal introspection, they can still yield universally applicable outcomes that resonate with a broader range of users who experience similar or related difficulties.

Similar to how researchers test their own systems before involving participants or other end users (Neustaedter & Sengers, 2012), autobiographical design allows for rapid prototyping and iterative design as it "empowers designers to respond quickly to aspects of the system which are ineffective or undesirable" (Desjardins & Ball, 2018). Iterative design and rapid prototyping play pivotal roles in design research due to their inherent value in refining and improving designs. Merging autobiographical and iterative design approaches allows design researchers to continuously and rapidly evaluate and modify their prototypes rather than relying solely on user tests for feedback which can be time-consuming to conduct. This accelerated self-driven feedback loop promotes early identification of design flaws, enabling timely adjustments and enhancements. The resulting prototypes can still be used for broader user tests to gather additional input and to counterbalance the self-focused aspects of the autobiographical approach (Neustaedter & Sengers, 2012).

I proposed this project to my supervisors motivated from my personal struggles and need for additional help with anxiety modulation. As there is a genuine need for the design project, it lends well to the use of an autobiographical design approach (Desjardins & Ball, 2018). This approach enables the exploration of both positive and negative personal coping mechanisms from an emotional perspective and within a socio-cultural setting that may not always be openly discussed (Lucero, 2018). By designing a wearable device through autobiographical design, this project endeavors to offer a universally relatable and effective tool for anxiety modulation, rooted in genuine empathy and firsthand understanding.

2. THEORETICAL BACKGROUND

2.1 Understanding Emotions, Mood, and Anxiety

A. Emotions vs. Mood

To design a wearable device or smart garments for anxiety modulation, it is crucial to have a comprehensive understanding of emotions and moods, as well as how they are regulated. Often the terminology “emotion” and “mood” are used interchangeably in colloquial language as they are used to express one’s mental state. At a fundamental level, both emotion and mood are used to describe what is commonly considered “feelings”, which are a combination of valence (pleasantness - unpleasantness; representing good/bad) and physiological arousal (activated - deactivated; representing energy levels) (Desmet, 2015). Russell’s two-dimensional “core-affect” model (Figure 2.1) visually portrays the blend of valence and arousal present in the simplest and primitive raw feelings of one’s conscious experience (2003). For example, cheerful mood is a blend of activation and pleasant affect state, whereas shameful emotion is a blend of deactivation and unpleasant affect state. Even though both emotion and mood share this fundamental core-affect, they are two different phenomena that differ in terms of cause and experiential/behavior manifestations (Desmet et al., 2016).

Mood represents the general state of mind that broadly influences one’s perceptions, judgments, and behavior towards their surroundings. Depending on the mood, our behaviors are subtly influenced, especially in the form of our “readiness for action” (Desmet et al., 2016). Moods can last from hours to several weeks and are induced through a cumulation of causes rather than a specific cause or event, such as combination of the weather, sleep quality, or series of recent events (Desmet, 2015).

Unlike moods that represent our general ongoing internal state, emotions are specific and intense feelings targeted towards our external environment. Emotions typically last for a brief period, ranging from a few seconds to a few hours at most, and are induced by an explicit cause, such as a particular event, person, or situation (Desmet et al., 2016). When an event or a cause is considered to be relevant as either favorable or harmful to one’s concern, emotions are elicited as a way to monitor and safeguard one’s well being (Frijda & Mesquita, 1994). Because emotions are evoked by threats or opportunities, they compel us to either mitigate the threat or take advantage of the opportunity through “emotion-specific action tendencies (e.g., to withdraw, attack, approach, examine, etc.)” (Desmet, 2015). Due to its interrelated nature between oneself and the external environment (Frijda & Mesquita, 1994), emotions dictate our decision making functions and impact how we navigate social interactions (Amstadter, 2008).

Although “mood” and “emotion” are used to describe two different phenomena relating to our core-affect feelings, they are still interlinked with each other; an aggregation of emotions can result in a particular mood, whereas being in a certain mood can lower the threshold for prompting different types of emotions (Desmet et al., 2016). Because of their interconnections, researchers often merge emotion and mood regulations under the overarching term of “affect regulation” (Parkinson & Totterdell, 1999).

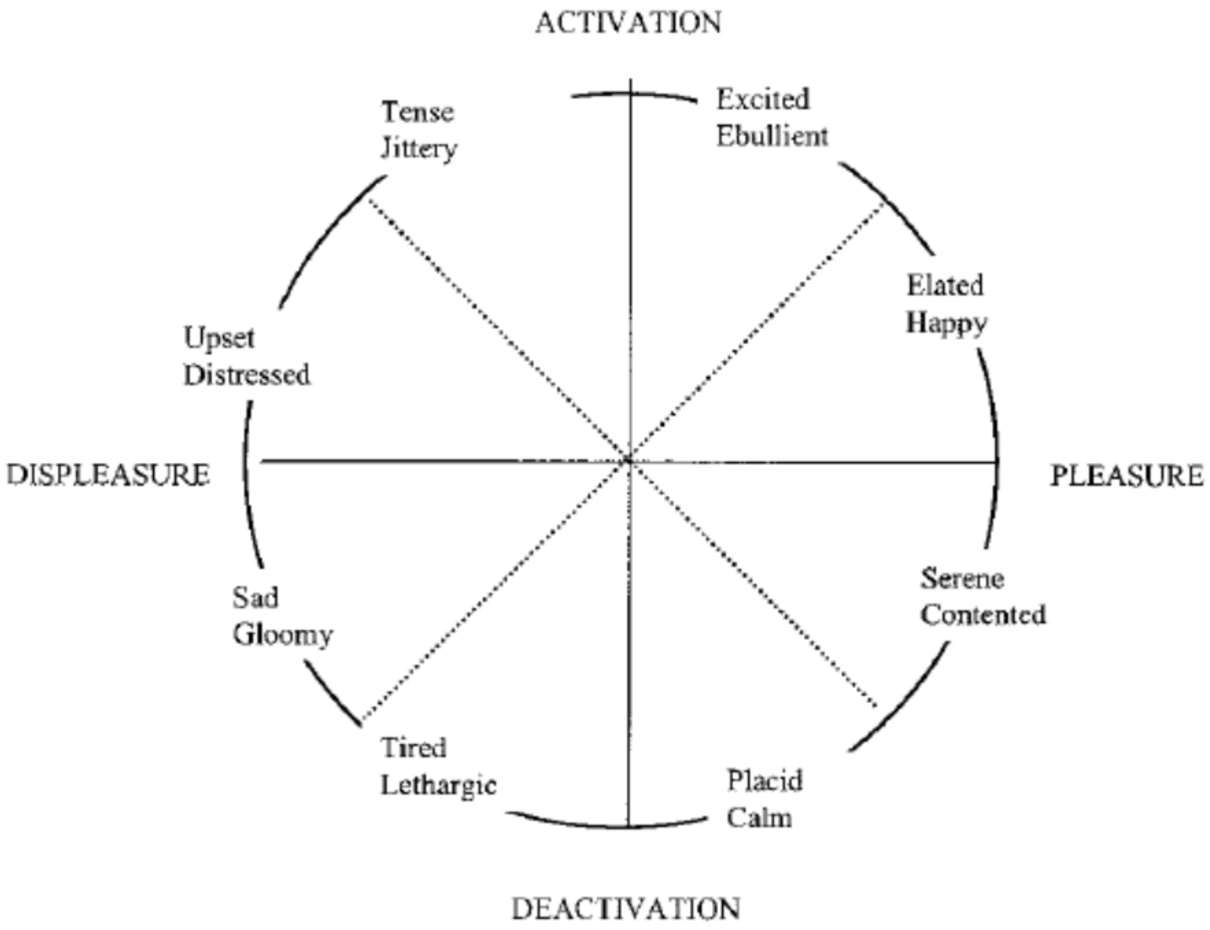


Figure 2.1: Core affect, a two-dimensional representation of “feelings”, with valence (perceived pleasantness or unpleasantness) and arousal (deactivation or activation); (Russell, 2003)

B. Anxiety: Normal Phenomena vs. Clinical Disorder

Anxiety is a natural “fight-or-flight” response that everyone experiences to perceived stress or threat (Haynes et al., 2022). According to Rosen & Schulkin, anxiety is driven by the emotion of fear that evolved as part of a self-preservative method in times of danger and serves as a motivating factor to relieve the negative emotional state (1998). Depending on the intensity at which someone experiences anxiety, it can be helpful or detrimental to one’s health. For instance, someone who lacks healthy amounts of anxiety exhibits socially unacceptable or reckless behaviors that could lead to social exclusion or dangerous situations like falling off a cliff (Marks & Nesse, 1994). On the other hand, someone who has too much anxiety could have a disproportionate reaction to the anxiety inducing situation or cause to the point of impairment. For instance, people suffering from public-speaking phobias will have “severe and debilitating autonomic, cognitive, and somatic reactions” towards even the thought of giving a public presentation and do everything they can to avoid speaking even if it is detrimental to their career and self-esteem (Rosen & Schulkin, 1998).

Although anxiety is a natural response, it can be considered an anxiety disorder that influences our physical and mental health if the response is excessive compared to the stimulus (Haynes et al., 2022). There are various subtypes of anxiety disorders depending on the type of triggering stimuli, which include but not limited to social anxiety disorder (SAD), cue-specific phobias, post-traumatic stress disorder (PTSD) or generalized anxiety disorder (GAD) (Marks & Nesse, 1994; Schneier & Goldmark, 2015; Rosen & Schulkin, 1998; Amstadter, 2008). However, the overarching primary characteristics of clinical anxiety disorders are associated with severe chronic hypervigilance, biased to real or hypothetical threats (Amstadter, 2008) and the feeling of loss of control, to the point of disruption with one's ability to function or concentrate on normal daily tasks (Rosen & Schulkin, 1998).

There are various factors that could cause the development of anxiety disorders, such as genetics, environmental risk factors, and exposure to single or repetitive traumatic experiences (Marks & Nesse, 1994). When an individual repeatedly experiences intense fear emotions over an extended period, anxiety transitions into a mood state characterized by a "hyperexcitable fear circuit" that is easily triggered and takes time to return to its normal baseline (Rosen & Schulkin, 1998). Approximately one third of the global population experiences some form of anxiety disorder during their lifetime (Haynes et al., 2022). However, there is also a common postulation that anxiety disorders are under-diagnosed (Zsido et al., 2020) as pathological anxiety can encompass other emotions like guilt, anger, or shame (Rosen & Schulkin, 1998). Even accounting cultural differences, mental illnesses are globally stigmatized due to lack of awareness, perception and education on the behavioral symptoms and complicated nature of mental illnesses (Shrivastava et al., 2012).

Unfortunately, the predominant treatment methods for anxiety disorders, such as psychological therapies and pharmacological treatments, tend to be costly, time consuming, and can result in significant undesirable side effects in the case of pharmaceuticals. Therefore, "developing safe, effective and affordable non-pharmacological methods that reduce anxiety is an important area of research" as nonclinical people can also suffer from periods of heightened anxiety state (Haynes et al., 2022). Even if this project is geared towards modulating daily levels of anxiety at a nonclinical level, encouraging the use of proper emotion regulation strategies could be helpful for both clinical and nonclinical individuals.

C. Detecting Anxiety Levels

Since anxiety is a natural response that everyone experiences, then how do we know if one's anxiety response is too much and requires modulation? In theory, it would be ideal to have a wearable device that could detect the user's anxiety levels and either alert the user or automatically initiate the anxiety reducing process. However, objectively assessing an individual's anxiety levels is challenging due to the varying experiential, behavioral, and physiological responses that individuals exhibit not only towards anxiety but also towards emotions in general (Amstadter, 2008).

POSSIBLE METHODS OF MEASURING ANXIETY LEVELS

Some "affective wearable" devices with integrated sensors try to measure physiological activities like respiratory rate, skin conductance, temperature, heart rate, and muscle activity to monitor the user's emotional state (Desmet et al., 2016). Although there are physiological responses that are commonly associated with anxiety, such as "changes in heart rate, blood pressure, respiration, and increased startle and attentiveness", having these physiological responses doesn't necessarily indicate that someone is experiencing anxiety (Rosen & Schulkin, 1998). For example, when someone goes through vigorous exercise, their heart rate, blood pressure and respiration increases from increased physical activity, but it would be inaccurate to say that they are experiencing high levels of anxiety. Since physiological responses alone cannot be used to measure distinct mood or emotion type, multimodal assessment is necessary to consider both the physiological signals associated with certain emotions and self-reported questionnaires that adds situational context (Amstadter, 2008).

The State-Trait Anxiety Inventory (STAI) is one of the commonly utilized questionnaires in research for measuring non-disorder-specific anxiety. Developed by Spielberger in the 1970s, the STAI questionnaire is a self-reported assessment tool to evaluate the participant's anxious state (A-State) and trait anxiety (A-Trait) (Zsido et al., 2020). A-State represents the participant's current emotion state influenced by situational stressors, whereas A-Trait represents their potentially anxiety-prone personality traits (Spielberger et al., 1971). There are numerous questionnaires similar to Spielberger's STAI to measure participants' emotions or anxiety levels, but these questionnaires can be time-consuming (Zsido et al., 2020) and disruptive to user's daily activities (Scollon et al., 2003). Whether through physiological responses or self-reported questionnaires, there are ethical concerns with repetitively tracking anxiety levels through products due to personal data privacy issues and unintentional exacerbation of anxiety.

ETHICAL CONCERNS WITH TRACKING ANXIETY LEVELS

Detecting and tracking anxiety levels through a wearable device can pose personal privacy concerns. Data gathered to detect and track anxiety levels are considered private health information that can be used by stalkers and others with malicious intent as a way to track the user's general location and routine activities (Dunne, 2010). Because data gathered from a wearable device are often wirelessly transmitted to a smartphone or cloud storage for data processing and back-up, they must have security measures to minimize risks involving wireless data access. Unfortunately, implementation of advanced security measures on consumer products are severely limited due to resource constraints such as "limited battery, CPU, memory, and device form factor" (Seneviratne et al., 2017). Even if there is no evidence of malicious intent, companies continue to launch new wearable devices with poor data security despite ongoing potential privacy concerns from consumers and researchers (Saponas et al., 2006).

Additionally, repeated assessments through self-reported questionnaires may increase the participants' attention to their own behavior and internal states. Especially in the case of anxiety, increased hyper attention to their anxious state may "trigger cognitions or ruminations that may lead to greater anxiety and worry" for the users (Scollon et al., 2003). For both healthy and clinical populations, there have been studies indicating that increased self-awareness is positively correlated to anxiety levels since individuals who are anxiety prone tend to have higher introspective awareness (Costa et al., 2016) and difficulty controlling their self-consciousness (Nezlek, 2002). Additionally, providing false representation of the user's physiological responses can influence the user's perception of their emotional state (Costa et al., 2016). For instance, if a wearable device automatically suggests that the user may be experiencing higher levels of anxiety based on physiological responses alone, this inaccurate feedback may influence the user to believe that they are in an elevated anxious state. Hence, integrating questionnaires assessing the user's anxiety levels or providing potentially inaccurate feedback through a daily-use product may have an unintended consequence of exacerbating anxiety.

2.2 Emotion Regulation and DTP

A. Process Model of Emotion Regulation

Emotions are vital as various functions, such as social and communicative functions or decision making functions. While emotions can be useful in many ways, uncontrolled or maladaptive emotions can negatively impact people's daily lives (Amstadter, 2008). Emotion regulation refers to the process that individuals use to influence when and what kind of emotions they have, as well as how they perceive and express those emotions. Because emotions are complex, multi-componential processes that evolve over time, emotion regulatory processes can be done consciously or unconsciously during one or more of the points when emotions are generated (Gross, 1998). It is important to note that everyone uses some form of emotion regulation to varying degrees in their everyday life to interact with the world around them as part of the socialization process (Amstadter, 2008).

The Process Model of Emotion Regulation defined by Gross has five different phases at which emotions can be regulated: situation selection, situation modification, attention deployment, cognitive change and response modulation (1998). As shown in figure 2.2, situation selection, situation modification, attention deployment and cognitive change are considered "antecedent-focused emotion regulation" that happens before the emotion is generated. On the other hand, response modulation is considered "response-focused emotion regulation" that happens after the emotion is generated (Gross, 1998).

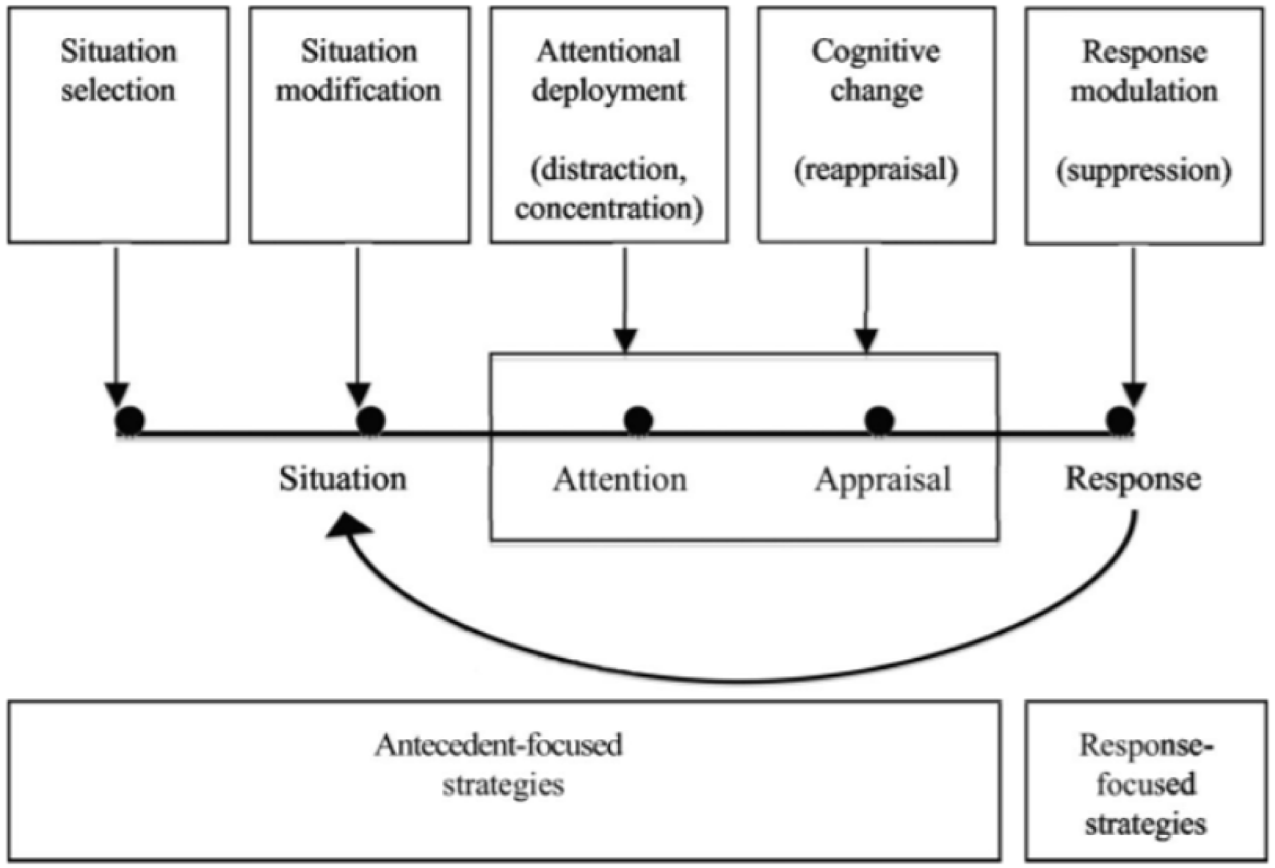


Figure 2.2: A process model of emotion regulation (Gross & Thompson, 2007)

Situation selection involves actively avoiding or seeking out certain situations to experience desirable emotions (Gross, 1998). After the situation selection, one can modify the external, physical environments of the situation itself to alter its emotional impact, referred to as the *situation modification* phase. Because modifying a given situation can effectively bring about a new situation, situation modification and situation selection phases could be difficult to discern (Gross, 2015). However, even after the situation has been selected and modified, there are times when undesirable situational outcomes arise. The next phase of emotion regulation, called *attention deployment*, can be used to direct one's attention "within a given situation in order to influence one's emotions" (Gross, 2015). Distraction is one of the most common forms of attention deployment, redirecting the concentration to different aspects of the situation (Costa et al., 2016) or changing internal focus to different thoughts or memories that can help bring out the preferred emotional state (Gross, 2015).

On the other hand, *cognitive change* refers to selecting what kind of meanings to attach to the situation (Gross, 1998) or modifying the way one thinks about the situation (Costa et al., 2016). Cognitive change can be applied to an external situation by trying to look for the silver lining, such as considering a failed interview as an opportunity to improve interviewing skills. It can also be applied to an internal situation by reframing the mindset, such as interpreting anxiety-related physiological responses as getting "pumped up" for enhanced performance (Gross, 2015). Even though cognitive change is considered part of the antecedent-focused strategies that happens before the emotion is generated, the most commonly studied example of cognitive change is reappraisal, or reinterpreting the meaning of the situation, that usually happens well after the emotion evoking situation is over in the form of Cognitive Behavioral Therapy (CBT) (Costa et al., 2016). CBT is a psychotherapeutic method with a goal of cognitive restructuring that challenges one's maladaptive thought patterns and helps develop healthier coping thoughts (Schneier & Goldmark, 2015).

Lastly, *response modulation* is the final phase of the Process Model of Emotion Regulation, which occurs after the emotion is generated. Response modulation methods are used to directly influence the experiential, behavioral, or physiological components of the response tendencies to the generated emotion (Gross, 1998). One common example of response modulation is expressive suppression, which involves suppressing or inhibiting behaviors or actions that express the felt emotions (Gross, 2015).

B. Emotion Regulation Technology

There are various technologies, products, or services for emotion regulation that can be used during the different phases of the Process Model of Emotion Regulation. Emotion regulation technologies are real-time interventions designed to help users manage their ongoing emotions as opposed to mood regulation technologies that can help improve user's overall affective state (Costa et al., 2016). Example technologies for different phases of the emotion regulation are as follows:

Situation selection/modification phase: Grippy, a combination of wearable gloves and a mobile app (Figure 2.3), for veterans with PTSD that tracks the user's stress level, location and time to help identify and overcome possible environmental or situational triggers (Li, 2022).

Figure 2.3: Final prototype of Grippy, including glove and strap shaped wearable and a mobile app. (Li, 2022)

Attentional deployment phase: One of the most common self-help techniques advocated by psychologists is sensory grounding technique (Shukla, 2020). Sensory grounding techniques involve redirecting one's focus from uncontrolled, spiraling negative thoughts to immediate physical and sensory experiences to help "ground" someone in the moment. For example, the 5 grounding technique involves visually looking at 5 things around you, physically touching 4 things, listening to 3 different sounds around you, identifying 2 unique smells, and lastly focusing on the taste of 1 thing such as eating food or brushing teeth (Shukla, 2020). ECHO;sweater is an example of an interactive clothing that can help ground the wearer with scented fabric and heated pocket (Hendriksma et al., 2020).

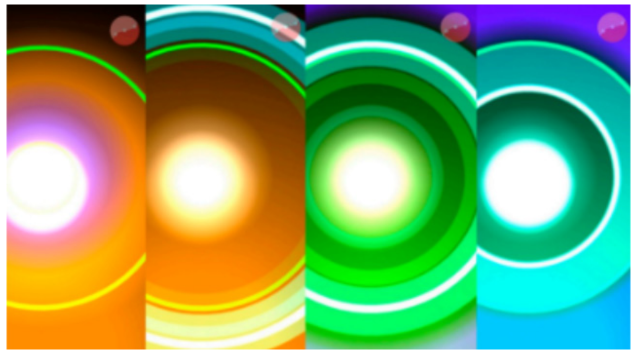


Figure 2.4: BrightHearts visualizations of the user's change in heart rate. (Höök et al., 2018)

Cognitive change phase: Sanvello mobile app allows users to keep a CBT journal for asynchronous mental health coach sessions (Sanvello, 2022) to reappraise or reevaluate the emotional situation and alter the way the user thinks or feels (Costa et al., 2016). Due to the nature of CBT techniques, it is ambiguous if technologies utilizing CBT techniques are indeed considered real-time interventions.

Response modulation phase: Technologies that support response modulation phase can truly be considered real-time interventions, especially the technologies that utilize biofeedback. By raising the user's self-awareness on involuntary physiological functions, such as heart rate or breathing rate, these technologies help the user to have better control over their responses to distressing situations (Costa et al., 2016). For example, BrightHearts mobile app (Fig. 2.4) externalizes the user's change in heart rate by displaying mesmerizing symbolic colorful animations and gentle chime sounds to help guide relaxation (Höök et al., 2018). Whereas EmotionCheck wristband (Costa et al., 2016) and Affective Sleeve (Papadopoulou et al., 2019) detect the user's breathing or heart rate and provide a rhythmic tactile feedback that represents a slower breathing or heart rate. By subtly providing a false, slower breathing rate, EmotionCheck and Affective Sleeve influenced their users to control their breathing rate and promote calmness (Costa et al., 2016), (Papadopoulou et al., 2019).

Among the various technological interventions for emotion regulation, wearable technologies have the greatest possibility to provide real-time interventions through the use of implicit emotion regulation. Implicit emotion regulation refers to regulation methods that do not require the user's full attention or need for conscious supervision (Costa et al., 2016). Real-time interventions that require too much of the user's attention can become the stressor itself depending on the situation and the intervention methods (Paredes & Chan, 2011). Unlike mobile apps that often require users' full attention to look at and interact with their phone screens, wearables (Chapter 2.3-B) can be designed to subtly influence the user with tactile feedback by redirecting the user's mind away from negative thought patterns. Thus, wearables can be a solution that provides the right balance between the type of distractions and the amount of attention it requires from the user in order to be a successful real-time intervention technology for emotion regulation.

C. Wearable Anxiety Regulation with Deep Touch Pressure

Some anxiety regulation wearable technologies rely on Deep Touch Pressure (DTP) as the main method to help reduce anxiety. DTP is a form of affective touch provided by holding, stroking, hugging and squeezing sensations, which elicits the feelings of safety, relaxation, and comfort (Chen et al., 2013). On the other hand, Light Touch Pressure (LTP) is superficial stimulation on the skin, such as tickling and very light touch that moves the hair on the skin. Occupational therapists have observed that LTP alerts the nervous system, causing arousal or excitement, while DTP leads to relaxation and calm (Grandin, 1992). For individuals with high anxiety levels, DTP sensations can serve as a calming or focusing agent to help with anxiety modulation (Chen et al., 2013).

Compression or squeezing sensation is mainly used to help reduce anxiety and overstimulation for individuals with Autism Spectrum Disorder (ASD) or Attention Deficit Hyperactivity Disorder (ADHD) in the form of weighted blankets or compression vests (Duvall et al., 2016). However, the anxiety reduction benefits of hug-like sensations are also evident in people without ASD or ADHD and even other animals (Grandin, 1992). Inspired by a cattle squeezing chute that was used for calming down cattles waiting to be seen by a veterinarian, Grandin developed a "Squeeze Machine" for humans that applies deep pressure to the full body (Fig. 2.5). Grandin's squeeze machine can be seen as the precursor to the many hug-like compression products (Figure 2.6) and wearable devices as technological advances allowed for compact, portable actuators that can create the necessary deep compression sensation.

Along with hug-like compression, stroking is another key DTP tactile sensation that elicits the feeling of calmness. Typically used to comfort a loved one, slow, gentle stroking touch is known to activate C-tactile sensory afferents, or CT afferents. CT afferents are nerve receptors in hairy skin that transmit affective touch information to the brain and induce pleasant sensations (Case et al., 2021). These afferents are most responsive to light pressured stroking sensations conducted at skin temperature and at the speed of 1-10 cm/s (Bendas et al., 2021), with the optimal speed being around 3 cm/s (Case et al., 2021). Although perceiving pleasantness of affective touch, like DTP sensations, through CT afferents is considered a natural innate conduct that doesn't require a learning process, it can be influenced by cognitive factors, such as the context and emotional correlation with the person administering the touch (Huisman, 2017). This led to the "social touch hypothesis" which states that CT afferents are attuned to social interactions by working with other mechanoreceptors to determine if the touch stimulus has social relevance (Haynes et al., 2022; Huisman, 2017). However, it is still largely inconclusive if touch emulating technologies require a social component for it to have stress reducing effects (Appendix A).

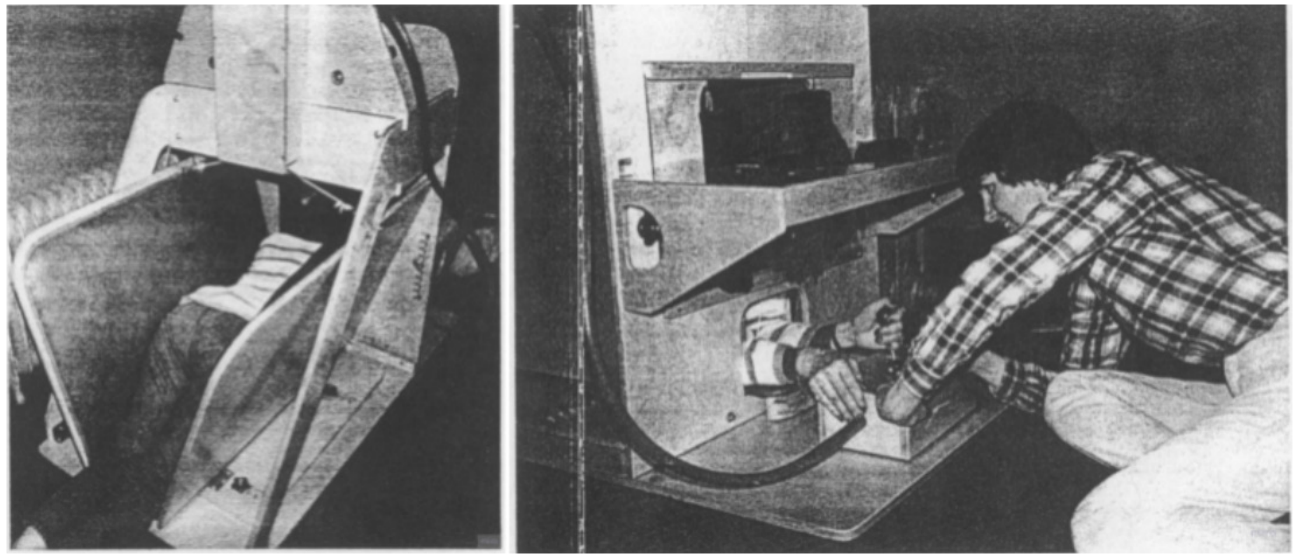


FIGURE 2.5: REAR AND FRONT VIEWS OF THE SQUEEZE MACHINE. (GRANDIN, 1992)

FIGURE 2.6: OTO THE HUGGING CHAIR DIRECTLY INSPIRED BY GRANDIN'S SQUEEZE MACHINE (AUDRAIN, 2023)

2.3 Wearable Product & Research Benchmarking

In addition to the physiological and psychological benefits for our well-being, touch is one of the natural human senses that generally doesn't require language or comprehension skills to experience its effects (Haynes et al., 2022). As such, the use of DTP or touch-like tactile sensations to elicit certain emotions from users has been explored in both commercial and research contexts.

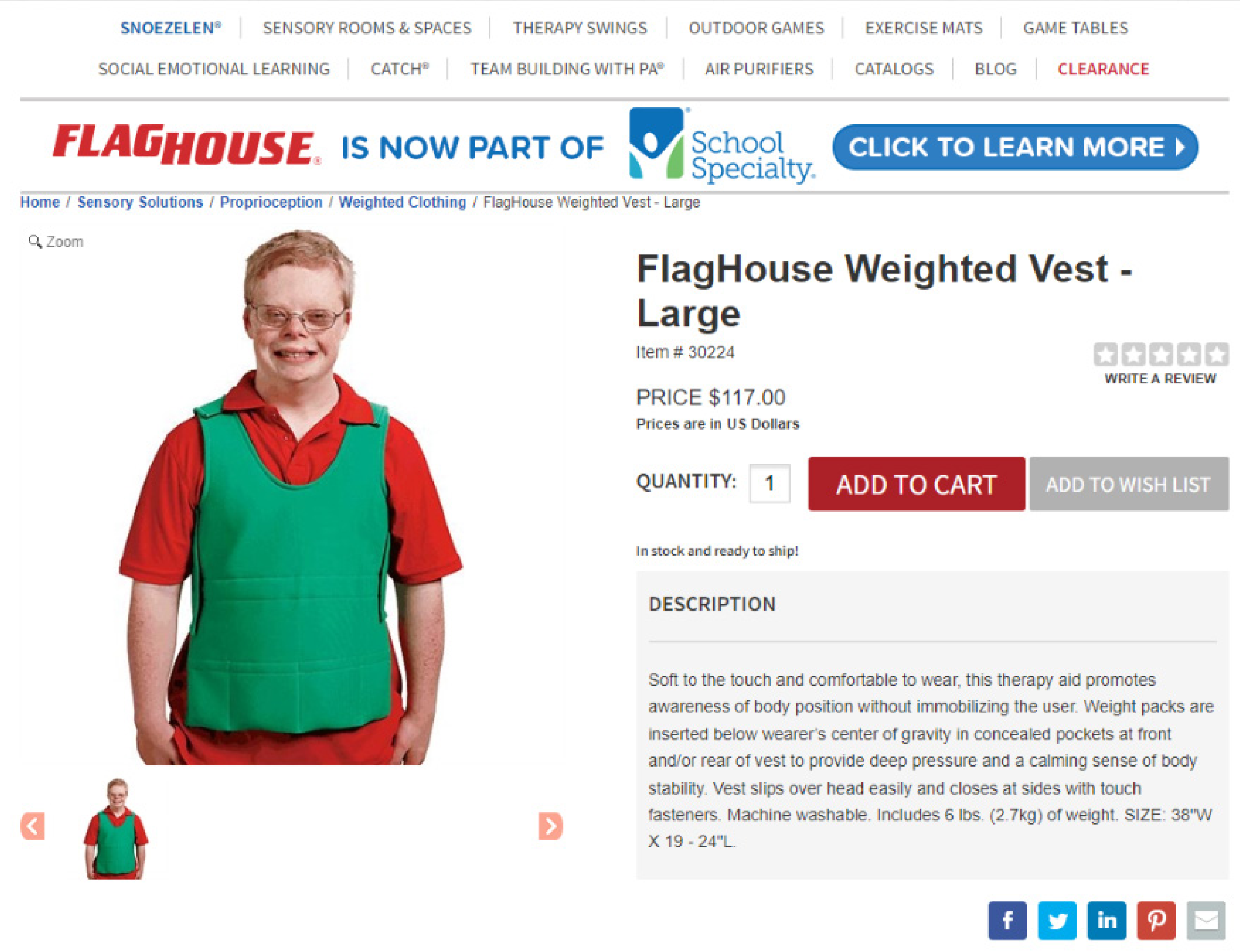
A. Commercial DTP Wearable Products

One of the most commonly available forms of DTP products is the weighted blanket, which is often used for anxiety modulation and to improve sleep quality (Chen et al., 2013). Weighted blankets are popularized enough that they are sold by major global store brands like IKEA. However, when it comes to wearable versions of DTP products, there are noticeably less commercial options available that are especially marketed for mental health. There are plenty of weighted vests advertised as sports equipment and compression garments for achieving certain body shapes. But DTP wearable products for anxiety modulation are often limited to niche online suppliers catering towards autistic "special needs children" who struggle with sensory overload (Figure 2.7). This type of niche marketing or pathologizing representation (Van Den Bosch et al., 2019; Tisoncik, 2020) can influence potential customers from associating DTP wearable products as medically necessary tools rather than everyday products, like the weighted blanket, that can be beneficial for anyone struggling with anxiety. Besides the patronizing marketing methods, commercially available DTP wearables for anxiety modulation often have critical design flaws that can either discourage their use or be counter productive to their intended use case.

Typically, commercial DTP wearables utilize two different mechanisms to create the squeezing pressure sensation: added weights (Figure 2.8- A) or hand-pumped inflatables (Figure 2.8- B). Unsurprisingly, weighted DTP wearables are often heavy, stiff and bulky due to the added weights. Users of weighted DTP wearables would have to don and doff the garment after a maximum of 10-15 minutes use since they can become habituated to the pressure with lessened positive DTP effects or lead to physical discomfort (Grandin, 1992). Wearing a heavy garment all day and having to don/doff the said garment every couple minutes to feel its effects would be physically demanding for the user as well as drawing unwanted attention in public.

As for commercial inflatable DTP wearables, they utilize attached hand pumps to create the necessary pressure (Figure 2.8- B). Compared to their weighted counterparts, inflatable DTP vests are significantly lighter in weight and easier to adjust the pressure to prevent pressure habituation. However, manually inflatable vests can still draw unwanted attention in public due to the inevitable pumping noise and creaking sounds from airtight plastic-like fabric, as well as having to display unusual behaviors, such as searching for and using an attached hand pump.

Lastly, commercially available DTP wearables tend to overlook the importance of aesthetics in favor of functionality. Since clothes have a significant impact on the wearer's self-expressed identity as they influence "body image, perceived social status, and societal roles", consumers are less likely to use wearable garments if the aesthetics do not match their usual personal style (Dunne, 2010). HugShirt by CuteCircut (Figure 2.9) is one notable example of a commercial wearables that isn't targeted for "special needs children" and looks aesthetically closer to a regular garment.. However, the HugShirt website listing is unclear as to what kinds of hug-like tactile sensations can be provide as they do not specify the type actuators they are using nor the type of embedded sensors that "capture the strength, duration, and location of the touch" (CuteCircut, 2020). An earlier prototype version of the HugShirt was featured in an episode of The Gadget Show, in which the show hosts stated they felt some warmth and vibration (The Gadget Show, 2018), so it is safe to assume that the HugShirt was meant for social touch technology rather than trying to emulate the DTP sensations felt during a hug.



Home / Sensory Solutions / Proprioception / Weighted Clothing / FlagHouse Weighted Vest - Large

FlagHouse Weighted Vest - Large

Item # 30224

PRICE $117.00

Prices are in US Dollars

In stock and ready to ship!

DESCRIPTION

Soft to the touch and comfortable to wear, this therapy aid promotes awareness of body position without immobilizing the user. Weight packs are inserted below wearer's center of gravity in concealed pockets at front and/or rear of vest to provide deep pressure and a calming sense of body stability. Vest slips over head easily and closes at sides with touch fasteners. Machine washable. Includes 6 lbs. (2.7kg) of weight. SIZE: 38"W X 19 - 24"L.

Figure 2.7: Example screenshot of a niche online supplier for "special needs children"

Figure 2.8: Commercially available DTP wearables [A] Weighted vest; OTvest, [B] inflatable vest; Squeasewear

FIGURE 2.9: "HUGSHIRT" (CUTECIRCUT, 2020)

FIGURE 2.10: EXAMPLE USE FOR [TOP] "COOL ME DOWN" WRAP/BANDAGE (VAUCELLE ET AL., 2009) AND [BOTTOM] "TAPTAP" SCARF (BONANNI ET AL., 2006) [RIGHT]

FIGURE 2.11: EXAMPLE USE FOR "TOUCH ME" WRAP (VAUCELLE ET AL., 2009)

B. Wearables in Research for DTP or Emotion Regulation

Research projects that fall under broader categories, such as influencing emotions through tactile sensations and social touch technologies, were also surveyed for benchmarking purposes. During the selection process, many of the projects that used vibrotactile motors were omitted to include a wider variety of actuator mechanisms. In general, vibrotactile motors are used most often in research for emulating touch even though vibration does not stimulate CT afferents (Huisman, 2017). 18 different wearable research projects from published journals were gathered to compare the type of provided tactile sensations, actuator mechanisms, wearable form, as well as the intended purposes of the sensations and body location where the sensations are applied. The compiled information can be seen in Table 1.

BODY LOCATION

Majority of the 18 examined research prototypes focused on providing tactile sensations to the upper body, especially on the torso and wrist area. The three exceptions, "TapTap" scarf (Bonanni et al., 2006), "Touch Me" wrap and "Cool Me Down" wrap/bandage (Vaucelle et al., 2009), suggested that their prototypes can be used anywhere on the body since they were closer to a flat sheet of fabric that didn't have a specific form factor. However, the provided example use case photos for "Cool Me Down" and "TapTap" (Figure 2.10) implied that the intended use would mostly stay in the upper body area rather than the legs or lower body. Conversely, the "Touch Me" wrap showed an example use case of the prototype being placed on the participant's lap and legs (Figure 2.11) since it was developed as "a tool for patient and therapist to explore touch together and determine the kinds of touch that are soothing to the patient" (Vaucelle et al., 2009).

Even though compression and brushing sensation on the leg had evidence of calming effects (Case et al., 2021), the overwhelming attention to the upper body could be because the lower body is typically not associated with social touch. According to Suvilehto et al.'s survey (Figure 2.12), both male and female touch receivers considered the lower body areas an uncomfortable location for touch regardless of the touch giver's gender (denoted in blue and red labels for male and female respectively) and could even be considered as a taboo region (black areas with blue outlines) (2015). Although only 5 out of 18 projects had direct correlation to social touch, researchers may have shied away from developing lower body wearables that provide tactile sensations to avoid uncomfortable situations during user tests. For projects emulating a hug, providing DTP sensations to the upper body is sensible, since tactile sensations from hugs are generally expected to be on the upper body area (Chapter 3.2-A).

WEARABLE FORM TYPES

Except for experimental cases like Springlet stickers (Hamdan et al., 2019) or devices meant to be used as a supplemental addition to online computer chat systems like HaptiHug (Tsetserukou, 2010), the wearables examined for research benchmarking were designed to mimic existing regular garments or accessories, such as vests, shirts, and wrist watches. By imitating familiar shapes and designs of traditional clothing or accessories, wearable devices can reduce the likelihood of attracting unwarranted attention (Costa et al., 2016). Additionally, garment and accessory form factors provide the surface area and physical proximity necessary for sensors to detect physiological signals, body positions, and activities which are useful for developing user-centered technologies used in everyday life (Dunne, 2010).

However, one of the main downsides of embedding electronics into garments is that individual clothes change on a daily basis depending on the environment and social context. Clothes that are worn throughout the day, like shirts or jeans, need to be washed frequently and tend to have a shorter overall lifespan than outerwears that are worn sporadically (Dunne, 2010). For instance, the Active "Hugging" Vest project integrated SMA spring actuators into one of the irremovable fabric layers (Figure 2.13), resulting in a future recommendation to design a removable layer for washability (Duvall et al., 2016).

TABLE 1:

Purpose	Tactile Sensation Type	Actuator Mechanism	Body Location	Wearable Form Type	Project Name/ Author
Emotional Effect Exploration	Compression, Heat	SMA	Torso, Upper Arm	Vest, Arm band	Preliminary Study of... (Foo et al., 2018)
Emotional Effect Exploration	Compression, Heat	SMA	Torso, Upper Arm	Vest, Arm band	User Experiences of Garment-based... (Foo et al., 2019)
Breathing Regulation	Compression, Heat	SMA	Torso	Vest	Soft Robotic Compression Garment... (Foo et al., 2020)
DTP	Compression	SMA	Torso	Vest	Active "hugging" vest (Duvall et al., 2016)
DTP	Compression	Inflatable	Torso	Vest	Squeeze Me (Vaucelle et al., 2009)
Breathing Regulation	Compression	Inflatable	Torso	Vest	Exploring Awareness of Breathing (Jung et al., 2021)
Sensory Grounding	Compression, Controlled pain	Inflatable	Forearm	Bracelet	Hurt Me (Vaucelle et al., 2009)
Sensory Grounding	Heat	Peltier junctions	Entire Body	Wrap/ Bandage	Cool Me Down (Vaucelle et al., 2009)
Sensory Grounding	Heat, Scent	Unspecified heating element, Scented fabric	Hands	Sweater	ECHO;sweater (Hendriksma et al., 2020)
Anxiety Modulation	Compression, Heat	SMA	Forearm	Sleeve	Affective Sleeve (Papadopoulou et al., 2019)
Anxiety Modulation	Vibration	Vibrotactile motors	Wrist	Wrist "watch"	EmotionCheck (Costa et al., 2016)
Touch Therapy	Vibration, Brushing	Flexible Vibrotactile motors	Entire Body	Wrap/Blanket	Touch Me (Vaucelle et al., 2009)
Touch Therapy/ Social Touch	Vibration, tap/ press, stroke	Vibrotactile motors, Solenoids	Entire Body	Scarf	TapTap (Bonanni et al., 2006)
Human Touch Emulation	Tap, Drag, Twist, Compression/ Squeeze	Servo motor	Wrist	Wrist strap	Design of Body-Grounded... (Stanley & Kuchenbecker, 2011)
Social Touch/Hug Emulation	Compression	Motor	Torso	Harness	HaptiHug (Tsetserukou, 2010)
Social Touch/Hug Emulation	Compression	Inflatable	Upper Body	Jacket	Huggy Pajama (Teh et al., 2009)
Tactile Actuator Exploration	Pinch, Stretch, Press/Pull, Drag/ Stroke	SMA	Upper Body	Stickers	Springlets (Hamdan et al., 2019)
Tactile Actuator Exploration	Compression, Heat	SMA	Wrist, Finger	Ring, Wrist band	HapticClench (Gupta et al., 2017)

* SELECTION OF WEARABLES RESEARCH PROJECTS FOR BENCHMARKING

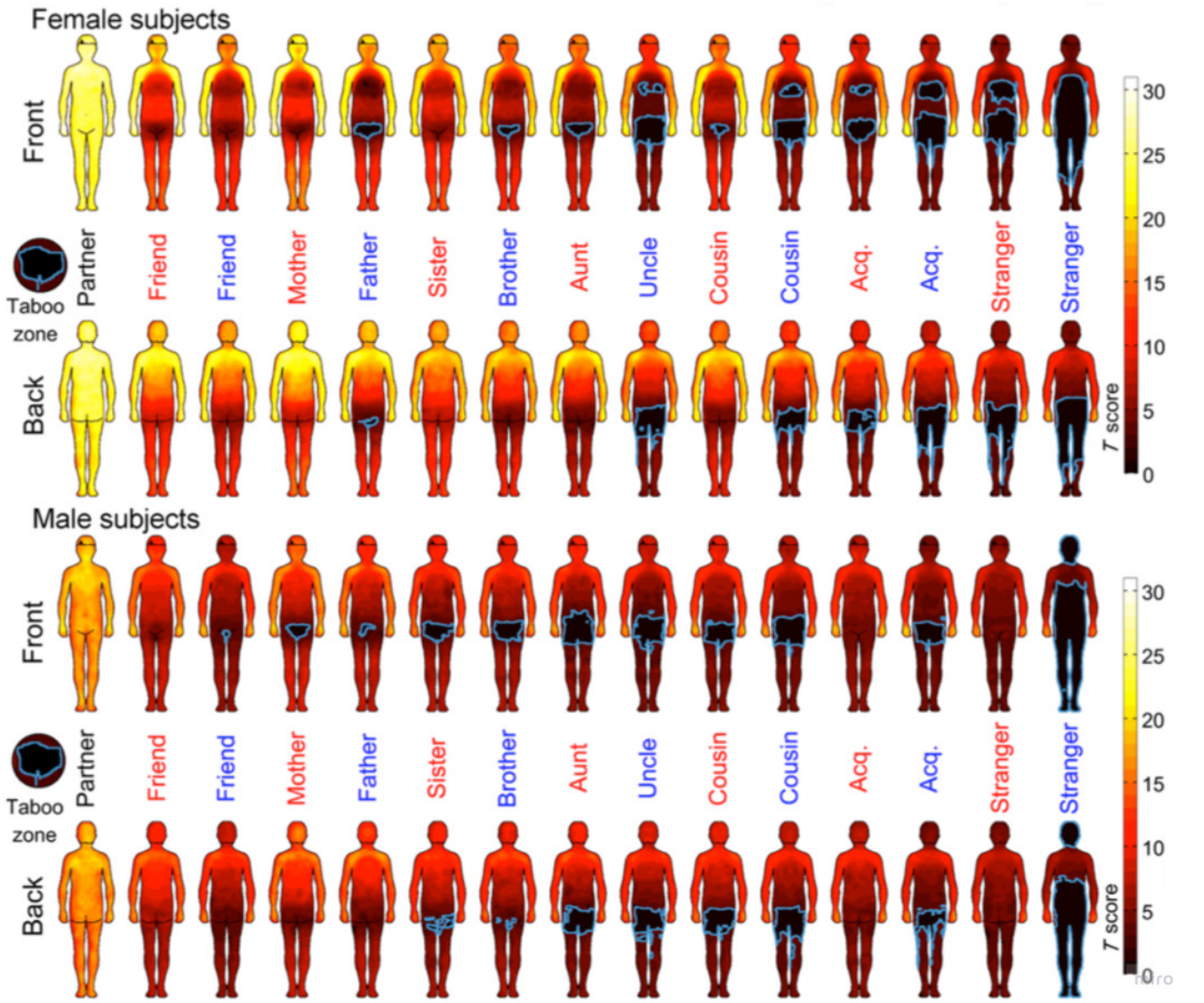


FIGURE 2.12 : RELATIONSHIP SPECIFIC TOUCH AREA MAPPING GATHERED THROUGH A SURVEY (SUVILEHTO ET AL., 2015)

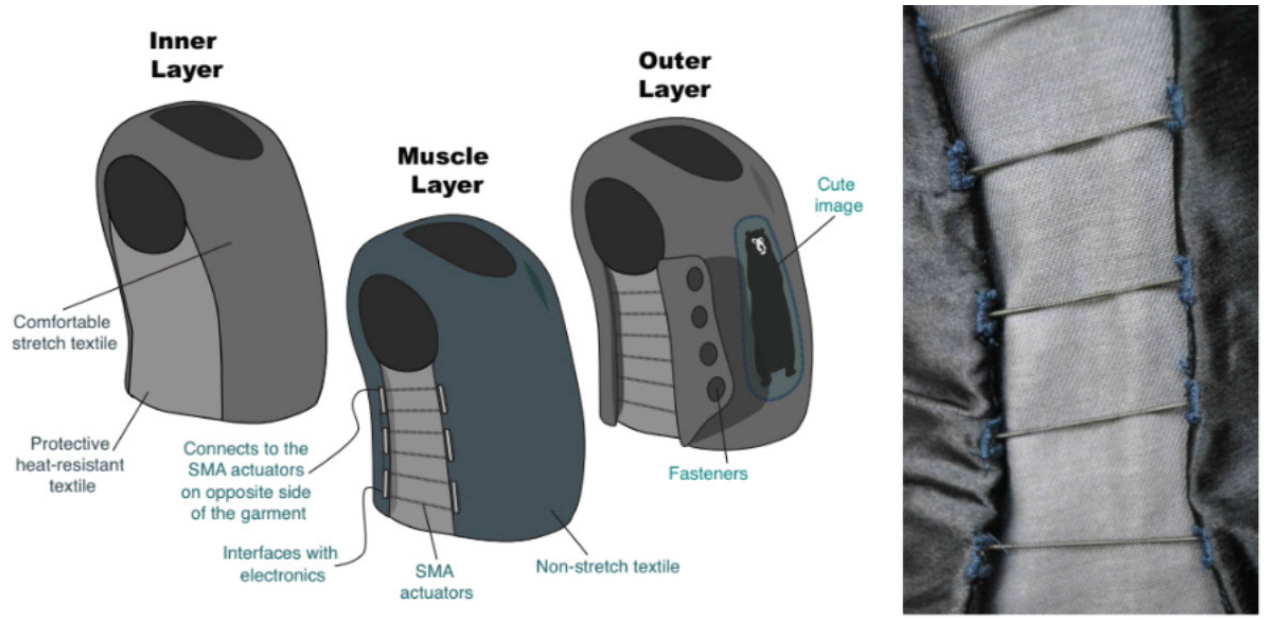


FIGURE 2.13 : ILLUSTRATION EXPLAINING THE CONSTRUCTION OF THE ACTIVE "HUGGING" VEST (DUVALL ET AL., 2016)

Moreover, the SMA based wearable garments have to fit well for the user while mostly made out of non-stretch fabric, since the compression profile and perceived pleasantness of the compression sensations varied depending on the garment sizing and fit (Foo et al., 2018). With the non-stretch fabric restriction, it becomes more difficult to create a well fitting garment that is also comfortable to wear (Chapter 2.5-B).

Conversely, wearable devices mimicking more sporadically worn garments, such as “Huggy Pajama” jacket (Teh et al., 2009) and “TapTap” scarf (Bonanni et al., 2006), do not require frequent washing compared to clothes worn throughout the day. But they tend to lose the ubiquitous presence that garments like T-shirts or vests have, since it is difficult to constantly wear a jacket or a scarf depending on the weather conditions, the social situations, and the user’s surrounding environment (Dunne, 2010).

Since accessories are easier to adjust the fitting, do not require frequent cleaning compared to garments, and can be worn daily for several days in a row, wearable devices in the form of accessories like wrist watches tend to have a better prospect of becoming commercialized as evidenced by the growing popularity of smart watches (Seneviratne et al., 2017). Unfortunately, wrist watches or other accessories are restricted in size, resulting in a smaller skin contact surface area. Applying compression sensations to a small surface area may not have the desired calming effect compared to applying compression to larger surface areas. For instance, participants disliked “hotspots” from compression vests and preferred uniformly distributed sensations (Foo et al., 2019). Additionally, some participants found the compression sensation from the armband (Figure 2.14) to be uncomfortable and akin to the pressure sensation felt when using a blood pressure cuff (Foo et al., 2018; 2019). This eventually led to Foo et al. abandoning the arm band design for their subsequent project in 2020.

On the other hand, participants found the rhythmic haptic action of “warmth and slight pressure along the arm” from the Affective Sleeve (Figure 2.15) as calming and anxiety reducing (Papadopoulou et al., 2019). Based on the Affective Sleeve replication attempts (Chapter 5.3-A), it is uncertain if the SMA actuators in the Affective Sleeve were able to produce enough pressure sensation to be considered DTP. Rather than DTP sensations, the Affective Sleeve’s calming effect may have been the result of the rhythmic haptic sequence from the palm to the elbow to provide tactile feedback that represents a slower breathing rate. Nevertheless, given the conflicting participant responses for different projects, it is difficult to conclusively say whether applying DTP sensations to a small surface area produces similar calming effects as on a larger surface area.

TACTILE SENSATION TYPES AND ACTUATOR MECHANISMS

Of the 18 research projects, 12 provided compression sensations, 7 provided warmth, 4 provided stroking or dragging sensations, and 3 provided tapping or pressing sensations. Of the 12 projects that provided compression sensations, 6 used SMA wires, 4 used pneumatic inflation, and 2 used belt winding motors as the actuator mechanism. Since utilizing SMA wires is one of the goals of this project, there has been a selection bias towards prototypes using SMA actuators when screening for benchmarking. But it is evident that the use of SMA actuators for compression sensations was a relatively recent development, starting in the latter half of 2010. Given how motors, servos, and pneumatic air compressors are noisy, bulky, and rigid, wearable devices that use those actuators tend to be difficult to wear or challenging to use on certain body parts (Hamdan et al., 2019). On the contrary, SMA actuators are flexible, noiseless, and lightweight, thus there is a growing interest in using SMA actuators for wearable devices (Bengisu & Ferrara, 2018).

Figure 2.14 : Arm band and vest wearable devices with SMA actuators for compression [A] (Foo et al., 2018); [B] (Foo et al., 2019)

One key unavoidable characteristic of SMA actuators is that they require some form of heat to activate, such as electrical resistive heating or direct body heat (Bengisu & Ferrara, 2018). Majority of the SMA based projects that provided warmth were unintentional, and the heat was considered as a byproduct of using SMA actuators (Foo et al., 2018; Foo et al., 2019; Foo et al., 2020; Gupta et al., 2017). Rather than incorporating the SMA heat as part of the intended tactile experience like the Affective Sleeve (Papadopoulou et al., 2019), they tried to eliminate the heat sensations with textile heat barriers.

It is rather peculiar how only one of the seven SMA based wearable projects decided to make use of the heat byproduct as an intentional tactile sensation, especially when CT afferents react the most to stroking sensations administered at skin temperature (Bendas et al., 2021). For instance, participants perceived a social robot as “significantly more friendly, trustworthy, and human-like” when holding hands with a warm robotic hand (Huisman, 2017). For projects like ECHO;sweater (Hendriksma et al., 2020) and Cool Me Down (Vaucelle et al., 2009), they used peltier junctions or other unspecified heating elements to intentionally provide warmth to the user. So incorporating the SMA heat as part of the intended experience could improve participants’ perception of the compression sensation as less artificial for greater positive emotional impact.

Lastly, the projects that provided a stroking or dragging sensation and tapping or pressing sensation did so in a variety of ways. Both “Touch Me” (Vaucelle et al., 2009) and “TapTap’’ scarf (Bonanni et al., 2006) utilized arrays of vibrotactile motors actuating in sequences to create a sensation similar to stroking. “TapTap” scarf also used an array of solenoids in tandem with vibrotactile motors to create a tapping sensation (Bonanni et al., 2006). Stanley & Kuchenbecker used a servo motor with different servo horn attachments and programmed motions to either create a tapping sensation (Figure 2.16- A) or a dragging sensation (Figure 2.16- B) (2011). On the other hand, Hamdan et al. used one SMA spring coupled with a flat plastic “end-effector” to create a pressing sensation (Figure 2.17- A) or two antagonizing SMA springs with round bead-like end-effectors to create a dragging sensation (Figure 2.17- B) (2019).

ADJUNCT OBSERVATIONS FROM RESEARCH BENCHMARKING

Since the research projects for benchmarking were selected in a broader category of “influencing emotions through tactile sensations”, some of the projects delved into automated, rhythmic haptic feedback patterns that could be beneficial in eliciting feelings of calmness. The use of rhythmic patterns typically fell into one of two categories: providing biometric feedback or guided breathing exercises.

EmotionCheck wristband (Costa et al., 2016) and Affective Sleeve (Papadopoulou et al., 2019)

Figure 2.15: Affective Sleeve prototype worn on the forearm (Papadopoulou et al., 2019)

provided haptic feedback that represented a slower breathing or heart rate to subtly promote calmness. Whereas the Soft Robotic Compression Garment (Foo et al., 2020) and inflatable DTP vest for exploring breathing awareness (Jung et al., 2021) provided rhythmic pulsing compression patterns for users to follow as mediation practices or breathing exercises. Jung et al. also explored adapting or altering the compression patterns based on the user's breathing rate that were continuously collected through an inductive respiration sensor (2021).

Both Jung et al. and Foo et al. observed that participants generally had positive opinions about the pulsing haptic patterns when their breathing rates were in sync, but some participants found it frustrating when they could not follow the patterns. Participants felt "feelings of guilt and frustration" when they could not follow the preprogrammed rhythm and even felt "dizzy or sea-sick" when the pattern was intentionally programmed to asynchronously oppose the participant's breathing pattern (Jung et al., 2021). Foo et al. suggested that some individuals have generally adverse opinions towards on-body haptics, which may have influenced those participants to perceive the haptic feedback as unpredictable or frustrating to follow (2020). Automated or preprogrammed haptic patterns have the potential to help with implicit emotion regulation through subtle biofeedback or guided breathing exercises, but they also have the potential to negatively impact the user's emotions based on how well the users can follow the patterns.

Additionally, having to sit through preprogrammed haptic patterns for breathing exercises wouldn't necessarily be welcomed in certain situations for real-time anxiety interventions. For example, if a user wants to get a quick and short hug-like sensation in the midst of a stressful job interview, the preprogrammed patterns' overall duration could be too long or the pulsing sensations could be too distracting from the task at hand. However, given how the haptic patterns' effects are dependent on context and user preference, it would be beneficial if the users could customize the patterns and had the option to switch between a single squeeze and patterned sensation modes.

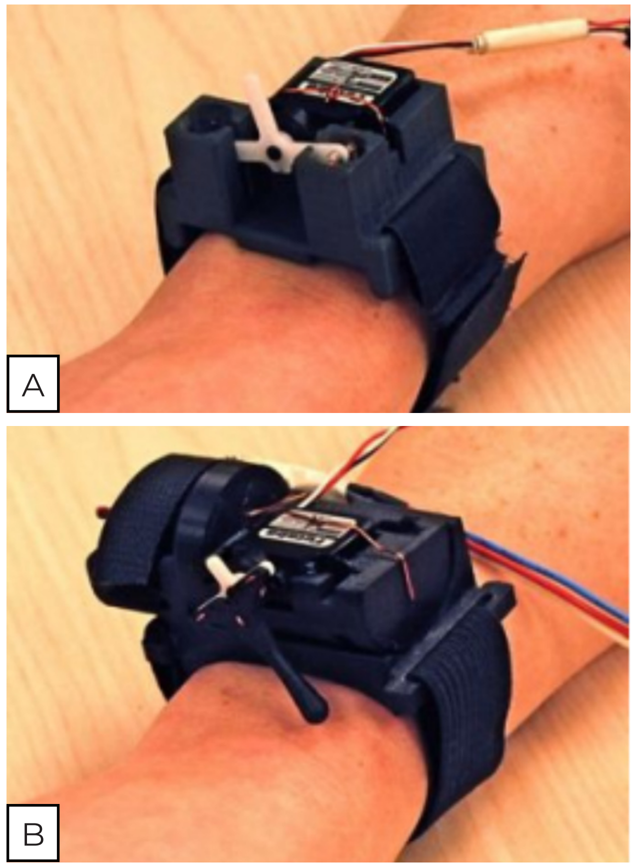


Figure 2.16 : [A] Tapper and [B] Dragger actuators comprised of a servo motor with custom horn attachments (Stanley & Kuchenbecker, 2011)

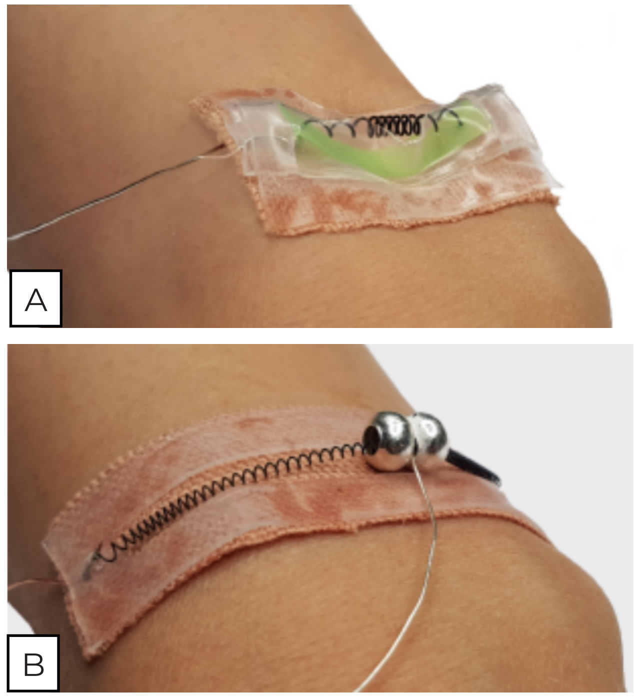


Figure 2.17: [A] Presser and [B] Dragger actuators comprised of SMA springs and end-effectors (Hamdan et al., 2019)

2.4 Shape Memory Alloys (SMA) in Wearables

As discussed in the research benchmarking (Chapter 2.3-B), some researchers used SMA actuators for the wearable prototypes because of their flexible, noiseless, and lightweight properties. However, SMAs are not commonly used currently in the field of design even though the first SMA was discovered almost 90 years ago (Mohd Jani et al., 2014). This section delves into what SMAs are and how they are utilized to gain a better understanding of the material as well as the reason why its usage has stayed mainly in research.

A. What is SMA?

As part of a family of shape changing materials, SMAs are a group of metallic alloys that undergo shape recovery through martensitic transformation when they undergo changes in temperature, stress, or magnetic field (Bengisu & Ferrara, 2018). This shape recovery phenomenon, or returning to a set "programmed" shape, is known as the shape memory effect (SME). SMAs can exist in two different phases - either as an austenite structure stable at high temperature, or as a martensite structure stable at lower temperature - with three different crystal structures of twinned martensite, detwinned martensite, and austenite (Figure 2.18) (Mohd Jani et al., 2014).

First reported type of SMA was gold-cadmium (Au-Cd) alloy discovered by Ölander in 1932 for its unusual rubber-like behavior (Bengisu & Ferrara, 2018). The importance of SMA was only recognized in 1962 when William Buehler and Frederick Wang showcased the SME in nickel-titanium (Ni-Ti), otherwise known as nitinol (Mohd Jani et al., 2014). Currently, most of the SMA commercial applications use nitinol for their affordability and reliability (Bengisu & Ferrara, 2018) since iron-based and copper-based SMAs tend to be brittle and unstable (Mohd Jani et al., 2014). Because nitinol is the most prevalent type of SMA and also used for this project, the term SMA will be used to refer to nitinol throughout this report unless specified otherwise.

The aforementioned martensitic transformation happens when SMA is heated from the martensite phase to the austenite phase. The transformation starts at austenite start temperature (A_s) and completes at the austenite finish temperature (A_f) (Figure 2.19). During the cooling process, the reverse transformation from austenite to martensite phase occurs starting at martensite start temperature (Ms) and ending at martensite finish temperature (Mf) (Bengisu & Ferrara, 2018). The transition temperature difference between heating and cooling ($\Delta T = A_f - M_s$) is referred to as hysteresis "which is generally defined between the temperatures at which the material is in 50% transformed to austenite upon heating and in 50% transformed to martensite upon cooling" (Mohd Jani et al., 2014). The austenite phase shape of SMA can be trained when it is annealed

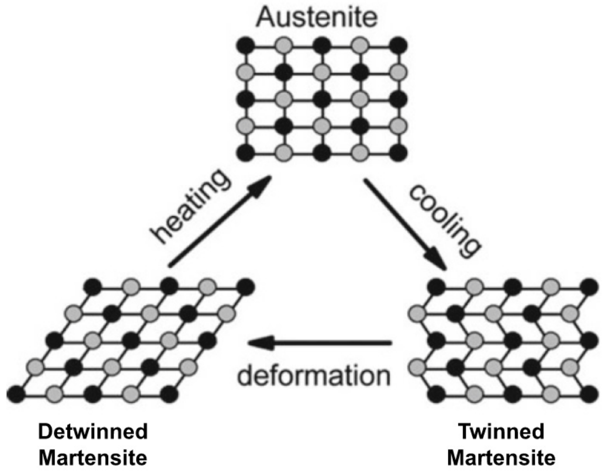


Figure 2.18: SMA's three different crystal structures; Modified to add "detwinned" and "twinned" (Bengisu & Ferrara, 2018)

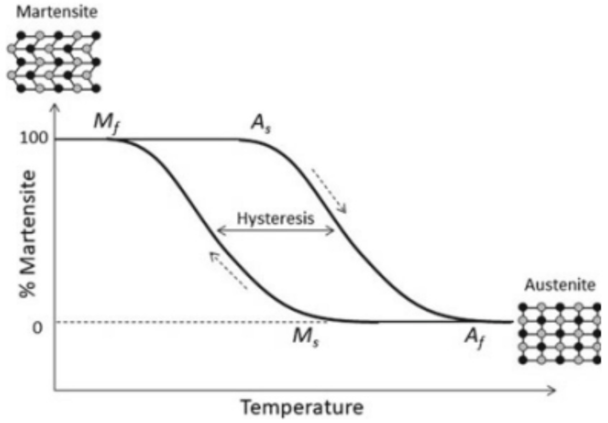


Figure 2.19: Martensitic transformation and temperatures illustrated as a graph. (Bengisu & Ferrara, 2018)

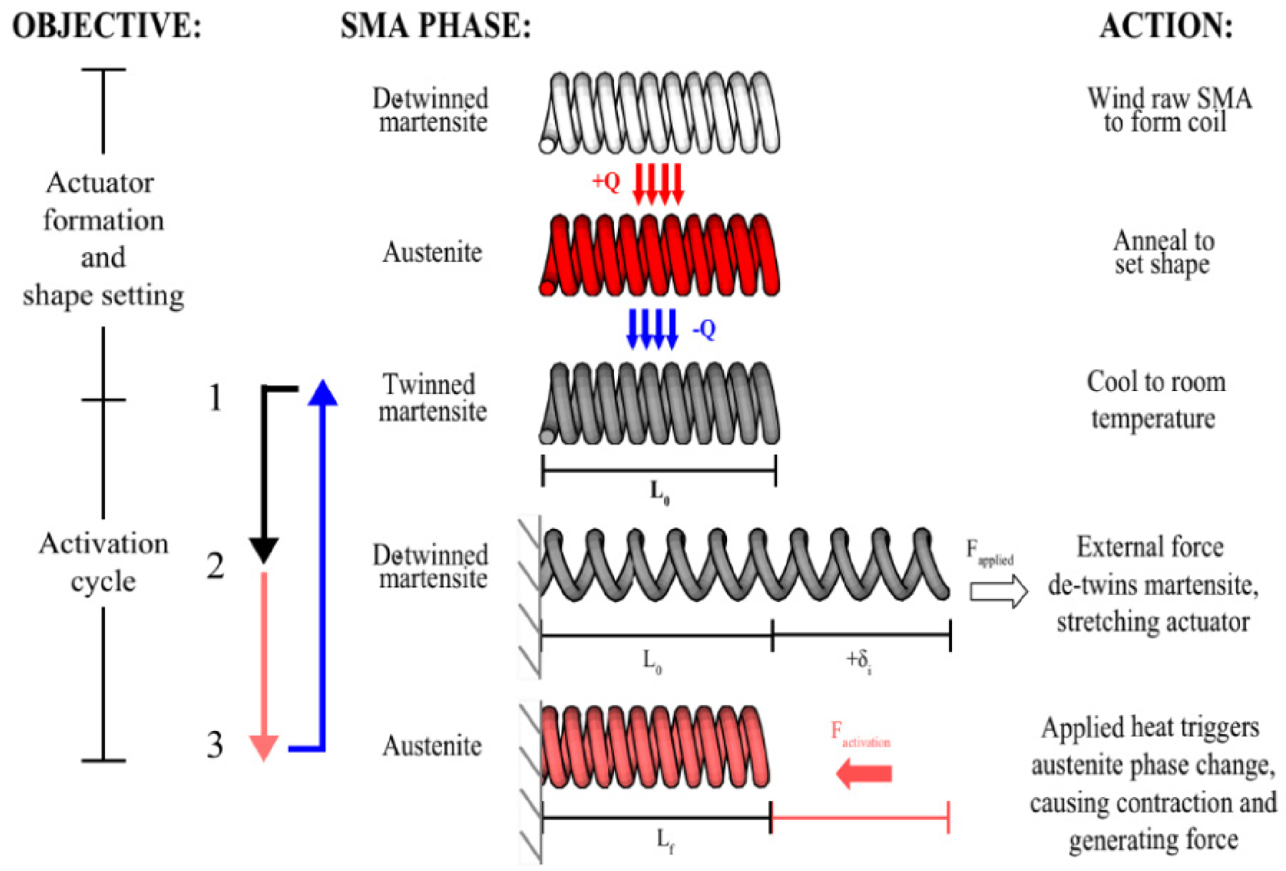


Figure 2.20: SMA spring actuator formation steps and activation cycle. (Holschuh et al., 2015)

or heated above A_s. The recommended annealing temperature differs depending on the alloy composition, but in general, the temperature for nitinol is around 500 - 550 °C (Bengisu & Ferrara, 2018). Generally, the alloy composition, annealing settings, and the working environment of the SMA actuators influence the transition temperatures and hysteresis behavior (Mohd Jani et al., 2014).

In layman's terms, SMAs can be trained to remember a certain shape by heating it to a high temperature of around 500°C then cooling it down to room temperature by quenching them in water or through natural convection. After the SMA is shape trained, it can be deformed below its activation temperature and will remain in the deformed shape. When it's heated to its activating temperature, the deformed SMA will return to the trained shape. This SME property can be used as an actuator, most commonly in the shape of a spring (Figure 2.20), since SMAs can undergo the deformation-to-trained shape transformation repeatedly and generate a net force (Holschuh et al., 2015).

Some of the physical and mechanical properties of SMA, such as Young's modulus (E), thermal conductivity, thermal expansion coefficient, and electrical resistivity, also change depending on the SMA's phase. At a high temperature, SMA's austenite structure is relatively hard and has a higher Young's modulus (E_A); whereas at a low temperature, SMA's martensite structure is softer and has a lower Young's modulus (E_M), resulting in a malleable and readily deformable material (Mohd Jani et al., 2014). The two different SMA material behaviors at low temperature (martensitic curve) and at high temperature (austenitic curve) are represented in a typical stress-strain curve in Figure 2.21.

Martensitic and austenitic curves both have initial portions (OA and OC segments) representing SMA's elastic behavior. Beyond the elastic portion, the constant-stress plateau represents inelastic behavior and permanent plastic deformation occurs after the maximum strain (ε_{adm}) is applied (Spaggiari et al., 2012). Most SMA applications will restrict the actuators' strain level to approximately 4% or less for nitinol to prevent the permanent deformation (Mohd Jani et al., 2014). In practice, SMA actuators remain in the elastic range at high temperatures but strained to the recommended maximum strain level beyond the elastic limit at lower temperature to maximize the actuator stroke displacement (Spaggiari et al., 2012).

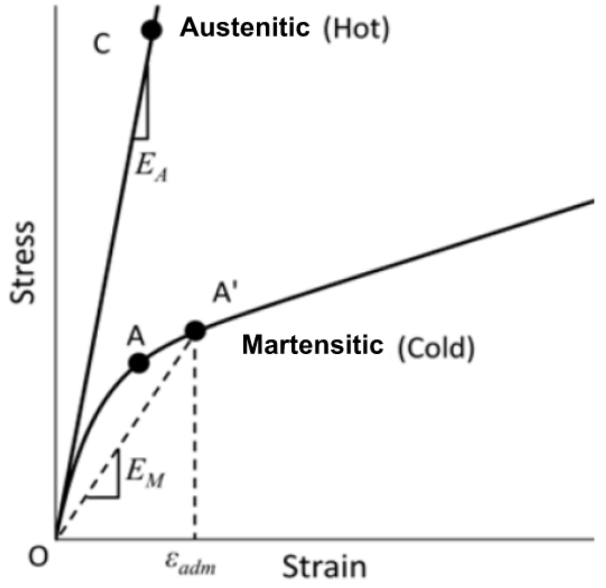


Figure 2.21: Typical material model for martensitic and austenitic phases of SMA; Modified for spelling correction (Spaggiari et al., 2012)

B. Types of SME and Typical SMA Actuator Configurations

Nitinol or SMAs with different alloy compositions can be purchased commercially from various specialized companies and manufacturers, either as untrained materials (wires, rods, tubes, ribbons, or sheets) or as trained products in the shape of spiral springs or wire actuators (Mohd Jani et al., 2016). Regardless of the alloy composition or shapes, SMAs can be largely categorized into three shame memory characteristics: one-way SME, two-way SME, and pseudoelasticity/superelasticity (Mohd Jani et al., 2014).

DIFFERENT TYPES OF SHAPE MEMORY EFFECTS (SME)

Pseudoelasticity or superelasticity refers to SMAs that can revert back to their original programmed shapes after applying mechanical loading without the need of heat or thermal activation. The pseudoelastic phenomenon is often used for special eyeglass frames and bra wires that recover their original shape immediately after accidental deformation (Bengisu & Ferrara, 2018). However, for the context of this project, pseudoelastic SMAs are irrelevant as they are not ideal for creating actuators for compression sensations.

One-way SME is the most commonly used type of SME (Bengisu & Ferrara, 2018) and the most relevant for this project. One-way SMAs can be programmed to have one trained shape that they return to when heated above their activation temperature. As shown in Figure 2.20, when an external force below the martensite yield strength (approximately 8.5% strain for nitinol) is applied to one-way SMAs at room temperature, the SMA deforms elastically into a detwinned martensite phase (Mohd Jani et al., 2014). When enough heat is applied, the elastically deformed one-way SMAs return back to their programmed shape and remain unchanged in that shape as it cools down.

Two-way SME has two trained shapes: a high temperature shape and a low temperature shape (Bengisu & Ferrara, 2018). Essentially, an elastically deformed two-way SMA returns to the high temperature shape when exposed to heat, but it does not remain in its high temperature shape as the temperature decreases. Instead, it transforms into a different, low temperature shape as it cools down. To train the low temperature shape, SMAs need to undergo a thermomechanical training process (Bengisu & Ferrara, 2018) which involves repeatedly stretching the SMAs beyond their martensite yield strength (Mohd Jani et al., 2014).

TYPICAL SMA ACTUATOR CONFIGURATIONS

Generally SMA actuators typically offer two types of motion: linear/prismatic or revolute/rotary motions. Use of mechanisms like levers and pulleys allows for change in direction and type of motion from linear to rotary and vice versa (Mohd Jani et al., 2016). In this section, only linear SMA actuator configurations are reviewed since pulleys and levers are out of this project's scope. Linear SMA actuators can be categorized into three basic configurations as shown in Figure 2.22: one-directional, bias-force, and antagonist actuator configurations.

One-directional actuator configuration is applicable for single or low-cycle use, such as "for fitting, coupling or fastening, self-healing and deployment mechanism", since it does not have a built-in method to deform the SMA actuator once it returns to its trained shape (Mohd Jani et al., 2016). The one-directional actuator configuration illustrated in Figure 2.22-A is classified as free recovery as it has minimal or no applied stress during its shape recovery when heated. On the other hand, constrained recovery refers to a one-directional actuator that is prevented from changing shape with a rigid structure to generate stress when heated (Mohd Jani et al., 2016).

Bias-force actuator configuration uses a bias spring or a deadweight to automatically return the SMA into its neutral position after the SMA contracts and cools down below its activation temperature (Figure 2.22-B). This type of configuration is applicable for devices requiring multiple cyclic actuators that can frequently and quickly return back to their neutral position. When another SMA is used to provide the bias force, it is considered an *antagonist actuator configuration* (Figure 2.22-C) (Mohd Jani et al., 2016). Unlike the bias-force configuration, the antagonist configuration does not automatically return to its neutral position since the antagonistic second SMA needs to be heated to deform the first SMA. Antagonistic configuration is not as quick as a bias-force configuration as it is limited to either of the SMAs' response times; however, it allows for on-demand control over the actuator position and can remain in a certain position without having to maintain a constant heated temperature for either of the SMAs (Mohd Jani et al., 2016).

C. SMA Actuators in Wearables

As showcased by some of the past research in wearable technology (Chapter 2.3-B), there is a growing interest in using SMAs because of how SMA wires can be used to create noiseless, low profile actuators ideal for integrating into garments (Duvall et al., 2016). Since wearable garments have to accommodate for body curvatures, the SMA actuator configurations used in the benchmarking projects were difficult to categorize into one of the three aforementioned typical linear SMA actuator configurations. Instead, the wearable SMA actuators were categorized based on how they interacted with other accompanying components that comprised the overall mechanism.

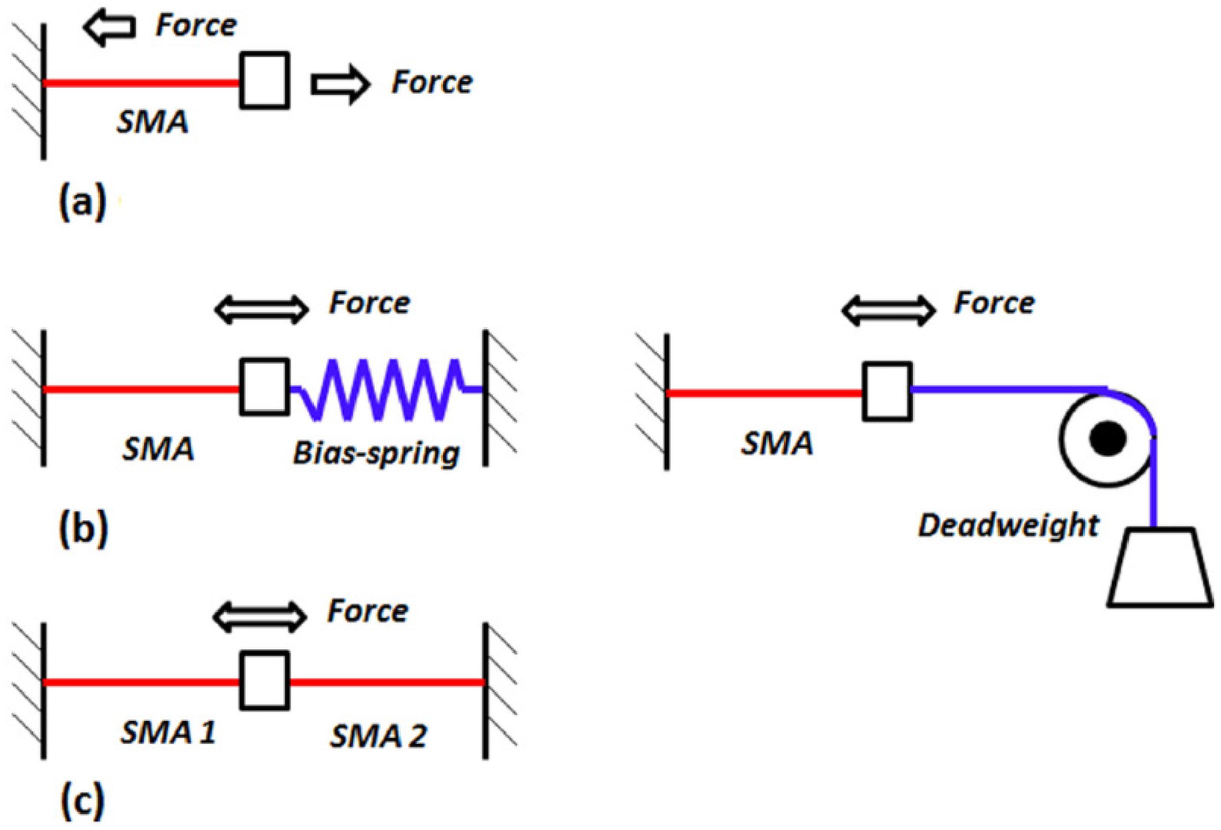


Figure 2.22: Typical linear SMA actuator configurations: (a) one-directional, (b) bias-force, and (c) antagonist actuator configurations (Mohd Jani et al., 2016)

SMA ACTUATOR CONFIGURATIONS

Based on the benchmarking research prototypes, there were generally three types of SMA actuator configurations used in wearable devices:

1. Spiral SMA spring(s) contraction force with or without non-stretch fabric for squeezing or compression sensation

2. Spiral SMA spring with plastic pieces and/or antagonistic SMA spring for pinching, dragging/stroking, or pressing/pulling sensations

3. Straight SMA wire form embedded into fabric as a composite for squeezing or compression sensation

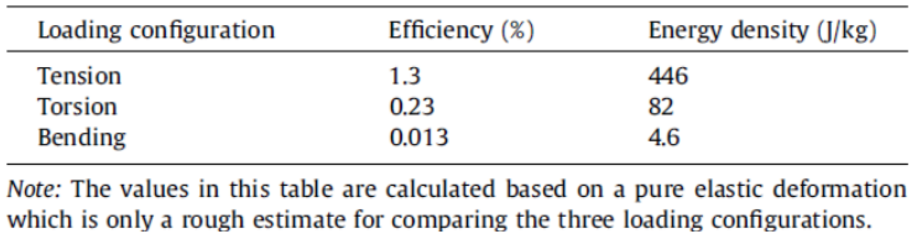
Compared to the second (Hamdan et al., 2019) and third types (Papadopoulou et al., 2019) of SMA actuator configurations listed above, the first SMA actuator type was used more often in different research projects (Duvall et al., 2016; Foo et al., 2018, 2019, 2020; Gupta et al., 2017). Spiral spring forms are also often used for SMA demonstration (Figure 2.23) because the spring geometry allows for larger displacement distance than a straight wire under the recommended 4% strain level (Mohd Jani et al., 2014) or 40~50% elongation (Bengisu & Ferrara, 2018).

As shown in Table 2, SMA actuators are able to perform more efficiently under tension rather than torsion or bending load configurations (Mohd Jani et al., 2014). Although SMA wires have significantly higher efficiency when under tension, only using SMA wires as a linear wire or a spring form under tension limits their potential use case in wearable devices. To get a visually observable amount of displacement using a linear SMA wire under tension, significantly longer SMA wire length is required than the actual amount of desired length displacement. As shown in Figure 2.24, two 50cm long 0.2mm diameter SMA linear wires with activation temperature of 70°C were wrapped around in circles to achieve a horizontal displacement of 2cm (Liu et al., 2022).

As for using SMA spiral springs under tension, the 3D geometry of a spring makes it difficult to embed them into fabric and can easily get stuck or damaged without a protective sheath. For example, a bead shaped "end-effector" paired with two opposing SMA springs for a Dragger Springlet prototype became stuck due to misplacement, resulting in noticeable heat accumulation as the SMA springs' movements were constrained (Hamdan et al., 2019). Although Hamdan et al. stated that the Springlet stickers have a silicone rubber sheet on top of the SMA springs as a protective enclosing layer, many of their example photos of the physical Springlet prototypes, especially ones that had taller end-effectors, did not have the protective layer (Figure 2.25). Even with the use of low friction textile as a base underneath the SMA springs to facilitate

Figure 2.23: Example photos of SMA demonstration (Bengisu & Ferrara, 2018)

Table 2:



Loading configuration	Efficiency (%)	Energy density (J/kg)
Tension	1.3	446
Torsion	0.23	82
Bending	0.013	4.6

Note: The values in this table are calculated based on a pure elastic deformation which is only a rough estimate for comparing the three loading configurations.

* Loading configuration comparison for SMA actuators (Mohd Jani et al., 2014)

smoother actuation motions, the SMA springs can easily get caught on nearby objects and stretched beyond their recoverable strain without a protective sheath like the ones shown in Figure 2.26. Foo et al. used Techflex Flexo braided sheaths to completely encase the SMA actuators "for electrical isolation, heat management, and facilitation of cyclic resetting of SMAs" (2019).

Instead of spiral spring forms, designers tend to gravitate towards using SMA wires' ability to be "programmed'' into any form, which allows for a wider variety of actuating motions and integration methods with fabric. Custom formed SMA wires enable easier integration with textiles through techniques like embroidery, felting, knitting, weaving, and hand stitching (Berzowska & Coelho, 2005). As showcased in Figure 2.27, 2.28 and 2.29, designers working with textiles turn to custom fabricated SMA wire shapes rather than trying to use and retain the spiral spring shapes. Because of the custom shapes embedded into fabrics, the SMA wires are under a combination of tension, torsion and bending load configurations. Similarly, the third type of SMA actuator configuration listed above (straight wire + fabric composite) tried to use straight SMA wires under bending load to create a compression sensation around the arm. However, using SMA wires in their nonidealic load conditions can lead to overstraining, resulting in degraded performance over repeated cycles and reduction in overall actuator durability (Mohd Jani et al., 2014). When the custom shaped SMA actuators experience degraded performance, it becomes difficult to only replace the SMA wires for maintenance especially if the SMA wires have been directly embedded into fabric using techniques like felting, knitting and weaving. Thus finding the appropriate working boundary conditions for custom shaped SMA actuators to have reliable long-term cyclic performance is complex and often beyond designers' expertise.

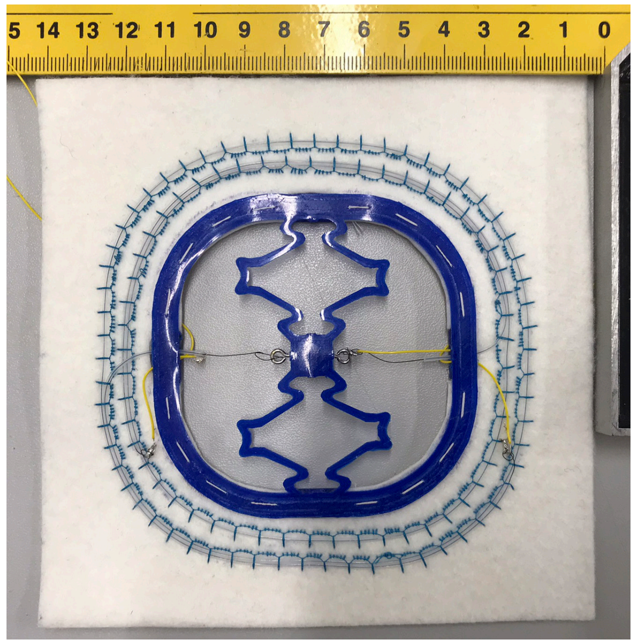


Figure 2.24: Sample linear SMA wire actuator prototype (Liu et al., 2022)

ACTIVATION METHODS FOR SMA ACTUATORS IN WEARABLES

In general, most SMA actuator applications generate the heat required for activation by conducting electricity through the SMA wires, which is known as resistive or Joule heating (Rao et al., 2015). Although nitinol wires can be manufactured to respond at human body temperature for biomedical applications (Mohd Jani et al., 2014), this would require a precise transformation temperature set just below 37W. The nitinol transformation temperatures are dependent on the Ni to Ti ratio and even a 1% increase in Ni can drastically change the activation temperature in about 100°C for alloys with more than 55% Ni composition (Bengisu & Ferrara, 2018). High purity and precise control of alloy composition during manufacturing is imperative to have accurate activation temperature with small temperature tolerance range. Depending

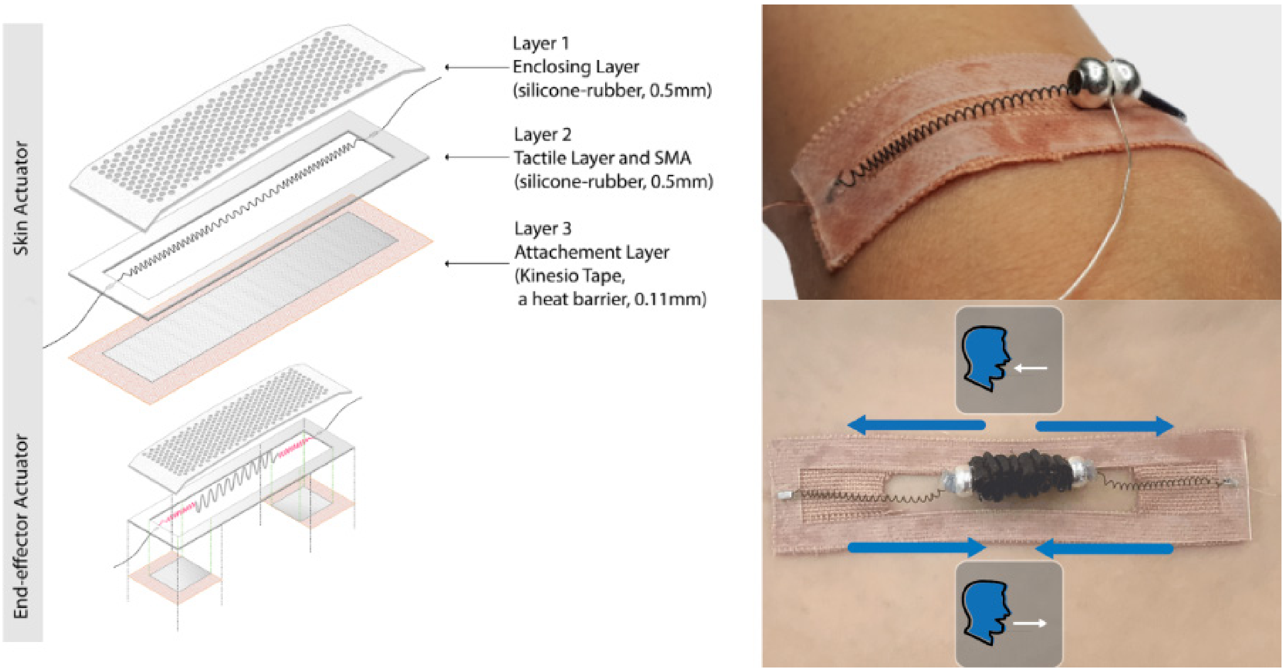


Figure 2.25 : [Left] Exploded diagram explaining the multi-layer sticker structure of Springlets; [Right] Two example images of physical Springlet prototypes in use without the enclosing layer (Hamdan et al., 2019)

Figure 2.26 : Spiral spring SMA actuator within a protective braided sheath (Foo et al., 2020)

Figure 2.27 : Shape memory textile designed and crafted by Marielle Leenders using thin nitinol wires weaved into or stitched onto the textile (Bengisu & Ferrara, 2018)

Figure 2.28: Kukkia Dress by XS Labs with nitinol wire stitched onto the petals for opening and closing of the flower (Berzowska & Coelho, 2005)

on the manufacturer, activation temperature may differ +/- 5~10°C for nitinol SMA wires (Figure 2.30). Additionally, the activation temperature of the wires may change during the annealing process, since the Ni to Ti ratio composition can alter from oxidation (Satoh et al., 2008).

Depending on the ambient temperature conditions, human skin temperature remains in a narrow range of 35~37°C or a wider range of 28~36°C for the fingertips (Wang et al., 2007). However, the range of skin temperature fluctuations is still narrower than the typical SMA activation temperature tolerance range. Given how difficult it is to get a precise activation temperature or maintain it during annealing process, it is unfeasible to design a wearable SMA actuator that is activated by natural changes in body heat unless it is meant to always be activated when the user is wearing the device. Additionally, the SMA wires have to be tightly affixed to the skin to effectively transmit the body heat which would likely cause discomfort for the user. Therefore, the body temperature activation method is not suitable for anxiety modulating wearable devices that are meant to give on-demand compression sensations based on user input.

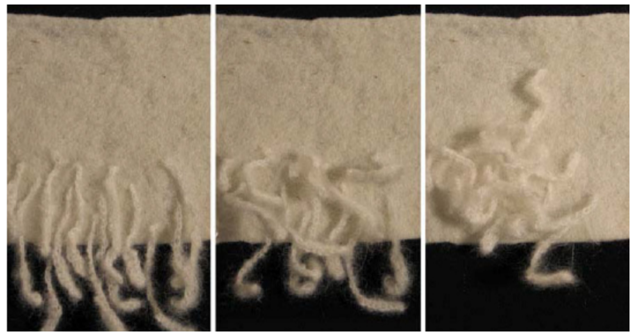


Figure 2.29: Example prototype with nitinol thread directly knitted into wool to create movement (Berzowska & Coelho, 2005)

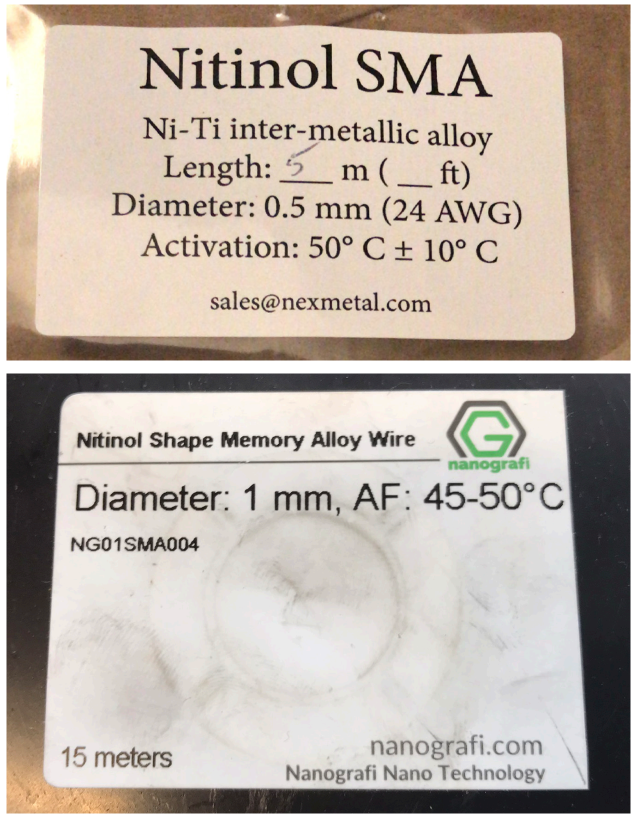


Figure 2.30: Example photos of +/- 5 ~10°C nitinol activation temperature tolerance range for two different manufacturer/ supplier (Nanografi and Nexmetal)

2.5 Lack of SMA in Design and Commercial Wearables

Although SMA has found many commercial applications in the engineering and medical industry, "applications in the field of design are quite rare" (Bengisu & Ferrara, 2018). Few examples of successfully mass produced SMA applications in the commercial market are brassiere underwire, special eyeglass frames, and mobile-phone antenna, but they rely on superelastic properties of SMA instead of heat triggered SMA actuators (Mohd Jani et al., 2014).

Even though there is a growing interest in using SMA actuators for wearable garments in research, there is a clear disjunction in technological degree between research and commercially available wearable DTP garments. It is important to investigate the potential causes of this disjunction to generate appropriate design directions and possible future implementations for this project. The difficulty for SMA actuators penetrating the commercial market, especially in the wearables industry, could be influenced by various factors such as technical difficulties involved with using SMA materials, lack of formal guidelines, challenges surrounding designing and manufacturing multidisciplinary products, and consumer acceptance. For the remainder of the report, wearable garments is used as an umbrella term to include smart garments.

A. Technical Difficulties and Lack of Formal Guidelines

In general, working with SMA material itself is challenging because of the material's poor bandwidth, limited displacement, large power consumption for activation, and difficulties with machining and welding (Mohd Jani et al., 2014; 2016). Nitinol is notoriously difficult to join with other materials, like regular electrical wires, to establish a proper electrical connection using traditional joining techniques, such as welding, brazing, soldering or adhesive bonding (Chapter 5.3-A). Currently the most reliable way to join nitinol SMA wires is through mechanical connections like crimping, swaging or staking (Rao et al., 2015)

Poor bandwidth refers to low actuation speed or slow response time for SMA based actuators. Mohd Jani et al. argue that the poor bandwidth of SMA actuators from slow cooling duration are one of the main reasons for failure in SMA application commercialization (2016). Without an active cooling method, such as force convection, thermoelectric cooler (TEC) or conductive fluid cooling system, SMA actuators have to rely on passive cooling methods like natural convection or higher surface area-to-volume ratio through geometric shape improvements (Mohd Jani et al., 2016). However, adding any sort of active cooling method would increase the overall bulk of the electronic components and power consumption which are undesirable traits for wearable garments. Thus SMA based wearables would have to rely on passive cooling methods that are subjected to environmental conditions like ambient temperature.

Limited displacement of SMA actuators are related to nitinol's inherent material property that requires approximately 4% or less strain level to prevent permanent deformation. Increasing the length of the actuators produces higher displacement, but then they consume more energy to activate and occupy more space as consequences (Mohd Jani et al., 2016).

Power consumption of the SMA actuators depends on the material properties, geometry of the SMA wires, and the desired response duration (Rao et al., 2015). The calculation involved in estimating the current requirement and power consumption of SMA actuators for activation is covered in further detail in Chapter 6.1-C. Ultimately, designing SMA actuators involve balancing and compromising between actuator force output, response time, displacement amount, power consumption, and durability, as well as the overall necessary electronic components' size and weight.

Difficulty obtaining a reliable manufacturer for SMA wires is another factor that adds complication to SMA actuator design (Spaggiari et al., 2012). Even a 1% change in Ni to Ti ratio during the

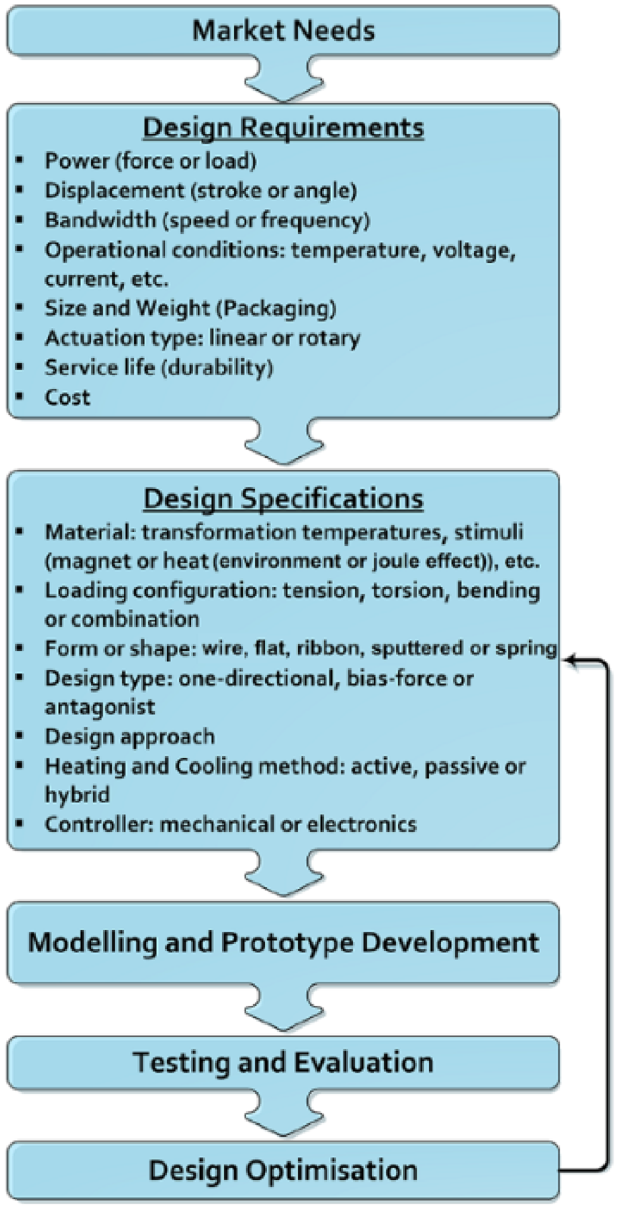


Figure 2.31: Process of designing SMA actuators. Image from Mohd Jani et al. (2016)

manufacturing process can drastically change the SMA's material properties. Additionally, the annealing temperature and duration can also result in changes to the Ni to Ti ratio from oxidation (Chapter 2.4-C). Because precise control of alloy composition and material purity is difficult, SMA wires from different manufacturers and suppliers have varying material properties even if with the same activation temperatures and diameters. While technical data sheets for the SMA wires may provide some material property information, they may not always be comprehensive (Appendix B). Therefore, the necessary calculations involved in SMA actuator design relies on the material property values determined through experimentation or material database values, resulting in a crude approximation that needs to be confirmed through further experimentations. Unfortunately, there is a *lack of formal guidelines,* design tools, and predictive models available for designing SMA actuators, such as a list of equations suitable for specific design constraints or conditions (Mohd Jani et al., 2014). White the utilization of superelastic SMA is well understood and established for manufacturing in limited commercial applications, the use of heat activated SMA actuators are still done through trial-and-error approach (Spaggiari et al., 2012). Since most of the previous SMA research conducted focused on the metallurgical properties, the available information requires specialized material science knowledge and is difficult to understand even by engineers from other disciplines (Mohd Jani et al., 2014). On the other hand, material scientists may not understand how to address the consumer needs through the product design development processes for SMA actuators (Figure 2.31). Hence a "closer collaboration between material scientists and engineering designers is essential" to convert highly specialized technical information to a more transparent and effective information that is easier to understand to promote further SMA applications and use (Mohd Jani et al., 2014).

B. Multidisciplinary Challenges in Design and Manufacturing

In the case of developing wearable garments that integrate electronics into fabrics, it requires collaborative effort over an even wider span of disciplines, sectors and countries involving, but not limited to, "scientists, artists, designers, computer experts, technologists, electrical engineers, manufacturers, and wearers in academia, government, and industry" (Ruckdashel et al., 2021). Currently, commercial wearable devices and garments are mainly developed by companies that focus on either clothing or personal devices, or through joint partnership projects between two companies from different specialty backgrounds (Dunne, 2010). Although interdisciplinary research is increasingly becoming more common, the divided approach to designing wearable garments results in collaboration challenges.

Outside of research, commercialization and mass manufacturing of wearable garments face further difficulties because of collaborating companies' conflicting interests, practices, cultures and fundamental understandings of one another. For instance, seamstresses at a manufacturing factory have to learn that certain traditional ways of garment construction need to be altered to prevent damaging the embedded sensors or circuity (Dunne, 2010). For wearables with SMA actuators, the manufacturing process would also involve annealing the SMA wires with custom fabricated jigs for training their shapes, which adds another layer of complexity to the adaptation beyond assembly. Without such efforts to adjust the entirety of the design and production process, development of wearables generally leads to grafting electronic devices onto existing forms of garments instead of developing a cohesive and comprehensive product (Dunne, 2010). The Nike+iPod Sports Kit (Figure 2.32) launched in 2006 is an example of a grafted wearable technology that tried to combine separate manufacturing processes with minimal adaptation by inserting a small sensor pod into a Nike shoe sold separately (Saponas et al., 2006).

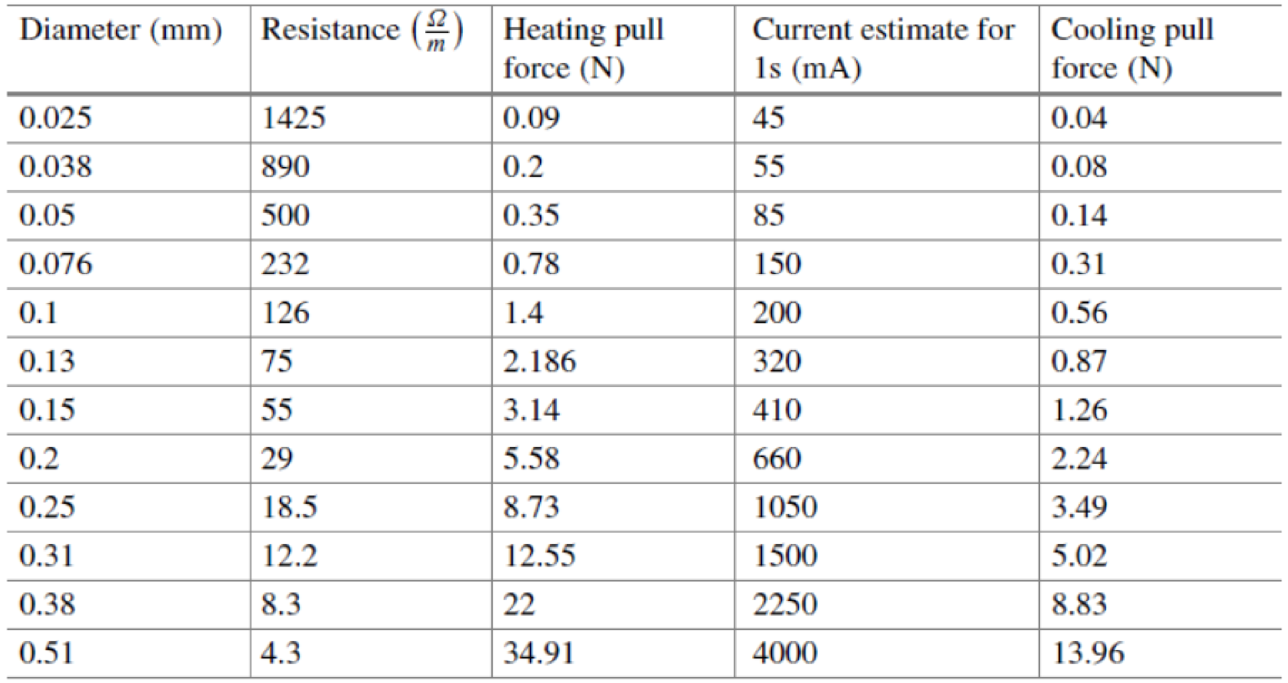
Grafting method may seem like an ideal and cost effective way to bypass the aforementioned difficulties with manufacturing adaptation; however, the grafting method would not be an appropriate strategy for SMA based wearable garments. Sensors inside the devices like the Nike+iPod, smart watches or fitness tracker wrist bands can easily be grafted onto regular garments or accessories because they are able to fit in a compact and relatively detached enclosure with excellent power efficiency from wirelessly offloading energy intensive computational tasks to external devices. For instance, UP4 fitness wristband uses 38mAh LiPo (Lithium-Polymer) battery and is advertised to last for 7-8 days without intermittent charging (Seneviratne et al., 2017).

Unlike the sensors, SMA actuators have poor energy efficiency and restricted displacement, necessitating a relatively large space to accommodate actuator length and bulky batteries to power the actuators (Mohd Jani et al., 2016). An estimate of current required for activating different diameters of SMA wires can be seen in Table 3. Even for the smallest diameter SMA wire of 0.025mm that has only 0.09N of pulling force, the estimated required current to activate the wire for 1 second is 45mA (Rao et al., 2015). Realistically, SMA actuators would consume more than 45mA depending on the SMA wire diameter, overall length and activation duration. These power and larger volume requirements render it infeasible to fit the SMA actuators within a compact enclosed pod for grafting.

Moreover, SMA actuators are an essential part of the wearable garment's mechanism that need to be integrated into the garment to correctly provide the intended tactile sensations. The series of vests developed by Foo et al. (Figure 2.14 and 2.26) were explicitly designed to accommodate or integrate SMA actuators (2018; 2019; 2020). Specific fabrics were chosen for their unique properties, like heat resistance, and were carefully oriented to align the fabric's non-stretch direction with the direction of the SMA actuator movements. This ensured that the whole garment acted as an extension of the SMA actuators to properly apply compression sensations to the users (Foo et al., 2020). Without these deliberate design decisions, the series of spiral spring SMA actuators would be unable to generate the intended compression sensations.

Figure 2.32: Nike+iPod Sports Kit launched in 2006 grafting an electronic sensor device to a Nike shoe and a receiver attachment to an iPod Nano. Figures from (Saponas et al., 2006)

Table 3:



Diameter (mm)	Resistance ($\frac{\Omega}{m}$)	Heating pull force (N)	Current estimate for 1s (mA)	Cooling pull force (N)
0.025	1425	0.09	45	0.04
0.038	890	0.2	55	0.08
0.05	500	0.35	85	0.14
0.076	232	0.78	150	0.31
0.1	126	1.4	200	0.56
0.13	75	2.186	320	0.87
0.15	55	3.14	410	1.26
0.2	29	5.58	660	2.24
0.25	18.5	8.73	1050	3.49
0.31	12.2	12.55	1500	5.02
0.38	8.3	22	2250	8.83
0.51	4.3	34.91	4000	13.96

* Rough estimates of current requirement for different SMA wire diameters to activate for 1 second. (Rao et al., 2015)

However, these vests are far from being equivalent to off-the-shelf regular clothes because of their poor breathability and limited mobility from the stiff or non-stretch fabrics (Foo et al., 2018; 2019). Unless the SMA spiral spring can fully surround the target body area as shown in Figure 2.33, they require non-stretch fabrics as part of the compression actuator mechanism, impacting the wearer's comfort. Therefore, simply grafting SMA actuators onto off-the-shelf regular garments would alter or nullify the intended user experience due to incompatible design requirements. On the other hand, embedding SMA actuators directly into garments can result in poor washability and maintenance difficulty.

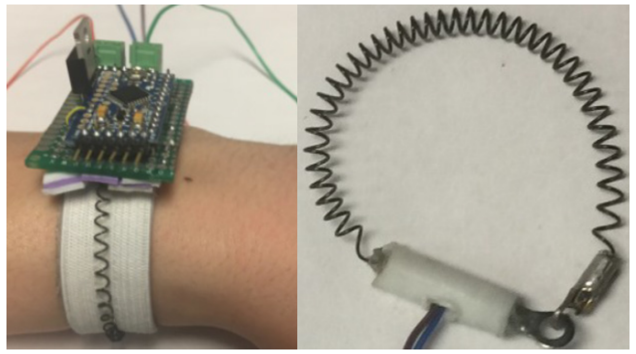


Figure 2.33: HapticClench wristband prototype using a spiral spring SMA wire around the entire wrist to create a compression sensation (Gupta et al., 2017)

C. Consumer Acceptance Towards Wearable Garments

Recent market reports present that there has been an increasing trend of wearable garments in the consumer market and "expected to reach 15 million units by 2020" (Seneviratne et al., 2017). But wearable garments are yet to be considered a common regular household item even in 2023 since general consumer acceptance is another major obstacle in wearable garment commercialization. Consumers are only likely to accept wearable garments if they are comfortable to wear, convenient to wash, have worthwhile functionality for the price point, and follow the ongoing fashion trends (Seneviratne et al., 2017; Dunne, 2010).

Electronic component implementation methods heavily influence the garment's perceived comfort and appeal. Unlike wearable accessories, garments have more stringent comfort requirements since "placement of [electronic] components, textile integration method, proximity to the skin, and surface texture all affect the comfort of a smart garment" (Dunne, 2010). Additionally, electronic components embedded into fabrics make the wearable garments difficult to repair and launder. Although developers have been recently giving significant attention to washability and durability of the wearable garments even at research stages (Seneviratne et al., 2017), consumers are still accustomed to different maintenance interactions depending on the type of products. For instance, consumers are accustomed to charging their mobile devices on a daily basis but not their T-shirts or jackets. Mixing electronics and clothing results in blurring of the distinct maintenance interactions which can be perceived as inconvenient for the potential consumers (Dunne, 2010).

Figure 2.34: The Shirtulator; T-shirt with an embedded functional calculator (Dunne, 2010)

Another aspect that influences consumer acceptances is the wearable garment's functionality. Especially in its infancy, some wearable garments were developed for the sake of novelty "because we can". Certain technologies, such as MP3-players or calculators (Figure 2.34), are better suited as standalone mobile devices, since the functionalities they provide may not justify the high price tags often associated with such products (Dunne, 2010). Even if the wearable garments are sold at affordable price ranges, there needs to be an acceptable balance between utility and usability to garner consumer acceptance (Seneviratne et al., 2017).

Lastly, the most important yet easily overlooked detail during the development process is the wearable garments' aesthetic style. Even though fashionability has been an on-going barrier to commercialization of wearable garments (Seneviratne et al., 2017), many of the researchers and companies involved with developing them are in STEM related fields, so garment aesthetic is often overlooked in favor of device functionality (Ruckdashel et al., 2021). Clothes and worn accessories have a significant impact on the wearer's identity and self-image since in some ways they become part or an extension of the wearer "exerting influence on body image, perceived social status, and societal roles" (Dunne, 2010). This level of intimacy creates a significant obstacle for the adoption of wearable garments and makes it nearly impossible for non-fashionable wearables to have commercial success (Seneviratne et al., 2017). Therefore the consumer acceptance process is fundamentally more complex towards wearable garments than wearable accessories and devices.

2.6 Insights from Literature Review

The following list summarizes the insights gathered from literature review. They are organized based on the list of research questions from Chapter 1.2-A and other related adjunct insights that do not strictly fall into the research question categories.

RQ 1.1 - WHAT KINDS OF DTP OR RELATED TACTILE SENSATIONS ARE USEFUL FOR DECREASING ANXIETY AT WHAT INTENSITY, FREQUENCY, AND LOCATIONS?

1. DTP is a form of affective touch involving compression and gentle slow stroking (~3cm/s) that elicits the feelings of safety, relaxation and comfort by activating CT afferent nerve receptors present in hairy skin.

2. CT afferents activate the most when DTP sensations are applied at skin temperature. Providing warmth along with DTP sensations in a wearable device helps reduce the feeling of artificialness.

3. DTP wearables can act as real-time implicit interventions for anxiety modulation during the attention deployment stage of emotion regulation by providing physical tactile sensations that users can focus on as part of sensory grounding technique.

4. Applying constant compression can lead to pressure habituation and discomfort after a maximum of 10-15 minutes, so it is necessary to periodically release the compression.

5. The perceived pleasantness and calming effects of the intensity and frequency of compression sensations are largely subjective.

6. Although there is some evidence that DTP sensations applied to the lower body have similar calming effects, the majority of the commercial and research DTP wearables focused on the upper body.

RQ 1.2 - WHAT KINDS OF WEARABLE FORMS, SUCH AS BELT/STRAP, VEST, AND BRACELET, ARE BEST SUITED FOR DISCRETION AND COMFORT?

1. Because the majority of the existing DTP wearables focused on the upper body, vests were the most common wearable form. Some of the less common forms were jackets, shirts, sleeves, scarf/wrap, and harness.

2. There is no one conclusive form factor that is best suited for discretion and comfort; however, mimicking familiar shapes and designs of regular garments or accessories can help reduce the likelihood of the wearable device attracting unwanted attention.

3. Uniformly distributed compression sensation over a large body area was generally better received by users than “hotspots” or compression on small surface areas. In some cases, compression on the upper arm was associated with uncomfortable blood pressure cuffs, but in another case, slight pressure along the forearm was perceived to have calming effects.

RQ 2.1 - WHAT LEADS TO THE TECHNOLOGICAL DISJUNCTION BETWEEN RESEARCH AND COMMERCIALLY AVAILABLE WEARABLE DTP PRODUCTS?

1. In general, wearable garments are currently not as common as wearable accessories or mobile devices in commercial products likely due to the difficulties involved in the multidisciplinary approach.

2. Majority of the researchers and companies that develop wearable garments are in technology focused STEM fields. So the devices’ needs often precede those of the users during the development process, which compromises on comfort and usability.

3. Consumer acceptance process towards wearable garments is fundamentally complex because clothing aesthetics have more intimate relation with the wearer’s identity and self-image.

4. Current commercially available DTP wearables tend to be marketed towards “special needs children.”

5. The niche marketing can act as a barrier for consumers outside of that target group.
SMA actuators can be potential noiseless, flexible, and lightweight solutions to provide DTP sensations; however, there are technical difficulties working with the SMA materials and lack of formal guidelines that are easy to understand by designers or engineers without a material science background.

RQ 2.2 - WHICH SMA CONFIGURATIONS CAN CREATE THE DTP OR RELATED TACTILE SENSATIONS USEFUL FOR ANXIETY MODULATION AND BEST SUITED FOR WEARABLES?

1. Combining SMA springs with non-stretch fabric or linear SMA wire forms embedded into fabrics can provide compression sensation.

2. Using SMA spring paired with plastic pieces and/or antagonistic SMA spring can be used to provide stroking sensation.

3. SMA heat byproduct can be used to provide a warm sensation that activates CT afferents the most and helps reduce the feeling of artificialness.

OTHER RELATED ADJUST INSIGHTS:

1. Sensor-measured physiological responses (heart rate, skin conductance, body temperature, respiratory rate, and muscle activity) alone cannot be used to measure anxiety levels. They have to be paired with self-reported assessments or questionnaires to understand the context.

2. Increased awareness of anxiety levels can have a negative effect on the users as it could lead to heightened attention to their behaviors and internal states.

3. Wearable devices often wirelessly transmit personal data to smartphones or cloud storage, which can pose personal privacy concerns.

3. AUTOBIOGRAPHICAL EXPLORATIONS

As discussed in Chapter 1.2-B, I proposed this project primarily because I struggle with regulating my own anxiety levels and believed that having a product capable of providing real-time interventions would be immensely beneficial. My lived experiences and genuine need for such a product make this project suitable for the application of an autobiographical design approach.

As with any research design methods, autobiographical design requires a degree of rigor that is different from rigor involved in scientific methods. It requires a "careful, critical reflection on one's work processes'' (Neustaedter & Sengers, 2012) and extensive record keeping to document the honest observations and introspections that blurs the line between work and personal life (Desjardins & Ball, 2018). Given how individuals who are more prone to anxiety tend to possess higher levels of introspective awareness (Costa et al., 2016), I have accumulated ample self-reflection and introspection throughout the years. However, coherently documenting my scattered internal self-reflecting thoughts and observing my hugging related behaviors in a rigorous manner brought about different challenges and tension points that I did not expect to experience. I have detailed my autobiographical design process and related challenges in this chapter.

3.1 Introspection

During therapy sessions, I often felt a sense of disconnect between how I actually felt during the time of an emotional crisis and how I retroactively explained the same situation. It felt like I was "closing the barn door after the horse had already escaped," especially since therapy sessions happened well after I had already dealt with the crisis and the negative emotions. Also therapy sessions can usually only happen in the daytime during normal business hours when my general mental health tends to be more stable and positive compared to the night time when I am more susceptible to uncontrollable spiraling negative thoughts. This is not to say that therapy is pointless; it has its own benefits in processing my past emotions, building better coping strategies for the future, and just having someone who can empathetically listen without having the potential negative impacts to my personal social relations. However, I wish there was something else in addition to therapy that can provide assistance at any given time.

I have tried various self-help techniques ranging from structured CBT exercises to simple breathing exercises. But I found they require a lot of cognitive energy and incredible self discipline to even utilize such techniques in the midst of a crisis. For example, when I have racing negative thoughts that are spiraling out of control, self-help techniques like meditation or grounding exercises often get interrupted by the constant stream of negative thoughts, resulting in seemingly negligible calming effects. When those attempts at self-help techniques feel ineffective, I often found myself more frustrated and resorted to unhealthy coping mechanisms that would allow me to drown out my turbulent thoughts. These include skin or nail picking, binge eating, and indulging in digital distractions such as mindlessly scrolling through social media, playing games or watching online videos for extended periods of time.

When I further delved into observing my own behavior, what I found the most effective in breaking out of the perpetual negative stream of thoughts is to have some form of noticeable, strong physical stimuli that my mind can latch onto instead of focusing on the spiraling thoughts. An adverse example of a physical stimuli that I resort to is picking at my acne, skin, or nails. Conversely, a healthy example that I tend to gravitate towards is getting a strong hug from my boyfriend.

But as a child growing up in Korea, I distinctly remember often squirming out of hugs that were forced onto me at extended family gatherings. Culturally in Korea (or at least to my understanding), hugs aren't a normative part of common social interactions even within immediate family members. Although there are some exceptions, hugs are typically reserved for significant others as they are mainly seen as romantic gestures. So instead of hugs, as a child, I subconsciously sought after the squeezing sensation at home by crawling under a squat, heavy coffee table or wedging myself into small gaps between cabinets even when I wasn't particularly upset. Unfortunately, as I grew up, I was discouraged from doing so as it is considered a socially odd behavior for an adolescent as well as me simply being physically too big to fit into those tight spaces.

When I immigrated to the US as a teenager, I learned that hugging is a common social conduct in Western cultures that even acquaintances would do as a form of greeting one another. Over time, eventually the meaning of a hug became blurred between a mix of Korean and American cultures. Now I give hugs to acquaintances as a form of greeting and to friends mainly as a comforting gesture for the friend. I am unsure why I tend not to seek out hugs from friends as a way to comfort myself; it may have to do with the lingering Korean association of hugs as romantic gestures. On the other hand, I often ask for hugs from my boyfriend as a source of comfort and a way to "recharge" my energy, especially when I'm in emotional distress. I don't have the same kind of reservation towards my boyfriend as I do to my friends when I ask for hugs to comfort myself. This may be due to the fact that I feel at ease the most with my boyfriend and have little to no barrier in terms of showing vulnerability.

3.2 Documenting and Analyzing Personal Hugging Experience

To get a better understanding of my hugging behavior, I documented my hugs with my boyfriend for a week whenever we were together in person. Since squeezing and stroking are two types of DTP tactile sensations (Chen et al., 2013), I tracked the locations and subjective intensities of pressure and stroking sensations I would get from hugging my boyfriend through journaling and pictorial representation. A sample page of the hug journaling entry can be found in Appendix C. For each hug mapping entry, I used two different colors (red for pressure, blue for stroking) with two varying shades (lighter for lesser intensity, darker for higher intensity) to denote the location and subjective intensities of the pressure and stroking sensation.

Before I could document my hugs, I had to first define what was even considered a hug. Some types of physical contact, like laying nestled in each other's arms in bed or sitting next to each other on the couch with his arm over my shoulder, had similar tactile sensations of a hug since I felt warmth and pressure at the places where I came in contact with my boyfriend. However, the warmth and pressure felt in those situations were mostly non-active since the pressure mainly came from the bodies or limbs leaning and resting on each other. Additionally, those ambiguous hug-like situations lasted longer (several minutes to hours with no interruptions) than what would be considered typical hug durations (average duration of 1.98 seconds for "Plain Hug'' to 3.4 seconds for "Great Big Hug''; (Tsetserukou, 2010)).

So I decided to define a physical contact as a hug only when it meets all of the following criteria:

1. One or both of us had to be standing or sitting down. If either one of us were laying down, then that does not count as a hug.

2. One or both of us had to have at least one arm placed around the other's torso and actively squeezing down to create a pressure sensation.

3. Duration of the physical contact had to last less than several minutes uninterrupted. If the physical contact is interrupted for whatever reason and resumed after the interruption, it should be considered as two separate physical contact instances.

After documenting the hugs with my boyfriend over a week, several notable patterns emerged.

A. Hug Analysis

DIFFERENT TYPES OF HUGS

As previously discussed, there are various physical contact types that can be ambiguous if it should be considered a hug. Similarly, there are also a variety of hug types, such as sideways hug, front to front hug, and one-way back hug, as illustrated in Figure 3.1.

I noticed that the tactile sensations I felt differed in terms of location and intensity depending on the type of hugs. For example, when I gave a hug to my boyfriend from behind (Figure 3.2), most of the pressures I felt were on the front of my torso and the inner forearm. Also the pressure intensity was directly related to how much I squeezed onto my boyfriend as I was the one actively giving the hug rather than getting a hug. On the other hand, when I got an underarm hug from the front (Figure 3.3) the most noticeable pressures were on my back where my boyfriend's hands were actively squeezing me. Additionally, there were stroking sensations on my back when I received the frontal underarm hug, whereas there were no stroking sensations involved when I gave the hug from behind.

PRESSURE AND STROKING SENSATION LOCATIONS

To get a general overview of the pressure and stroking sensation locations, I compiled the pictorial mappings from all the journal entries into one image. As shown in Figure 3.4, the tactile sensations were felt on the upper half of my body, which corresponds to what would typically be expected from a hug. However, the tactile sensations were not just localized to the torso; the inner forearms, palms and sides of my head were also key locations that frequently experienced pressure sensations during a hug.

Figure 3.1: Different types of hugs; Illustration from mindbodygreen.com

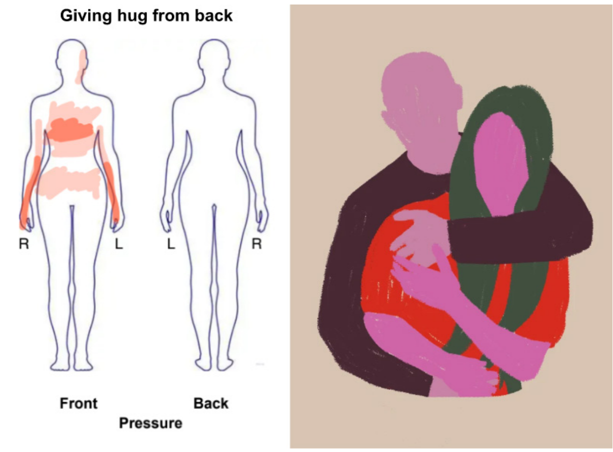


Figure 3.2: (Left) Pressure location and intensity mapping of (Right) hug given from the back

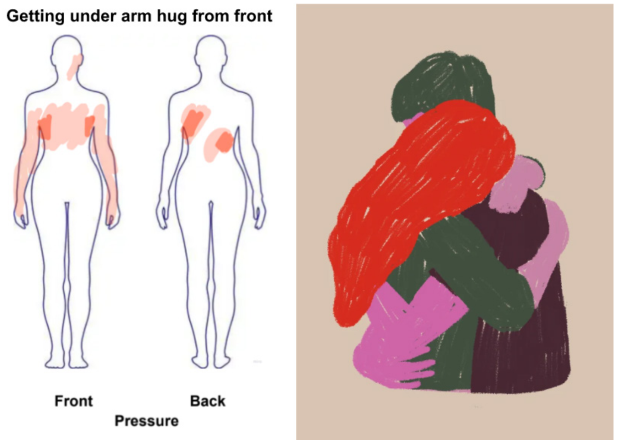


Figure 3.3: (Left) Pressure location and intensity mapping of (Right) getting an under-arm hug from the front

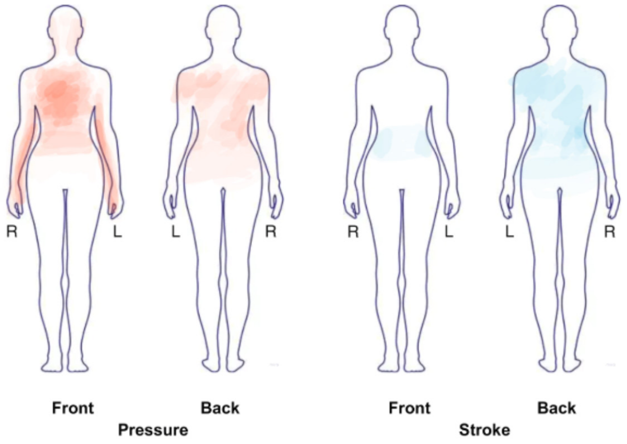


Figure 3.4: Compilation of hug mapping

The pressure felt on the sides of my head mainly resulted from height discrepancies since my head often ended up being pushed against my boyfriend's upper chest when I hugged him from the front or against his upper back when I gave him back hugs. Whereas the pressure felt on one or both of the inner forearms and palms were always present during a hug except in the case of receiving a hug from the back. Because arms are used to provide the squeezing sensation in a hug, there will always be an equal and opposite force being applied to the inner forearm. However, both the commercial and research DTP wearables that attempted to emulate a hugging sensation examined in Chapter 2.3 primarily focused on providing compression to the torso, if not exclusively. Therefore, providing tactile sensations to the inner forearm might be a worthwhile exploration for this project.

HUGGING BEHAVIOR ANALYSIS

Even though there are different types of hugs resulting in different behaviors and tactile sensation locations, there were certain overarching behaviors that were present in the majority of my documented hugs. Except for the cases of one-way hugs, the general notable hugging behavior types present in the recorded hugs were:

1. Fluctuating pressure intensities and multiple pressure "peaks" within one hug duration

2. Reciprocal nature of a hug - the intensity of received pressures correlated to the intensity of pressure given

3. Alternating mix of pressure and slow stroking sensation within one hug duration

4. Use of faster stroking (occasionally followed by few gentle taps) to indicate the end of the hug

Behavior type 3 and 4 were mainly exhibited by my boyfriend. I noticed that I tend not to initiate the stroking sensations to him; instead, when I do give stroking sensations, it was mainly as a reciprocal action mimicking his behavior. For behavior type 3, typically the pressure and stroking sensations were alternating. Also the stroking sensations were gentle and at a slow speed akin to the slow stroking speed optimal for CT afferents (Case et al., 2021). However, the 1-to-1 alternating pattern of pressure and stroking sensations wasn't always consistent. Sometimes the pattern changed, for example to a pattern of pressure - pressure - stroke or pressure - stroke - stroke, but there was no observable reason as to why the pattern varied besides my boyfriend's whim. As for behavior type 4, although there were few instances when we mutually stopped hugging each other without any particular indicative behaviors, this was typically initiated by my boyfriend because generally, I prefer to hug for a longer duration than him.

It is important to note that the aforementioned four hugging behavior types are specific to the hug interactions between my boyfriend and me. For example, the pressure plot (Figure 3.5) for a "big hug level" from Tsetserukou's research study implies that the pressure stayed relatively constant during the "steady-state" phase of a hug over the duration of approximately two seconds (2010). However, in my case, I noticed that the "steady-state" phases of hugs typically lasted longer than two seconds and had multiple fluctuating peaks of pressure intensity.

This difference in behavior may be due to personal preferences, the nature of the relationship between the two huggers, and the setting when the hug was recorded. Tsetserukou did not specify what kind of relationship the three pairs of male and female participants had with one another. Also the hugs were most likely recorded in a lab setting since the participants had pressure sensors attached to their chests and upper back sides, and they were instructed to "hug each other three times with three different intensities (plain hug, big hug and great big hug levels)" while being monitored by the researcher (Tsetserukou, 2010). Because participants may unintentionally behave differently outside of their natural settings (Scollon et al., 2003), Tsetserukou's research participant's hugging behavior may be influenced by the research observation setting.

On the other hand, the hugs I documented were done at home to observe the natural hugging behaviors explicitly between my boyfriend and me. I was not using sensors or timers to precisely record the pressure force or the duration, so the

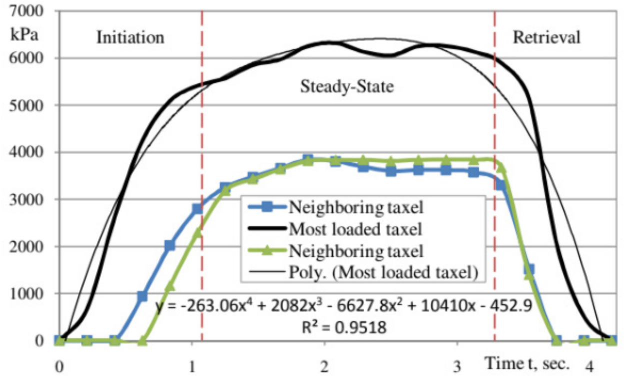


Figure 3.5: Example pressure plot for “big hug level” from (Tsetserukou, 2010)

documented results may have some cognitive biases or recall effects that are typically present in ESM (Scollon et al., 2003). Nonetheless, I noticed that my hugs with my boyfriend lasted longer than the longest average hug duration (3.4 seconds) in Tsetserukou’s study (2010). When I estimated the duration of shorter hugs by counting internally, they lasted around 5 to 8 seconds. Whereas longer hugs lasted anywhere between ~10 seconds (internal counting) to upwards of several minutes. I often lost track of counting for hugs that lasted longer than ~10 seconds, but there were instances when I could estimate that the hug lasted longer than a minute based on the duration of the background music or video we were listening to.

Especially when I was under emotional distress and seeking comfort, the hugging duration became longer because I was either trying to do breathing exercises or explaining why I was upset while I was still hugging. Due to the longer hugging duration, it was possible to have fluctuating pressure intensities and multiple pressure “peaks” within one hug (behavior type 1) instead of one steady pressure peak as seen in Figure 3.5. The alternating mix of pressure and slow stroking sensation (behavior type 3) also contributed to the pressure intensity fluctuations.

Lastly, the reciprocal nature of a hug (behavior type 2) is a key observation that could be pertinent for this project. I noticed that I could nonverbally adjust the intensity of the squeezing pressure received throughout a hug by demonstrating the desired pressure level with my own squeezing intensity. For example, if I squeezed my boyfriend as hard as I could, then he would respond by squeezing back as hard as he could. Similarly, if I lowered my squeezing intensity while I was being squeezed hard, my boyfriend would also adjust his squeezing intensity accordingly. This reciprocal behavior was present in all three of the hugging stages (initiation, steady-state, and retrieval; (Tsetserukou, 2010)) regardless of the hug duration. There were some delays between when I initiated the pressure changes and when the reciprocal adjustments occurred, but they were negligible enough to infer that the two actions were correlated. Even if the responses aren’t instantaneous, giving users the option to adjust a wearable device’s pressure intensity output could give them a sense of control and be more receptive to the tactile sensations.

Figure 3.6: Photo of a boy covering his head with a blanket taken by Mikhail Nilov

B. Adjunct Observations Related to Hugs

Besides squeezing and stroking, there were other notable recurring sensations and behaviors that I found calming when hugging my boyfriend. For example, we noticed that we were both unconsciously changing our own breathing patterns to match one another during longer hugs. By doing so, our breathing became slower and deeper, most likely for ease of synchronization and to accommodate some minor breath duration discrepancies. Additionally, I realized that there were more than just DTP sensations involved in longer hugs. Depending on the hug type and body orientation, I could listen to my boyfriend’s heartbeat or smell his deodorant and natural body odor. I find those auditory and olfactory stimuli calming even outside of the context of a hug.

I noticed that I would occasionally wedge my head under my boyfriend’s arm or press my face into the side of his torso when we’re sitting on a couch to seek emotional comfort and security. In those instances, there may be other factors in play that add to the feeling of security, such as reduced ambient noises, and warmth and compression sensations to my head. Since I also find it comforting to wrap a thick blanket around my head similar to Figure 3.6, compression to the head could be an effective way to reduce anxiety. But given how Suvilehto et al.’s survey (2015) implies that the head region is a socially unacceptable location for touch outside of intimate relationships, a head compressing wearable device may be off-putting to many users.

Moreover, heartbeat and body odor are only comforting to me when they are coming from my significant other, possibly due to psychologically associating my boyfriend as a source of emotional security. However, the calming effect of a significant other’s heartbeat seems to depend on personal preference as well. For instance, my boyfriend does not enjoy listening to anyone’s heartbeat because the sound makes him think about the heart as an anatomical organ transporting blood, which he finds uncomfortable and squeamish. Thus using the sound of heartbeat or certain smells in a wearable device may not be a reliable method to reduce anxiety given how the efficacy of their calming effects are highly dependent on context and personal preferences.

C. Difficulties and Limitations with Documenting Hugs

Because of how hugs can be a highly context dependent and subjective experience, I wanted to get a better insight into my own hugging behaviors through this autobiographical journaling documentation. The hugs were documented as an experience sampling method (ESM) study to capture my innate behaviors and mental headspace within a natural setting. For this reason, I did not take quantitative measures using sensors or timers as doing so would disrupt and influence my innate behaviors. So the insights from this study should be taken more as a holistic and idiosyncratic representation of my own hugging experiences with my boyfriend.

Apart from the limitations of this journaling documentation, there were some unanticipated difficulties that emerged during this process. Despite how the hug journaling was meant to capture my innate behaviors in a natural setting, I still felt disruptions to my normal daily routine during the one week when I documented my hugs. For example, I had to record a journal entry immediately after each time I hugged, which resulted in two to three journal entries per day. That number may not seem a lot in the grand scheme of things and feels like they shouldn’t be disruptive, but the two to three daily entries were only done in the evening between when my boyfriend came to visit me after his work to when we went to sleep. We didn’t interact in the morning since he woke up earlier than I did to travel to his work, so there were no journal entries to be made. Additionally, because we were not living together, he came to visit me for four weekdays during the week I was documenting my journals.

So the three to five hours of evening time I got to spend with my boyfriend were limited and valuable intimate hours. Putting everything on hold to immediately write down a journal entry after each time we hugged felt remarkably disruptive especially since some of the hugs were coming from vulnerable moments of seeking comfort for emotional distress. Even though I fully understood the importance and started the hugging documentation on my own accord, I still couldn’t help but feel annoyed at the disruptions it caused. It’s an unfortunate and unavoidable aspect of autobiographical design as it “blurs the distinction between work and personal life and can put significant pressure on personal relationships” (Desjardins & Ball, 2018). Luckily the week of my hug documentation didn’t put significant pressure on our relationship. All things considered, I still got valuable insights that I otherwise would not have gotten through literature, but I wanted to touch upon these limitations and difficulties as a cautionary note for those who are also considering autobiographical design for their own projects.

3.3 Insights from Autobiographical Explorations

Although autobiographical design methods can yield universally applicable insights for a group of users who struggle with anxiety modulation, it is important to note that there may still be some discrepancies at an individual level since the insights were gathered solely from my personal experiences and perceptions. The following list summarizes the insights gathered from my autobiographical exploration through introspection and hugging journal documentation:

1. The efficacy in eliciting a calming sensation through a hug is subjective and context dependent since various factors, such as cultural background, the type of relationship, and the type of setting when the hugs occurred, can influence the meaning of a hug for different individuals.

2. The pressure and stroking sensations felt during a hug occurred on the upper half of the body. Although the sensations were mainly on the torso, there was pressure felt on the inner forearms and palms for all types of hugs with the sole exception of getting a hug from the back.

3. Hugs are generally reciprocal in nature. During a hug, the intensity of squeezing pressure received tends to change as a response to the intensity of pressure given to the other party.

4. There is no discernible duration, frequency or pattern of squeezing and stroking sensations in a hug. But in longer hugs, squeezing and stroking are used interspersedly and liberally based on personal preference.

5. Besides DTP related sensations, there are other stimuli involved in a hug that can be comforting, such as smell and heartbeat sound. However, they are not universally comforting as personal preference and circumstances influence their perceived valence to different individuals.

4. MATERIAL TINKERING AND EXPLORATIONS

4.1 SMA Spring Shape Explorations

To get a better understanding on how to work with SMA wires, various spring shapes were formed using 0.5mm diameter Nitinol wires with activation temperatures of 40°C and 50°C from Nexmetal. Those activation temperatures were chosen because they are just above the regular body temperature range (28-37°C; Chapter 2.4-C) and require less energy to actuate than wires with higher activating temperatures. As previously discussed in Chapter 2.4-A, spiral springs are the most common shapes used for SMA actuators. However, due to their 3-dimensional geometry, it becomes difficult to integrate spiral springs into fabrics without potentially damaging their height. Flat zigzag shaped springs could be a viable alternative to spiral springs, thus both the spiral and zigzag spring shapes were explored.

A. Spiral Spring Shapes

Spiral spring shapes can be formed by coiling a piece of SMA wire around off the shelf mechanical bolts as a jig. Standard M6, M5, and M4 bolts were used to create three different sizes of spiral springs. These bolt sizes were chosen based on what was available in the lab and on their pitch (Figure 4.1) dimensions that could accommodate 0.5mm diameter Nitinol wires. One of the difficult parts about training SMA wire shapes is that the wires need to be formed and fastened in place so that the wires can't move during the annealing process. To fasten the SMA wires around the bolts, the ends of the wire were wedged between two washers, and hexagon nuts or the bolt head were used to secure the washers together (Figure 4.2). Once the SMA wire ends are fastened in place, the mechanical bolt jigs were placed in a 550°C oven for 30 minutes and quenched in water after the annealing process was done.

After quenching in water, the formed SMA spring needs to be carefully removed from the jig by gently rotating it off the bolt. Simply yanking the SMA spring off the bolt can result in permanent deformation that cannot be undone through shape recovery. As shown in Figure 4.3, one end of the spring was accidentally lodged between the washers during the removal process and the hexagon nut stretched a portion of the SMA spring. This resulted in a damaged, nonuniform spring shape that could not be corrected with shape recovery. Sometimes the SMA springs would adhere to the bolts and the washers after the annealing process. In which case, the SMA spring had to be gently detached from the bolt by slowly twisting it back and forth while wrapped in a paper towel until the spring loosened up enough to be removed.

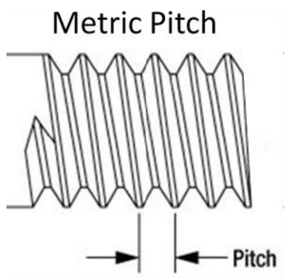


Figure 4.1: Pitch of a bolt.

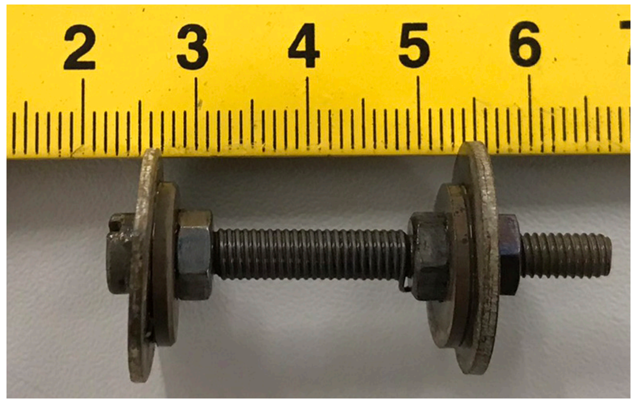


Figure 4.2: Bolt jig method used to form SMA wires into spiral springs.

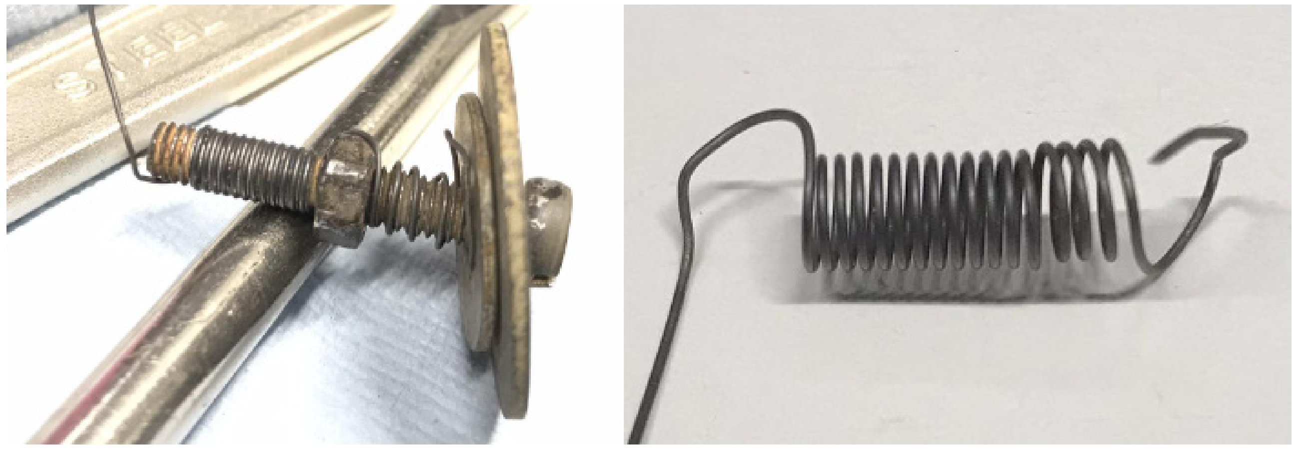


Figure 4.3: Accidental permanent deformation of SMA spiral spring during a removal process from the mechanical bolt jig

Figure 4.4: Example of a zigzag spring formed using the geometries of a perforated metal sheet

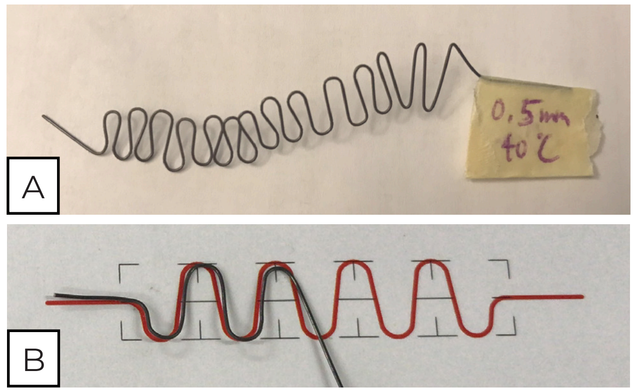


Figure 4.6: [A] Free-formed zigzag spring, [B] hand forming zigzag spring with a printed guideline

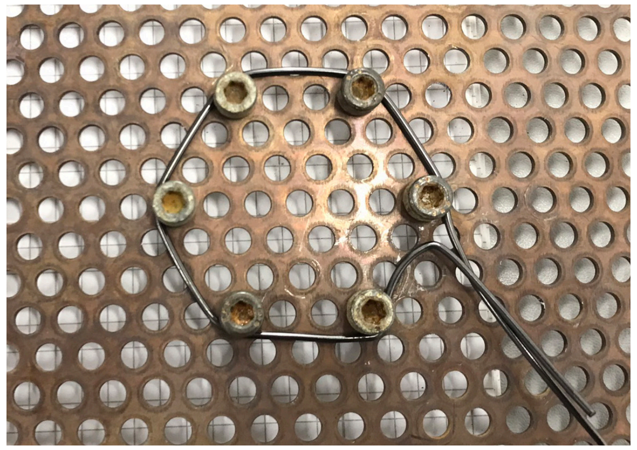


Figure 4.5: Fastening an SMA wire onto a perforated metal sheet with bolts and nuts to prevent the wire from moving during annealing process

B. Flat Zigzag Spring Shapes

Two different methods were used to form the zigzag spring shapes: hand forming or using perforated sheet metal with bolts. The method using perforated sheet metal (Figure 4.4) is faster and easier to recreate the same zigzag shapes, but it limits the zigzag shapes that can be formed since this method relies on the perforation pattern. The SMA wire needs to be fastened down to the perforated metal sheet with bolts and nuts in a similar fashion to Figure 4.5. Additionally, some perforation patterns do not allow for bolts and nuts to be placed adjacent to one another as the holes were too close to each other to accommodate the bolt head and nut sizes. This influences how tightly packed the zigzag shapes can be. Custom fabricated perforated sheets can be used to overcome this limitation, but the radius of curvature for the zigzag shapes are still dependent on the bolt's shaft diameter.

On the contrary, manually forming the zigzag shape by hand allows for custom shapes rather than relying on premanufactured perforated metal sheets. However, hand bent zigzag spring shapes take a long time to form, difficult to get precise shapes even with guidelines, and are impossible to repeatedly and reliably recreate the same shape. Nonetheless, some zigzag pattern guidelines (Appendix D) were drafted using Rhinoceros 7 to help create more precise

shapes than free-forming (Figure 4.6- A). Using Rhinoceros 7 allows for precise control over the zigzag pattern dimensions, such as the radius of curvature and the angle at which the tangent lines came off of the curves. Additionally, the software can calculate the wire length necessary to form the zigzag shape.

As shown in Figure 4.6- B, the zigzag shapes were created by bending a piece of SMA wire and comparing the shape to the printed guidelines throughout the forming process. Each zigzag spring took a couple hours to hand form; however, the duration depended on the complexity of the shape as well as how closely I wanted to follow the guidelines. During the hand forming process, there was always some excess SMA wire length of approximately 5 ~ 10 mm left even when using wires cut to the calculated length from Rhinoceros 7. This may be from accumulation of human error as the hand formed shapes deviated from the guidelines, or the SMA wires could be elongating when they are bent into the zigzag shapes. It is important to note that 0.5mm diameter SMA wires could not be bent into curves with 1 mm radius of curvature without creating a sharp corner, but 2 mm radius of curvature was easily achievable. A sharp corner on a SMA wire may cause damage and result in the wire breaking during the bending process. This is especially the case for thicker diameter wires, such as the 1.5mm diameter SMA from Nanografi as shown in Figure 4.7, so the possible radius of curvature needs to be determined experimentally.

Unlike the zigzag springs formed using the geometry of a perforated sheet metal, the hand formed zigzag springs had to be tightly secured between two perforated metal sheets with strategically placed bolts to prevent the SMA wires from moving during the annealing process (Figure 4.8). However, even when the bolts were tightened down as much as possible, the resulting zigzag springs still slightly deviated from the original shape after annealing as shown in the before and after comparison photos (Figure 4.9). This deviation can be lessened by adding more bolts right next to or near the SMA wires where they could potentially move, but some deviations are inevitable in tight corners or places where a bolt cannot fit in.

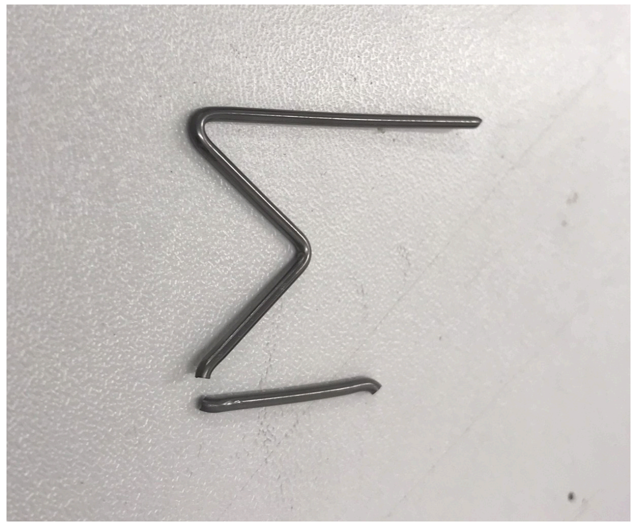


Figure 4.7: 1.5 mm diameter SMA wire from Nanografi breaking at a sharp corner during the hand forming process

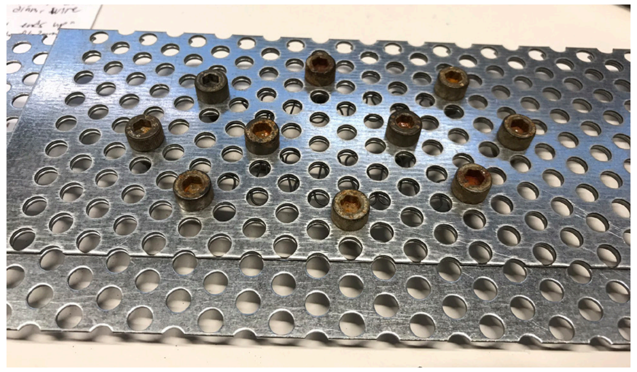


Figure 4.8: Hand formed SMA zigzag springs secured between two perforated sheets and strategically placed bolts for the annealing process

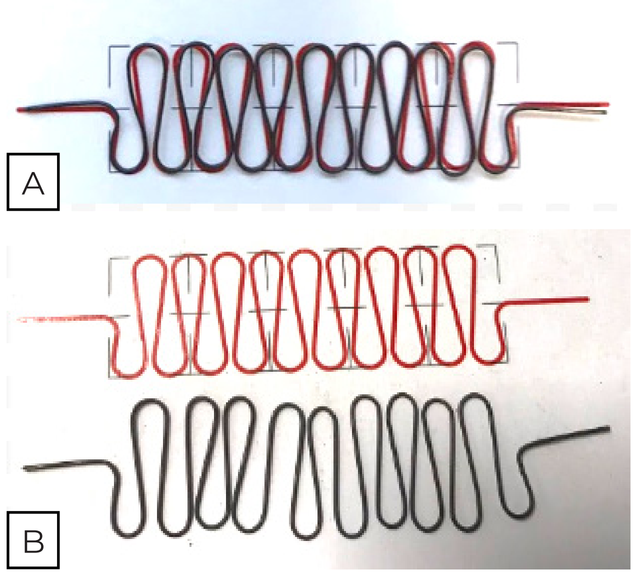


Figure 4.9: [A] Hand formed SMA zigzag springs before annealing, [B] Same zigzag springs that morphed during the annealing process

C. Initial Observations from Forming Spiral and Zigzag Springs

During the SMA spring forming explorations, some initial observations were made regarding different advantages and disadvantages between the spiral and zigzag shapes.

SPIRAL SPRING ADVANTAGES:

1. Easier to get varying sizes of off-the-shelf bolts

2. Requires less components to form one jig (1 bolt, 4 washers, 3 nuts), so it's generally quicker to form the SMA wires

3. The 3-dimensional element of the spiral shape gives more stability to the spring, so it doesn't get deformed as easily and has a more stable shape recovery.

SPIRAL SPRING DISADVANTAGES:

1. Difficult to make custom shaped bolts, so spiral springs are strictly limited to the off-the-shelf bolt size, thread and pitch.

2. SMA wire diameter has to be smaller than the bolt pitch dimension, and the radius of curvature that the wires can bend to has to be smaller than the bolt shaft radius.

3. Springs can easily be damaged during removal process from the jig

4. The 3-dimensional element of the spiral shape makes it difficult to integrate into fabrics as it protrudes above the fabric surface

ZIGZAG SPRING ADVANTAGES:

1. Hand forming zigzag shapes allows for complete customization

2. Easier to make custom perforation pattern sheets, so zigzag shapes can be customized rather than strictly relying on off-the-shelf perforated metal sheets.

3. Flat 2-dimensional shape allows for easier fabric integration without protruding above the fabric surface.

ZIGZAG SPRING DISADVANTAGES:

1. Required more components to form one jig (Perforation method: 1 perforated metal sheet, several sets of bolts and nuts for each peak/valley of a zigzag; Hand forming method: 2 perforated metal sheets, several sets of bolts and nuts to prevent SMA wire from moving)

2. More time consuming to form zigzag shapes even when using off-the-shelf parts for the jig.

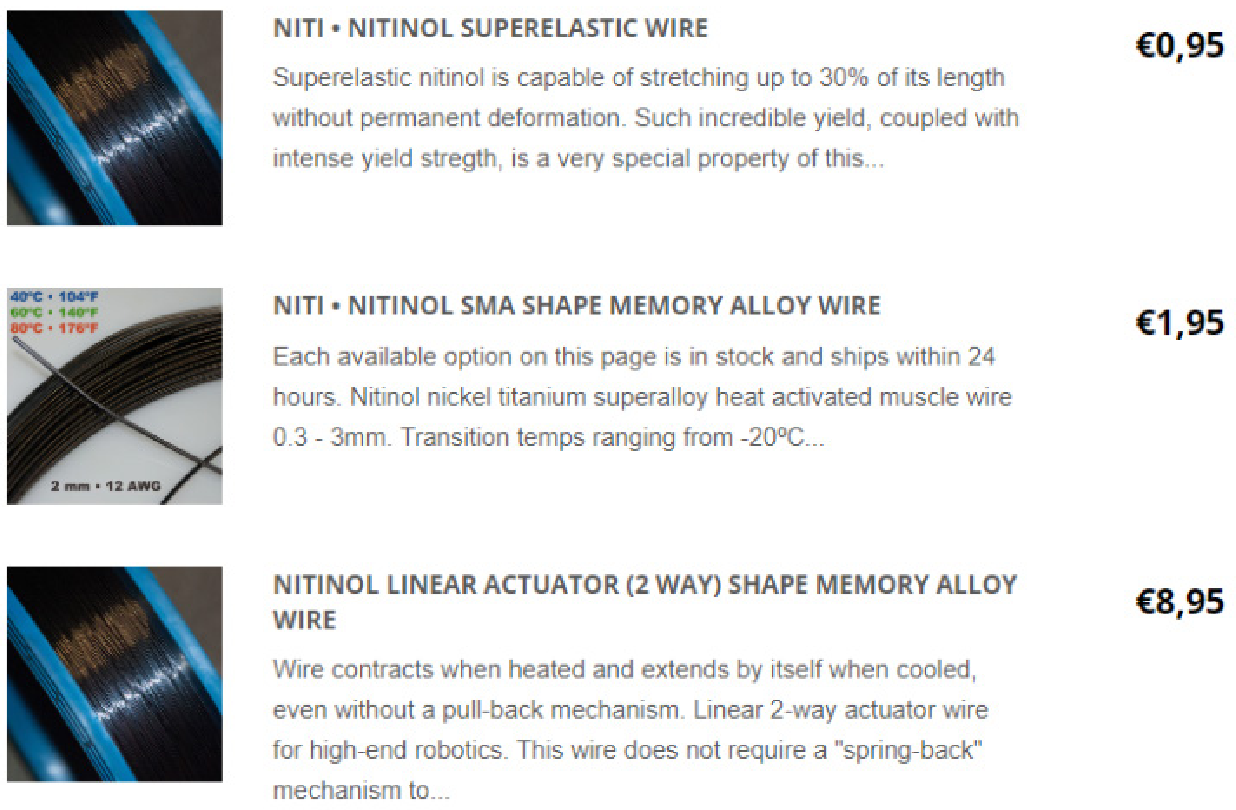
3. Difficult to near impossible to replicate precise shapes when hand forming because of human error and the SMA wires can move more easily during the annealing process even with strategically placed bolts and nuts.

4. Lack of the 3-dimensional element in the zigzag shapes results in the springs easily deforming and difficulty gliding over non-smooth surfaces. Less stable shape recovery.

Based on the initial observations, it is difficult to conclusively say whether spiral or zigzag shape is better for making SMA springs in general. Since either shape has its own advantages and disadvantages, one shape may be more advantageous than the other depending on the use case and application.

4.2 SMA Tinkering Roadblocks

Another key observation made during the SMA spring forming explorations was the formation of "pseudo two-way" or elongating behavior in some of the springs. Regardless of the shapes, the springs made with the Nexmetal Nitinol SMA wire with 50°C activation temperature started to exhibit a visibly noticeable difference in length at room temperature than the original trained shape. The difference in length increased each time the springs were stretched, heated, and cooled down to room temperature. The SMA wires purchased from Nexmetal (Figure 4.10) were specifically chosen to be the regular one-way nitinol SMA wires. Despite purchasing the one-way SMA wires, the springs were still developing low temperature shapes that were longer than the original trained shape and increasing after each stretch. After some initial investigations (Appendix E), it was determined that 50°C activation temperature wire exhibited the elongating behavior far more than the 40°C activation temperature wires.



NITI • NITINOL SUPERELASTIC WIRE

€0,95

Superelastic nitinol is capable of stretching up to 30% of its length without permanent deformation. Such incredible yield, coupled with intense yield stregth, is a very special property of this...

NITI • NITINOL SMA SHAPE MEMORY ALLOY WIRE

€1,95

Each available option on this page is in stock and ships within 24 hours. Nitinol nickel titanium superalloy heat activated muscle wire 0.3 - 3mm. Transition temps ranging from -20ºC...

NITINOL LINEAR ACTUATOR (2 WAY) SHAPE MEMORY ALLOY WIRE

€8,95

Wire contracts when heated and extends by itself when cooled, even without a pull-back mechanism. Linear 2-way actuator wire for high-end robotics. This wire does not require a "spring-back" mechanism to...

Figure 4.10: Product listings on Nexmetal's website; Screenshot taken on 15-April 2023 from nexmetal.com

A. Spring Stretch Tests and Cycle Tests

Although the springs made of 40°C activation temperature SMA wire were not developing elongated heated and cooled lengths detectable by mere visual observation, there was still a possibility that the springs could be slowly increasing in length over time. Especially if this elongating behavior is a result of residual stress and plastic deformation aggregation, the springs made of 40°C activation temperature SMA wire may eventually start elongating when they are stretched beyond their martensite yield strength.

SPRING STRETCH TEST METHOD

To experimentally determine the maximum stretch length percentage for springs made of the 40°C activation temperature Nexmetal SMA wire, the following method was used:

1. After a spring was gently removed from its bolt jig (Figure 4.2), its inner diameter, outer diameter, and length at room temperature were each measured three times using a digital caliper before the spring was stretched or deformed. Then the average of those three measurements were used as the initial reference point.

2. Based on the average initial length of the spring, the target spring stretch lengths were calculated with increasing increments of 10% stretch percentages till 400% (e.g. 110%, 120%, 130% ... 400%)

3. Starting from the 110% spring stretch percentage, the spring was stretched to the calculated length for each stretch cycle (e.g. 110% for cycle 1, 120% for cycle 2 etc.). Then the length of the stretched spring was measured three times using a digital caliper.

4. Thermocouple wires (connected to RS 1319a k-type thermometer) and two small electrical clips (connected to a DC bench power supply) were attached to the stretch spring's extra wire ends that are not part of the spiral spring area (Figure 4.11).

5. The power supply was turned on and set so that the SMA spring would heat up to around 45 - 60 °C and stay within that temperature range since the SMA wire has activation temperature of 40°C.

6. While the SMA spring is within the appropriate temperature range and fully contracted, its heated spring length was measured three times using a digital caliper with electrically insulating caps (Figure 4.12). The caps were made using

heat shrink tubing for electrical wires to prevent the digital caliper's metal prongs from shorting the electrical power supply. It is important to recalibrate the digital caliper with the insulating caps by resetting the zero point to take the caps' thicknesses into account.

7. Once the heated spring length measurements were taken, the power supply was turned off and the electrical clips were removed to allow the SMA spring to cool down to room temperature. A hand-held fan was used to speed up the cooling process.

8. Once the SMA spring cooled down to room temperature according to the thermometer reading, the spring's cooled length measurements were taken three times.

9. Steps 3 to 8 were repeated until the stretch percentage of 400% was reached. Then the resulting spring's inner and outer diameters were also measured three times each.

For this experiment, only the spiral springs were used since the zigzag springs take too long to hand form and harder to create uniform and consistent shapes along the spring. Additionally, M4 and M6 spiral springs, each made with 30 cm long 0.5mm diameter Nexmetal SMA wires with 40C activation temperature, were used to compare if different spiral spring dimensions had an impact on the maximum stretch percentage.

It is important to note that the M4 and M6 springs used for this experiment were made from SMA wires that already underwent an annealing process and were initially trained to a different spring shape. Unfortunately, SMA wires had to be reused because of a delay on the new SMA wire shipment. The process of reforming an already trained SMA spring into a different shape involved stretching out the spring to almost a flat wire and rewinding it around the M4 or M6 bolt jigs, which most certainly stretched the SMA wire beyond its recommended strain level. Additionally, the SMA wire's alloy composition may change during the annealing process due to oxidation (Chapter 2.4-C). Although there is no concrete evidence on the influence of alloy composition ratio on formation of the elongating behavior, the repeated annealing process on top of the inevitable stretching of the SMA wire during the reforming process may further influence the resulting spring behavior. However, given the circumstances, it was not possible to use untrained SMA wires for this test.

SPRING STRETCH TEST METHOD LIMITATIONS

Along with reusing SMA wires, there are other limitations to the revised spring stretch test method that may have influenced the measured data. The list of limitations and the possible ways to minimize their effects are listed below:

A. Measuring the spring length using a caliper that tightens around the spring can compress the spring during the measurement process. Additionally, a stretched SMA spring can be deformed and remain compressed depending on how much the calipers pressed down on the spring. Unfortunately, the only way around this was to gently and slowly close the caliper around the spring until it barely touched the ends but enough to pick up the spring without falling out. Additionally, the caliper compression's impact on the spring length measurements can be further minimized by taking the average of three measurements.

B. When there is electricity running through the SMA spiral springs, the spring becomes slightly magnetic and sticks to the metal prongs of a digital caliper even with the presence of insulating caps. The magnetic force is not enough to visibly stretch the springs, but the digital length readings may be slightly influenced by the springs sticking to the prongs. Using a plastic caliper could help resolve this issue; however, depending on the caliper's material, the plastic prongs may melt when they come in contact with a heated spring. Since there were no plastic calipers in the lab, the measurements had to be made with the metal digital calipers. Since this magnetizing issue was present for all the heated length measurements and the average of three measurements are used, it is safe to assume that the slight magnetic attraction's impact would be negligible.

C. The weight of the electrical clips can influence the spring's behavior if the clips are too heavy compared to the force the spring can generate. This is especially applicable when the spring is still expanding from the elongating behavior during the cooling phase. Thus removing the clips at the beginning of the cooling process can help prevent the clips' weight from influencing the spring's behavior.

D. The springs were stretched manually by holding the ends of the springs which can lead to two potential errors:

D-1. The actual stretched length can be overshot or under the intended calculated stretch length. Once the spring is stretched beyond the calculated stretch length, the potential permanent plastic deformation has already occurred and cannot be undone. When this happened, the spring was either stretched further to meet to the next target stretch length or the test was conducted as is, and the actual calculated stretch percentage was used for the data scatter plots.

D-2. Because the spring ends were held during the stretching process, the spring was stretched unevenly along its length as shown in Figure 4.13. This may influence the elongating behavior as certain parts of the spring may experience higher strain than others. However, a similar uneven stretching phenomenon would also occur in an actuator application since the ends of the spring have to be affixed to connecting wires or other materials to utilize the SME effects.

E. Since the elongating behaviors are formed by repeatedly stretching the spring beyond its martensite yield strength, the stretch percentage at which the spring begins to display noticeable elongating behavior could already be well beyond the spring's martensite yield strength. To confirm the maximum stretch percentage that would not contribute to the elongating behavior formation, the springs underwent repeat stretch cycles at the same stretch percentage as discussed in the following section of this chapter.

SPRING STRETCH TEST RESULTS AND DISCUSSION

As mentioned in limitation D-1, sometimes the springs were stretched past the target stretch length by accident, so the actual stretched percentages were calculated based on the measured stretch lengths. As shown in Figure 4.14 and FIgure 4.15, both of the retrained M4 and M6 springs exhibited elongating behaviors as the springs were increasingly stretched at higher stretch percentages. Similar to the previous tests, both the cooled and heated spring lengths elongated compared to the initial spring length.

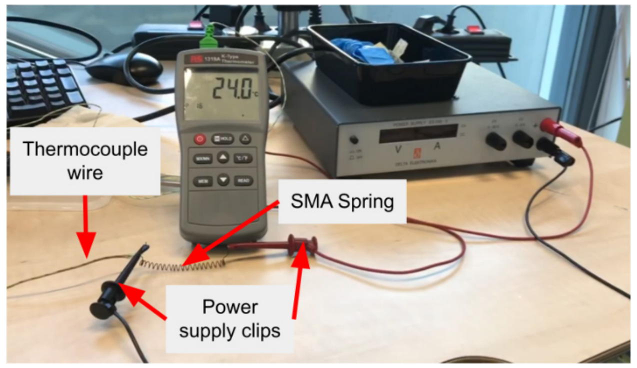


Figure 4.11: Spring stretch % test setup

Figure 4.12: Electrically insulating caps for the digital calipers made using heat shrink tubing for electrical wires

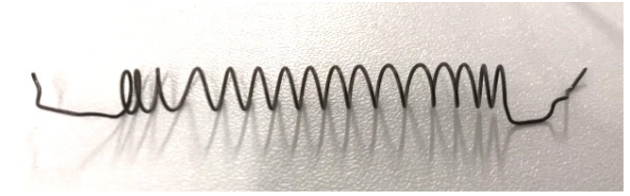


Figure 4.13: Example case of a spring being stretched unevenly along its length

It is interesting to note that the retrained M6 spring may have already exhibited minor elongating behavior even before the stretch test. The initial average length of the retrained M6 spring was 15.36mm, whereas the average first heated length was 14.97mm with the stretched percentage of 118.9%. On the other hand, the initial average length of the retrained M4 spring was 15.14mm, and the average first heated length was 15.16mm with the stretched percentage of 112.7%. However, with a difference of 0.39mm, it is unclear if this is truly the case of the elongating behavior for the retrained M6 spring or if it is due to the influences of this test method's aforementioned limitations.

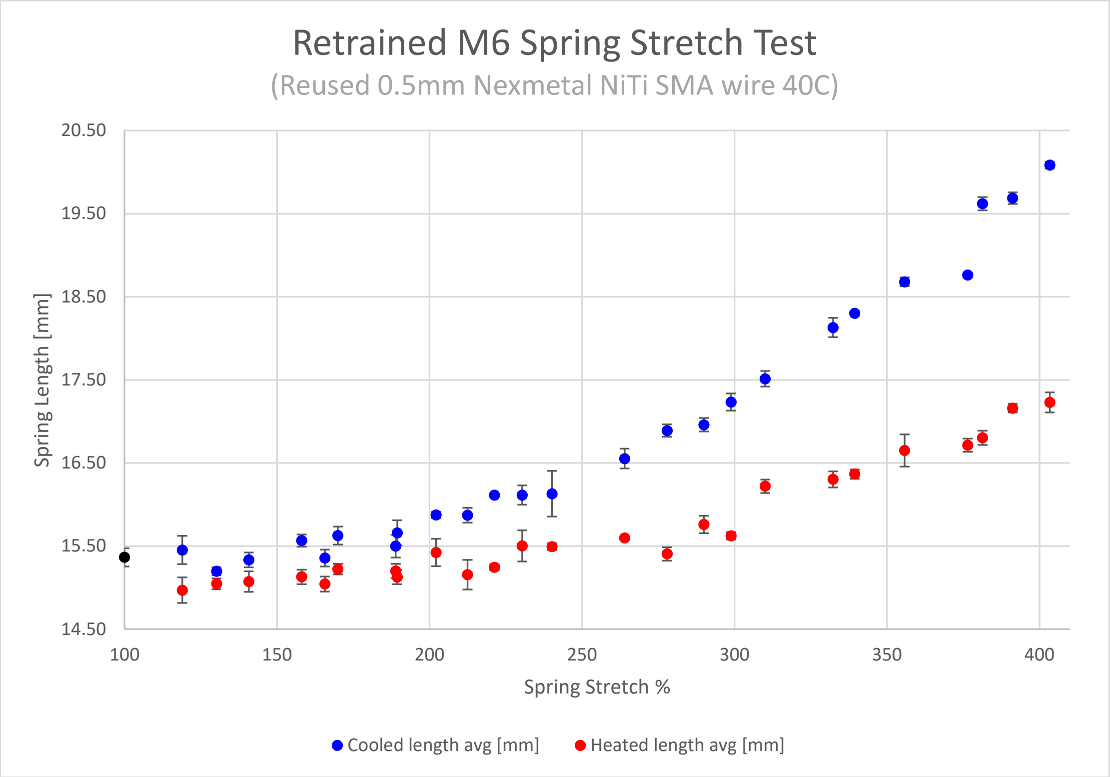


Figure 4.14: Retrained M6 SMA spiral spring (made from previously used 0.5mm diameter Nexmetal SMA nitinol wire with activation temperature of 40°C) exhibiting elongating behavior with increasing spring stretch percentage. Black dot: the initial spring length at room temperature.

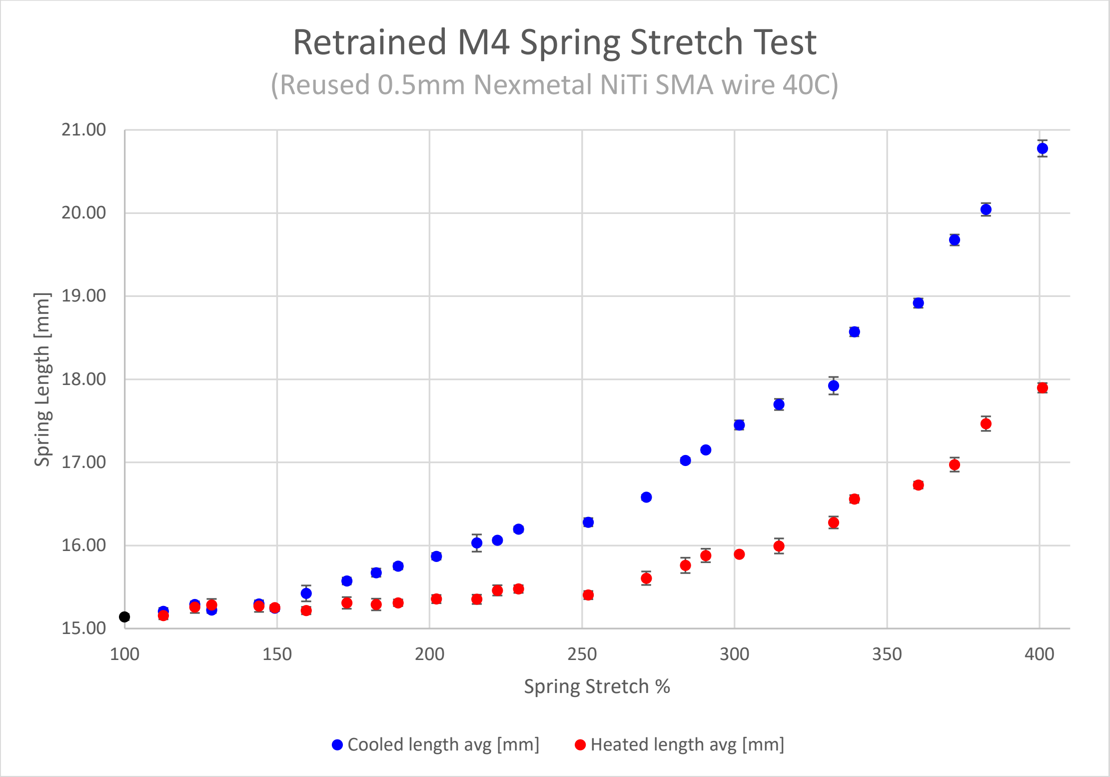


Figure 4.15: Retrained M4 SMA spiral spring (made from previously used 0.5mm diameter Nexmetal SMA nitinol wire with activation temperature of 40°C) exhibiting elongating behavior with increasing spring stretch percentage. Black dot: the initial spring length at room temperature.

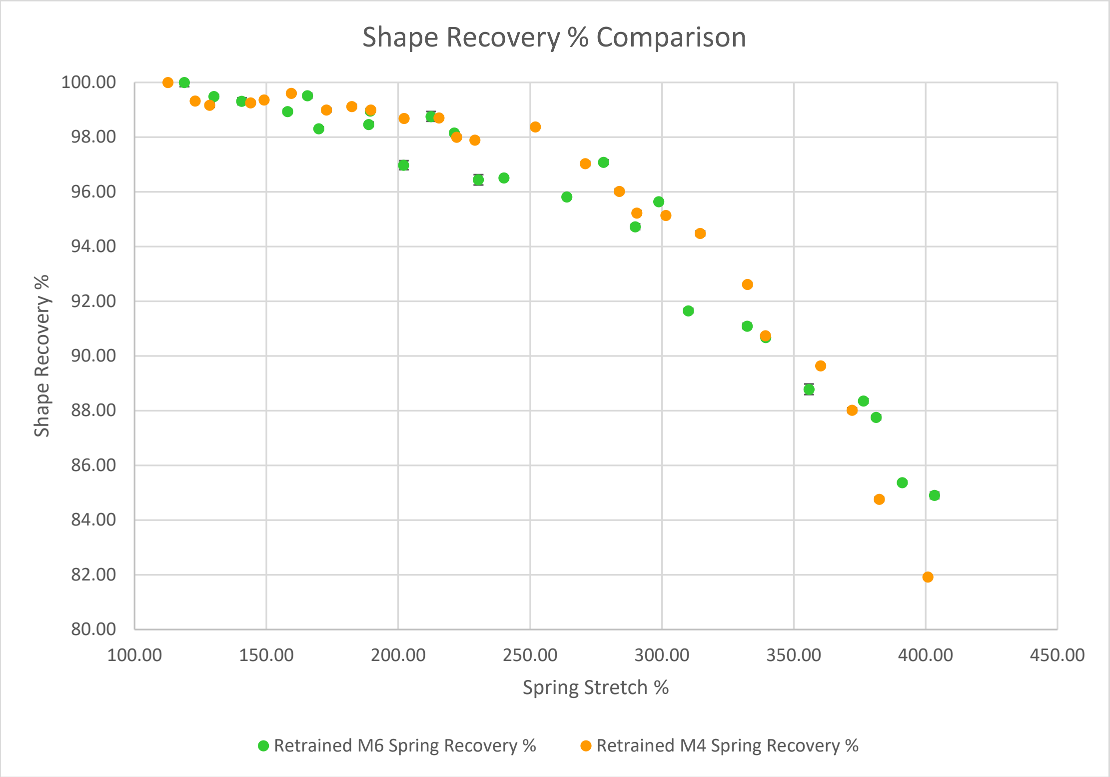


Figure 4.16: Comparison between calculated shape recovery percentages of retrained M4 and M6 springs

Regardless, both the retrained M4 and M6 springs exhibited similar elongating behavior formations as the spring stretch percentage increased. To better compare the springs' elongating behaviors, shape recovery percentages were calculated using (1) where Avg stands for Average, HL stands for Heated Length. Typically the shape recovery percentage would have been calculated using the average initial heated length (Avg HL$_0$) of the spring; however, due to oversight, only the initial spring length at room temperature was measured. Thus, the shape recovery percentage calculations were done using the average heated length of the first stretch cycle (Avg HL$_1$) under the assumption that stretch percentages of 118.9% and 112.7%, for M6 and M4 springs respectively, would be sufficiently below the recommended 4% strain level. The calculated shape recovery percentages of retrained M4 and M6 springs are compared in a scatter plot in Figure 4.16.

$$Recovery\ \% = \frac{AvgHL_0 - (AvgHL_n - AvgHL_0)}{AvgHL_0} \times 100 \quad (1)$$

Based on Figure 4.16, the retrained M4 and M6 springs both had a similar decreasing trend in shape recovery percentage based on the increasing spring stretch percentage. This outcome suggests that the elongating behavior formation to spring stretch percentage is similar regardless of the spring's spiral geometries. The reheated M4 spring had 22 turns, 3.28 mm average initial inner diameter, and 4.35 mm average initial outer diameter. On the other hand, the reheated M6 spring had 16 turns, 4.83 mm average initial inner diameter, and 5.83 mm average initial outer diameter. Even though the springs' initial geometries were different, both springs were made using 30 cm of the same type of SMA wire.

Interestingly, the shape recovery percentage already starts to degrade at stretch percentages above 120%. Between the stretch percentage of 200% to 250%, the shape recovery percentage is around 98%. Beyond 250%, the shape recovery percentage deviates more than 2% and exponentially decays. Since the retrained M6 spring has more than 2% deviation in shape recovery at 250% spring stretch, 200% spring stretch seems to be the maximum spring stretch percentage without potentially developing the elongating behavior. To verify this, the retrained M6 spring was put through three different stretch percentage cyclic tests.

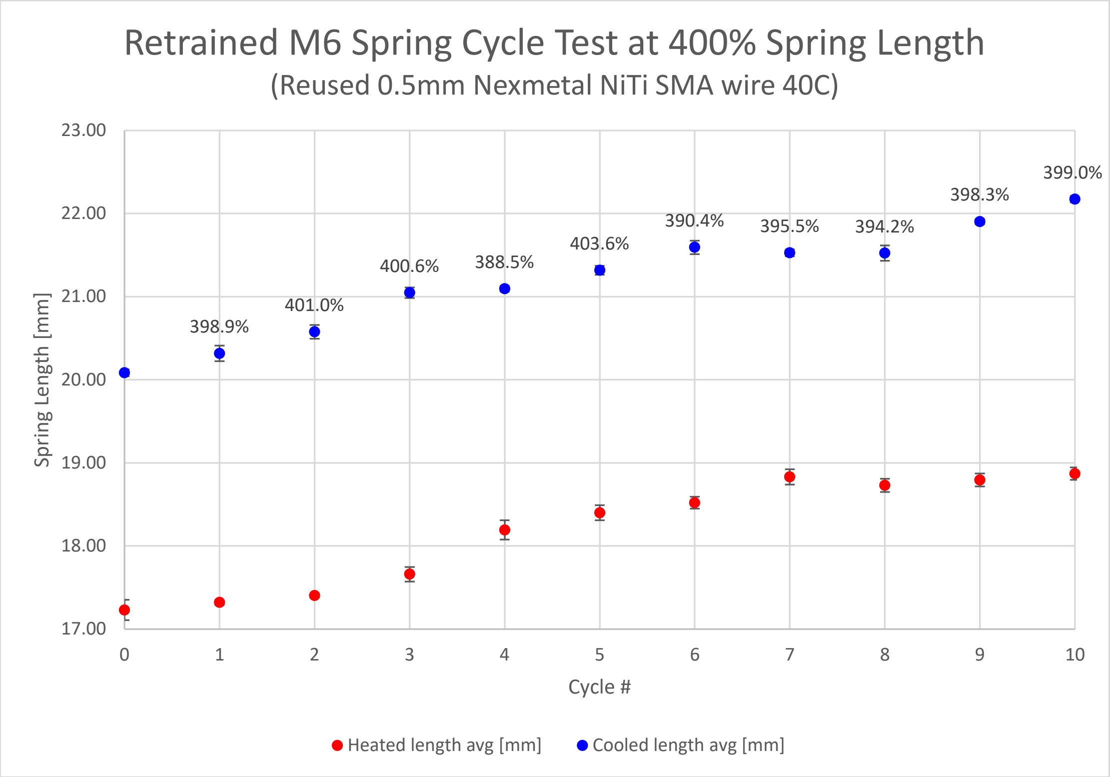


FIGURE 4.17: RETRAINED M6 SPRING CYCLE TEST AT 400% SPRING LENGTH CALCULATED BASED ON THE INITIAL TRAINED SPRING LENGTH

RETRAINED M6 SPRING CYCLIC STRETCH TEST METHODS

Using the retrained M6 spring from the spring stretch percentage test that is already exhibiting the elongating behavior, cyclic stretch tests were conducted at three different stretch percentages of 400%, 200%, and adjusted 200%. The retrained M6 spring was first stretched 10 times to 400% stretch length calculated from the stretch percentage tests. Then it was stretched 10 times to 200% stretch length also calculated from the stretch percentage tests. Lastly, the spring's 200% stretch length was recalculated based on the resulting spring's room temperature length and stretched 10 times based on the adjusted 200% length. This adjustment was made since the original 200% calculation was made based on the spring's initial trained length before it underwent repeat strain training and was no longer a representation of the newly formed spring's cooled room temperature length. The same spring length measurement method from the spring stretch percentage test was used for the cyclic stretch test.

RETRAINED M6 SPRING CYCLIC STRETCH TEST RESULTS AND DISCUSSION

The retrained M6 spring displayed increases in both heated and cooled spring lengths when it underwent the cyclic stretch test at 400% spring stretch length as shown in Figure 4.17. It is important to note that the 400% spring stretch length used for the cyclic test was approximately 61.45mm calculated from the initial spring length of 15.36mm before the spring underwent any stretch tests. Since the spring's starting cooled or room temperature length for the 400% cyclic test was 20.08mm, the adjusted spring stretch percentage would be approximately 300% instead of 400%. Despite this, the retrained M6 spring still continued to grow in length for both the heated and cooled spring lengths over the cyclic stretch test.

On the other hand, the retrained M6 spring maintained its heated and cooled shapes for the cyclic tests at 200% spring stretch length as shown in Figure 4.18. Similar to the 400% cyclic test, the 200% spring stretch length used for the cyclic test was approximately 30.73mm calculated from the initial spring length of 15.36mm before the spring underwent any stretch tests. However, the spring's starting cooled or room temperature

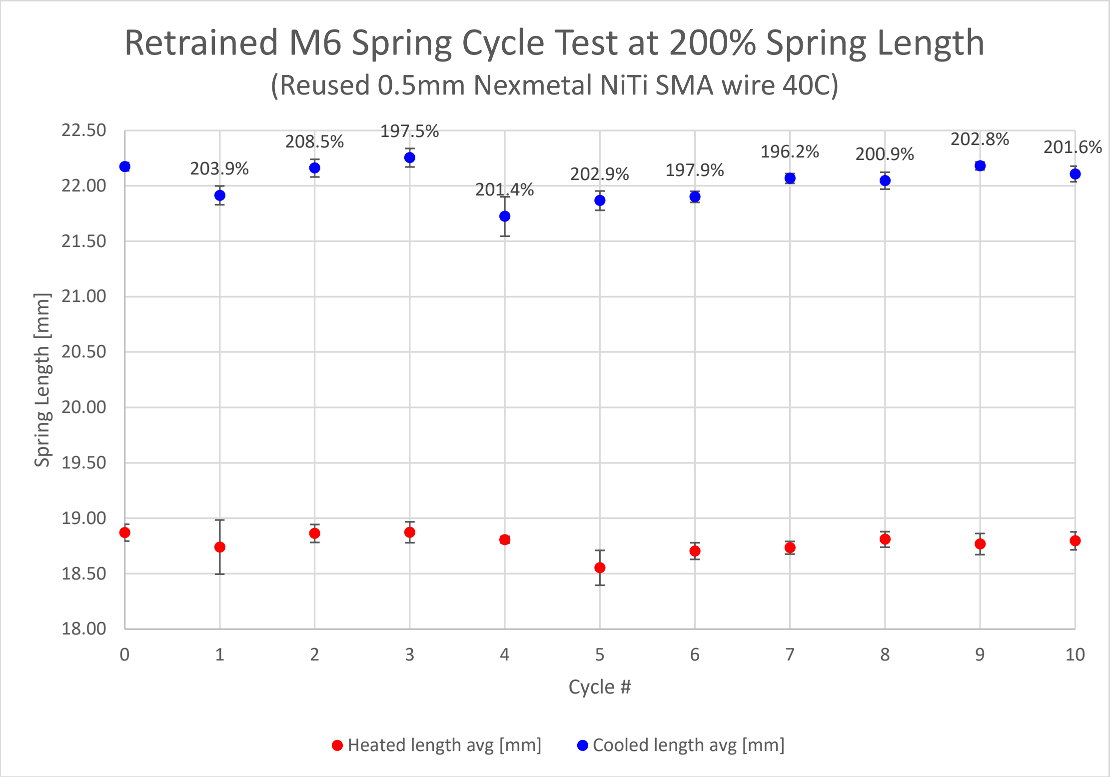


FIGURE 4.18: RETRAINED M6 SPRING CYCLE TEST AT 200% SPRING LENGTH CALCULATED BASED ON THE INITIAL TRAINED SPRING LENGTH

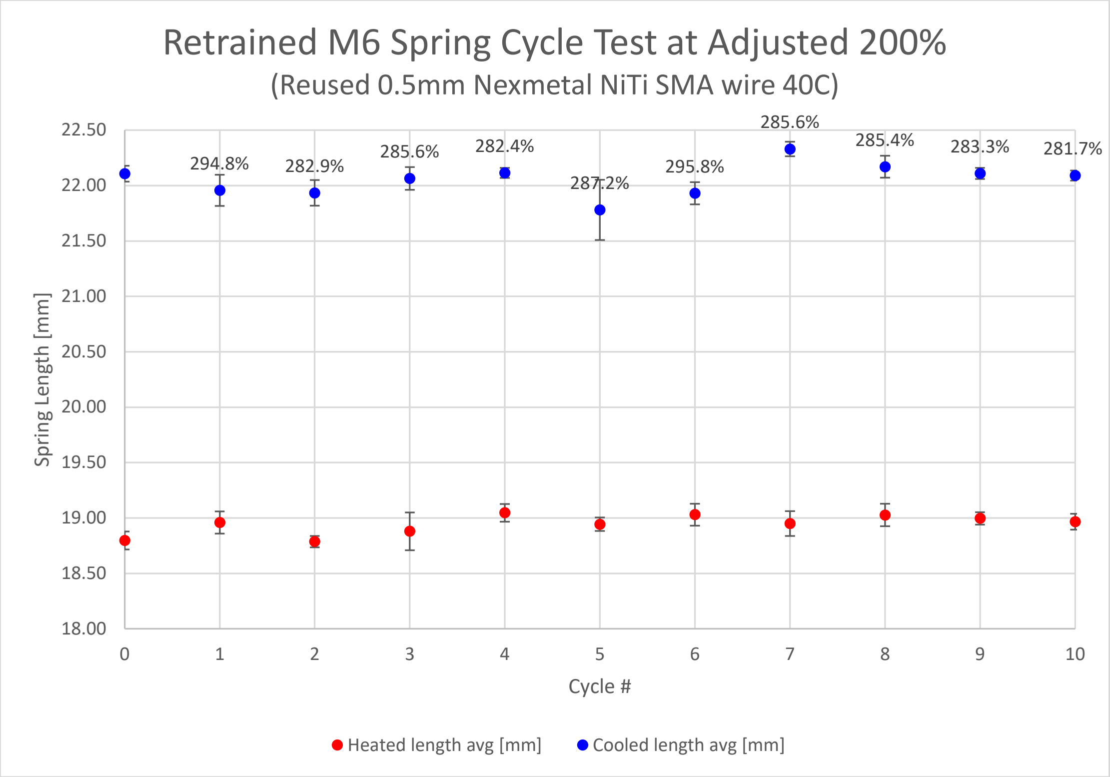


FIGURE 4.19: RETRAINED M6 SPRING CYCLE TEST AT ADJUSTED 200% SPRING LENGTH CALCULATED BASED ON THE COOLED ROOM TEMPERATURE SPRING LENGTH AT THE START OF THIS CYCLE TEST

length for the 200% cyclic test was 22.17mm after the 400% cyclic test, so the adjusted spring stretch percentage would be approximately 140% instead of 200%.

The spring also underwent another cyclic test at the adjusted 200% spring stretch length of 44.21mm based on the 22.11mm cooled average length of the spring at the end of the unadjusted 200% cycle test. As shown in Figure 4.19, the retrained M6 spring was able to still maintain its heated and cooled length with the adjusted 200% spring stretch length. Therefore, stretching a SMA spiral spring to twice its length does not seem to form or exasperate the elongating behaviors.

B. Overall SMA Tinkering and Testing Conclusions

Given how both of the one-way SMA nitinol wires from Nexmetal with activation temperatures of 40°C and 50°C formed the elongating behaviors after repeat stretch cycles, it is likely that any nitinol wires will display elongating behaviors. The elongating behavior formation could be an accumulation of plastic deformation and geometric spring back effect within the SMA springs. However, it is difficult to conclusively say that stretching any SMA spring shapes to twice their length would not result in the elongating behaviors.

Although the repeat (unadjusted or adjusted) 200% cyclic tests for the retrained M6 spring made with 40°C activation temperature SMA wire did not change in heated and cooled length, the zigzag spring made with 50°C activation temperature SMA wire did have increase in heated and cooled length when it was repeatedly stretched to approximately 200% its original trained length. This difference in behavior could be due to shape differences (spiral spring vs. zigzag flat springs), but since the springs were made of different SMA wires, further testing with a zigzag spring made of 40°C activation temperature nitinol wire would be necessary. Due to the limited time constraint of this project, further tests related to the SMA wire's elongating behavior formation could not be conducted.

4.3 Textile Explorations

As discussed in Chapter 2.3-B, heat is an unavoidable characteristic of SMA actuators since SMA activates when it is heated above its activation temperature. Many of the benchmarking SMA actuated research projects tried to eliminate or reduce the heat sensations felt by the users with textile heat barriers. The heat barrier textiles used in those research projects were thick felt fabric (Papadopoulou et al., 2019), cotton aramid, unspecified reflective heat shield (Foo et al., 2018), neoprene fabric (Foo et al., 2020), Kinesio tape (Bengisu & Ferrara, 2018), unspecified heat-resistant textile (Duvall et al., 2016), or a composite of Kapton tape and polyester rubber bands (Gupta et al., 2017).

A. Textile Selection for Exploration

Since the projects using Kinesio tape or Kapton tape and polyester rubber band composite were for designed either to be a small sticker (Bengisu & Ferrara, 2018) or a narrow wrist band (Gupta et al., 2017), those textiles were omitted from the list of possible textiles to explore as they do not translate well for wearable garments that require larger surface area. Additionally, cotton aramid was also omitted from the potential textile explorations. Cotton aramid is a term often used interchangeably with Kevlar, which is a brand name of the first aramid fiber developed by DuPont and synonymous with aramid textile in general (Webb, 2022). According to ExtremTextil (extremtextil.de), a textile supplier for specialized fabrics, Kevlar requires specialized micro-serrated scissors to cut since normal scissors would quickly become blunt and poorly cut the fabric. Although Kevlar is well known for its heat resistant property, it was eliminated from the list of potential textiles for testing because of its high cost and cut resistant property that requires specialized tools to cut.

Disregarding the unspecified textiles, Kinesio tape, Kapton tape composite, and Kevlar, the remaining fabrics for heat protection from benchmarking prototypes are thick felt and neoprene fabric. 3mm dense (580g/m^2) polyester

felt fabric, that is often used for making bags, was used to create the initial prototypes (Chapter 5 & 6) because felt fabric is relatively cheaper and easier to find than specialized fabrics like neoprene. However, the prototypes made using 3mm felt fabric turned out to be stiff and uncomfortable, so a different textile was needed to replace the felt fabric. The following fabrics were chosen for the textile exploration: polyester stretch fleece, 3mm COOLMAX elastic 3D mesh (Figure 4.20), and neoprene-like 2-layer fabric with a knitted layer (Figure 4.21). Polyester stretch fleece was chosen for its soft, moisture wicking, and breathable properties. The COOLMAX mesh fabric, that is often used as padding on backpacks, was chosen for its soft pliable nature, moisture wicking knitted carrier fabric and 3D mesh geometry promoting air flow. The 2-layer neoprene-like fabric was chosen for soft and potentially heat resistant properties; unfortunately, it was not possible to further identify this particular fabric because it was a sample fabric available in the lab from a different project without a written identification note. The best information available was from the lab's textile expert who simply stated that it's a "neoprene-like" fabric. Regardless, the polyester stretch fleece, 3mm COOLMAX elastic 3D mesh, and neoprene-like fabrics are softer and more compliant than the 3mm polyester felt fabric, so the three fabrics were tested for their heat insulating and dissipating properties.

B. Textile Temperature Test

The main focus of this textile temperature test was to find the best textile or combination of textiles that can help insulate some of the SMA heat, promote heat dissipation to prevent heat build up, and be comfortable to wear. Unlike many of the benchmarking research prototypes, warmth is an important part of the intended tactile sensations and experience for this project. Additionally, SMA actuators have poor bandwidth due to slow cooling duration (Chapter 2.5-A). Therefore, selecting a textile that can provide some heat protection as well as have heat dissipating property is necessary for embedding SMA actuators for DTP wearable garments.

TEXTILE TEMPERATURE TEST METHOD

The following method was used to test how well the polyester stretch fleece, 3mm COOLMAX elastic 3D mesh, and neoprene-like fabrics could insulate and dissipate heat.

1. Approximately 5cm long Nanografi nitinol wire with 1mm diameter and 40°C activation temperature was sewn onto a piece of fabric using a sewing machine with zigzag stitch setting (Figure 4.22). The ends of the wire were not sewn down.

2. Thermocouple wires (connected to RS 1319a k-type thermometer) and two small electrical clips (connected to a DC lab power supply) were attached to the ends of the SMA wire.

3. The test sample was placed on the outer forearm with the SMA wire side away from the skin. The power supply was then turned on, allowing the SMA wire to heat up until the wire heat felt uncomfortable to the skin and/or before reaching 100°C.

4. Before the temperature reading reached 100°C, the power supply was turned off and the test sample was placed on a table for the SMA wire cooled down with natural convection. A stopwatch was used to measure the time it takes for the temperature reading to cool down from 70°C to 30°C. This process was repeated three times to take three measurements of the cool down time.

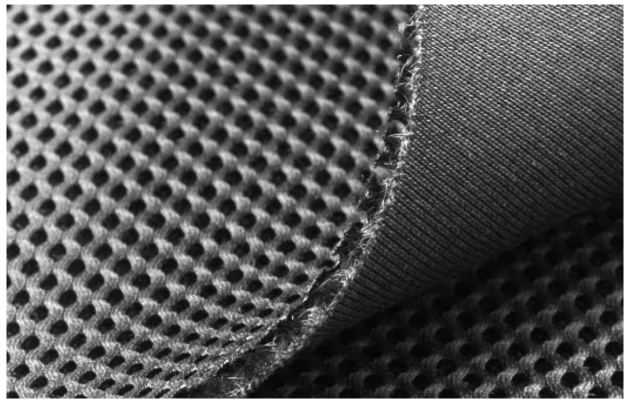


Figure 4.20: 3mm COOLMAX elastic 3D mesh fabric

Figure 4.21: 2-layer knitted, Neoprene like fabric

Figure 4.22: Textile temperature test samples

TEXTILE TEMPERATURE TEST RESULT AND DISCUSSION

As shown in Figure 4.22, four different samples were made for the textile temperature test: double layer polyester fleece, single layer neoprene-like fabric, single layer 3D mesh fabric, and composite of single neoprene-like fabric layer and single 3D mesh fabric fused together using Vliesofix. The polyester fleece textile had to be doubled because a single fleece layer was too pliable and stretchy. The test results of the four samples are compiled into a Table 4.

Except for the composite sample, the three samples (double polyester fleece, single neoprene-like fabric, and single 3D mesh fabric) had similar cooling durations for the embedded SMA wire to reach 30°C from 70°C. The 3D mesh fabric did have a marginally shorter cooling duration of 4 to 5 seconds. The composite sample had the worst cooling duration out of the four samples. On the other hand, the single layer neoprene-like fabric did not insulate heat well since it started to feel uncomfortably warm at 60°C. It is important to note that the comfortable temperature on the skin is subjective, and it may feel different when the textile and SMA wires are in a prototype configuration than simply being placed on the skin like it did for this textile temperature test. Especially for the 3D mesh fabric, the felt temperature on the skin would differ if the SMA wire presses down to reduce the mesh gap between the wire and the skin. However, a single layer 3D mesh fabric seems to be the best candidate to embed SMA wires for wearables because it has the fastest cooling duration while allowing some warmth transmission to the skin.

Table 4:

	Double layer polyester fleece	**Single layer neoprene-like fabric**	**Single layer 3D mesh fabric**	**Neoprene-like + 3D mesh + Vliesofix**
Cooldown time 1	1 min 7 sec	1 min 8 sec	1 min 3 sec	1 min 26 sec
Cooldown time 2	1 min 11 sec	1 min 8 sec	1 min 4 sec	1 min 24 sec
Cooldown time 3	1 min 9 sec	1 min 9 sec	1 min 5 sec	1 min 27 sec
Avg time	1 min 9 sec	1 min 8 sec	1 min 4 sec	1 min 26 sec
Noticeable temp.	Started to feel warmth ~80°C. Hardly noticeable.	Started to feel warmth ~50°C. 60°C felt a bit uncomfortable	Started to feel warmth ~70°C. 80°C felt a bit uncomfortable	Started to feel warmth ~85°C. Hardly noticeable.

* Textile temperature test result comparison. Cooldown time refers to the duration it took for the embedded SMA wire to reach 30°C from 70°C

4.4 Insights from Material Tinkering and Explorations

The following list summarizes the insights gathered from material tinkering and exploration on SMA springs and textiles:

1. Flat zigzag springs are easier to embed onto fabrics than spiral springs because they lack the 3D height element. However, this also means that the zigzag springs are easier to deform.

2. All SMA wires could exhibit elongating behaviors when they undergo repeat stretch cycles beyond their recommended strain level. The elongating behaviors formed similarly between different sized spiral springs.

3. For spiral springs, stretching to twice their length (200% stretch) seems to be safe and does not result in the elongating behavior formation. However, further testing is required for the zigzag springs.

4. Since warmth is another key tactile experience for DTP wearable garments, balancing between heat protection and heat dissipation through textile selection is important for embedding SMA actuators.

5. 3mm COOLMAX elastic 3D mesh fabric has the fastest cooling duration for the embedded SMA wire and allows some warmth transmission to the skin.

5. WORKING CONCEPTS, PROTOTYPES, AND EVALUATIONS

5.1 Existing Product Inspirations and Concept Ideation

Wearable devices that mimic existing garments or accessories are easier to be discreet or hide in plain sight (Chapter 2.3-B). However, mimicking a daily worn clothing item like T-shirts also means that the wearable garment would have to be easily interchangeable and washable. With those insights in mind, two existing products served as inspirations for this project's concept ideation.

A. Harness Concept

The Harness Concept was inspired from a reflective runner's harness vest with LED lighting for visibility at night (Figure 5.1) and HaptiHug by Tsetserukou as shown in Figure 5.2 (2010). A harness can be seen as a skeletal version of a vest that can be worn underneath or on top of regular clothes. Because it can be worn under other clothes, fashionability and style aesthetics would not be an issue. Additionally, a harness would not require as much washing compared to daily worn clothes like shirts, tank tops, and vests.

Based on an existing runner's harness, the following harness concept was generated (Figure 5.3). The harness straps allow for easy size adjustability which allows better garment fit that's needed for proper compression sensation. The narrow front allows for the harness to be worn by female bodied users without compromising fit and comfort. The harness concept utilizes stroking sensations on the back with a wider back panel and compression sensations along the straps. The stroking sensation would be provided by SMA actuators similar to Dragger Springlets (Hamdan et al., 2019) and the compression sensation would be provided by spiral spring SMA actuators similar to DTP vests in research (Duvall et al., 2016, Foo et al., 2018; 2019; 2020).

Figure 5.1: NeatTimes reflective harness vest with LED lighting for running at night

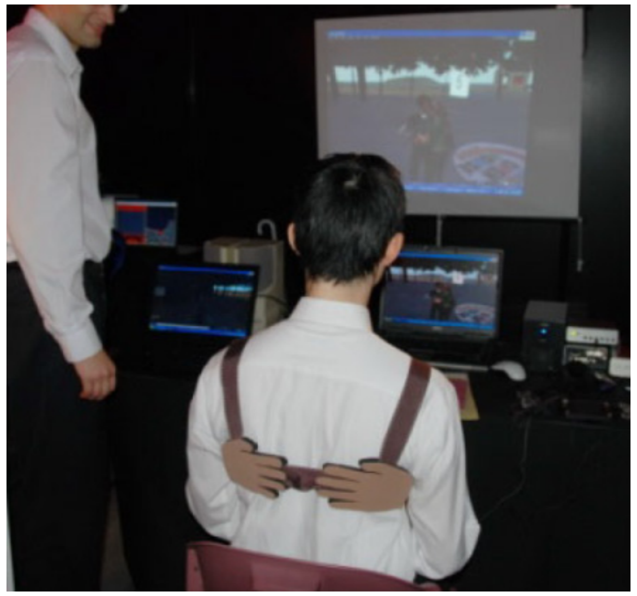


Figure 5.2: HaptiHug harness prototype (Tsetserukou, 2010)

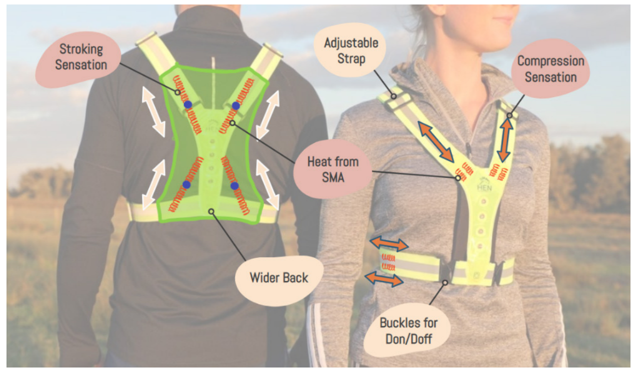


Figure 5.3: Harness concept with stroking, compression, and warmth sensations

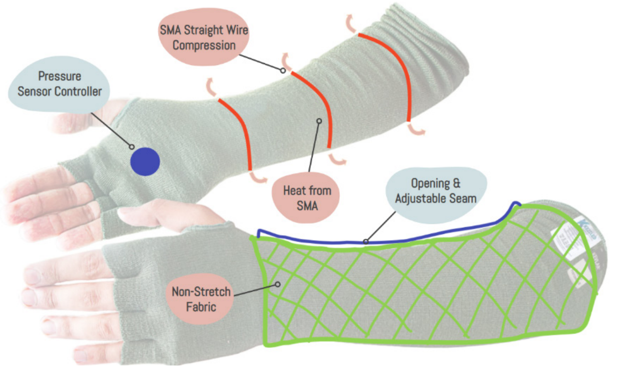


Figure 5.5: Sleeve concept providing compression and warmth sensations and controllable with pressure sensor

B. Sleeve Concept

The sleeve concept was inspired from compression sleeves for sports (Figure 5.4- A) and fingerless glove sleeves (Figure 5.4- B). Detached sleeves can be considered as items in between a garment and an accessory; they can be worn discreetly underneath other clothes or visibly as a fashion statement because of their low profile. Many of the commercial and research DTP wearables focused on providing compression sensations to the torso to emulate a hug, but there was pressure and warmth also present on the inner forearms based on the autobiographical investigation. So a DTP sleeve paired with a DTP vest could further enhance the hug emulating experience.

Also drawing inspirations from Grippy (Li, 2022) and Affective Sleeve (Papadopoulou et al., 2019), the following sleeve concept (Figure 5.5) was generated. The warmth and pressure sensations can be from a composite of straight SMA wires and non-stretch fabric. A pressure sensor embedded on the palm area of the fingerless glove sleeve can be used as a controller for the SMA actuators. The pressure sensor can also be paired with wireless signal transmitters as a way to intuitively control a DTP vest or the harness concept rather than relying on mobile apps or a tethered buttoned controller.

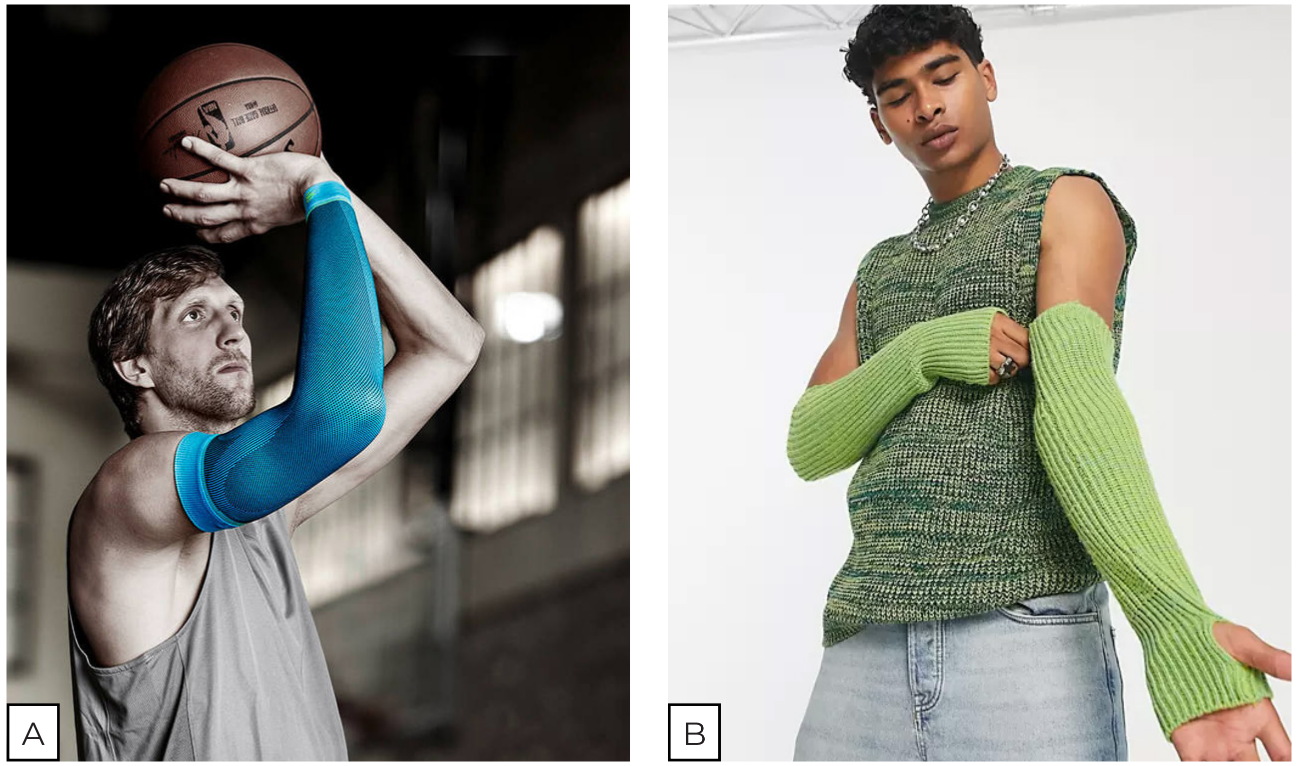


Figure 5.4: [A] Sports compression sleeve; [B] Fashion statement fingerless glove sleeve

5.2 Stroking Prototype Development and Evaluation

A. Stroking Prototype Development

Stroking falls under the umbrella of DTP sensations along with compression sensations. Since the harness concept includes providing stroking sensations to the back, a stroking SMA actuator prototype was developed with inspirations from Hamdan et al.'s Springlet dragger (Figure 2.17-B) (2019).

The Springlet dragger uses rigid "end-effector" beads in between two SMA springs that are antagonistic to one another (Hamdan et al., 2019). The end-effector bead drags across the skin to create a stroking sensation by activating one of the springs. To develop my own stroking actuator, I first tried to make a similar but larger version of the Springlet dragger. Based on the material tinkering explorations, SMA springs could only be stretched to approximately twice their length before forming two-way SME behaviors. The goal was to create an actuator that can provide a stroking sensation to a large area on the back of a torso, so it was necessary to create long springs to cover a larger distance. The bolt jig (Figure 4.2) used to create the springs in Chapter 3.1-A could only create approximately 2.4 cm springs because of the washers and hex nuts taking up large portions of the bolt length. Additionally, the jig setup made it difficult to dictate the direction of the extra SMA wires at the spring ends, resulting in springs with inconsistent end wire directions. Thus the previous bolt jig was revised to increase the resulting spring's length and to have control over the direction of the spring end wires.

As shown in Figure 5.6, the revised jig allows for the ends of the excess SMA wire to be affixed to perforated metal sheets with different sets of bolt, washer and hex nut. The main M4 bolt used to form the spring shape was held in place by using L-brackets. This revised configuration resulted in 2.8 cm springs. Using a longer M4 bolt or a threaded rod would yield longer springs, but 2.8 cm springs were long enough for the first version of a stroking actuator prototype. The revised jig can be mounted onto one perforated sheet rather than two sheets arranged in a V shape as shown in Figure 5.6. However, due to the limited height of the L-brackets, it was difficult to wrap the SMA wires around the bolt without losing the tension necessary to form a consistent spiral shape. To work around this issue, the perforated sheets were arranged into the V shape configuration for more working space and easier access to the bolt.

Two 2.8cm long M4 spiral springs were created with the revised jig using approximately 55 cm of 0.5mm diameter 40°C activation temperature nitinol wire (45cm for the spring, 10cm for excess wire ends). The end-effector that connects the two M4 springs were made out of an 8mm diameter wooden dowel. A segment of a wooden dowel was sanded down to create a flat surface for one end of the spring to sit flush against (Figure 5.7). Then a small hole was drilled next to the flat surface for the SMA wire end to fit through. The 8mm diameter wooden dowel was too narrow and fragile to have both sides sanded down and drilled holes for the springs to align. Instead, a Z shaped end-effector was made using the 8mm wooden dowel as shown in Figure 5.8.

Figure 5.6: Revised bolt jig for longer spring length and controlled spring end wire directions

Figure 5.7: Wooden end-effector with a flattened side and a small hole for 0.5mm diameter SMA wire to fit through

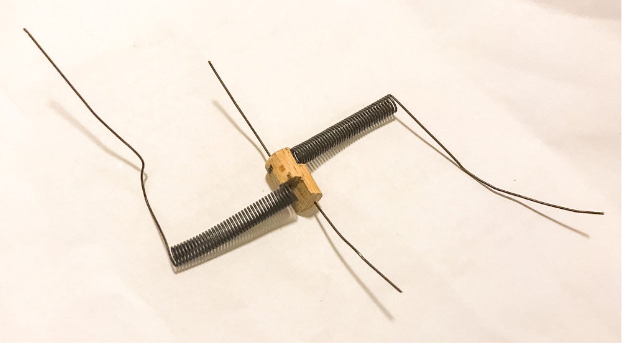


Figure 5.8: Z shaped wooden end-effector with two SMA springs

Figure 5.9: Stroking actuator prototype with two M4 SMA springs in antagonistic directions connected through a wooden end-effector

The SMA springs were tied to the Z shaped wooden end-effector using regular sewing threads to avoid using glue that could melt or burn off when the SMA springs are heated. The other ends of the SMA springs were sewn to a rigid 3mm felt fabric frame attached to double layered muslin fabric as shown in Figure 5.9. The felt fabric frame length was based on the width of the end-effector and three times the SMA spring length so that when one of the springs is activated and contracted to its trained length, the antagonizing spring would be stretched to twice its trained length. As a result of this configuration, the end-effector lifted away from the surface where it was meant to provide the stroking sensations, so sewing threads under tension were placed along the end-effector to apply a downward force.

B. Stroking Prototype Evaluation

To evaluate the effectiveness of the stroking SMA actuator, the prototype was strapped around my arm (Figure 5.10) and the springs were heated using a lab electric power supply. Unfortunately, hardly any stroking sensations were felt when the appropriate springs were heated to activate the stroking actuator. Even after one of the muslin fabric layers was cut out to reduce the fabric barrier, I could still hardly tell the stroking sensations on my forearm.

One of the reasons contributing to the lack of stroking sensations could be due to the muslin fabric. The end-effector had trouble gliding on top of the coarse muslin fabric and would create a jagged dragging movement rather than smooth stroking movement. Some of the benchmarking projects used low friction fabrics like Teflon (Foo et al., 2018) and lycra (Duvall et al., 2016) to promote smooth SMA actuation, so replacing the muslin fabric with a low friction fabric could improve the stroking prototype.

On the other hand, the jagged movement could also be attributed to the SMA springs twisting when activated because of the misalignment of the springs. Even if the springs were aligned, the rigid electrical wires connected to the SMA wire spring ends at the end-effector could still cause the springs to twist because the wires were not secured to a surface. However, the wires coming off of the end-effector also need to glide along to provide an electrical pathway without restricting the end-effector's movement, so attaching the wires to a fixed point would not be an option. Having a plastic channel or guide rails along the length of the stroking prototype could provide a place for the electrical wires to sit in and better control their movements, but the rigidity of the channels would likely cause discomfort in a wearable garment setting.

Regardless of the cause behind the jagged movements, the stroking prototype could only produce about 2cm of displacement. The 2cm of stroking movement is inefficient especially compared to the 10cm long space necessary for the entire stroking prototype. Additionally, the stroking prototype is not flush against the skin due to the end-effector and SMA springs' height. This could result in the SMA springs getting caught on other surfaces or clothes when used for the harness concept. Therefore, the stroking prototype was deemed impractical for this project and further iterations were not developed.

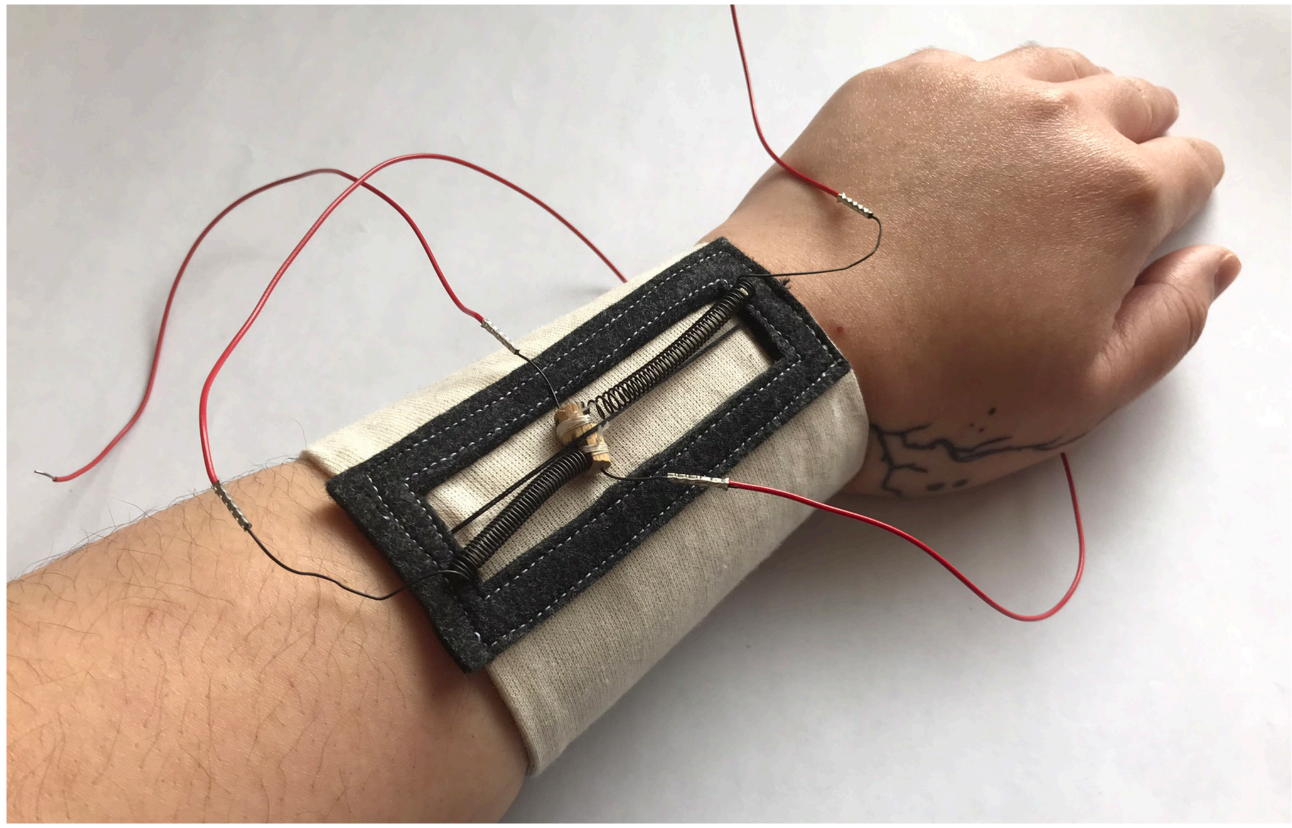


Figure 5.10: Stroking prototype wrapped around my forearm

5.3 Wrist Prototype Developments and Evaluations

Unlike the harness concept, the sleeve concept is based around using SMA wires in straight forms rather than springs, and it was heavily inspired from Papadopoulou et al.'s Affective Sleeve SMA actuator mechanism. Affective Sleeve has straight trained 0.5mm diameter nitinol wires with 45°C activation temperature sandwiched between two insulating layers of thick felt fabrics. The straight trained SMA wires are bent around the forearm when wearing the Affective Sleeve. As the SMA wires are activated, they try to return to their straight forms, resulting in "a slight sensation of pressure and warmth on the forearm" as the wires tug on non-stretch fabrics (Papadopoulou et al., 2019).

I was drawn to Affective Sleeve's actuator mechanism because SMA wires already come straight trained and negates the need to anneal the SMA wires to train them. This simplifies the prototype fabrication process and possibly manufacturing process if this method were to be used in commercial wearables. Additionally, straight wires are easier to embed into fabric and less bulky than springs for wearable garments. So I attempted to recreate the Affective Sleeve's actuator mechanism based on the limited prototype fabrication method information available in Papadopoulou et al.'s literature publication as a starting point to my prototype development.

A. Affective Sleeve Replication Attempts and Evaluations

For my first attempt at replicating the Affective Sleeve's actuator mechanism, I used a single 10cm long SMA wire with 0.5mm diameter and activation temperature of 40°C on a wrist band made of 3mm thick black felt fabric and muslin fabric (Figure 5.11). The SMA wire was sewn directly onto the felt fabric using regular sewing threads. Even though I used the same diameter nitinol wire with similar activation temperatures and similar felt fabric, the first replication attempt did not yield any feeling of pressure sensation. When the SMA wire was removed from the prototype, the felt fabric slightly melted and partially fused onto the SMA wire even when the fabric's recommended maximum ironing temperature was 110°C. Additionally, the SMA wire "reprogrammed" itself from straight to a curved shape similar to my wrist curvature when it was placed in boiling water. The accidental reprogramming may have contributed to the lack of pressure sensation. Even if there was some slight pressure sensation, the warmth from the SMA wire could have been overpowering and distracting. Moreover, there are other possible variables that could have impacted the degree of felt pressure sensation such as the number and length of SMA wires used.

Figure 5.11: First wrist prototype attempt with 1 SMA wire

NUMBER OF WIRES

As shown in Figure 5.12, Affective Sleeve used 2 of 0.5mm diameter SMA wires per cuff (Papadopoulou et al., 2019). Even though I used the same diameter SMA wire for my first attempt, it only had 1 wire, so there may not have been enough generated force to overcome the bending geometry. Therefore, the subsequent iterations used more than 1 SMA wire to generate the pressure sensation. However, connecting the two straight SMA wires to establish a proper electrical connection posed an electrical connectivity challenge.

LENGTH OF WIRES

Additional to the number of wires, the length of the SMA wires could have also contributed to the lack of pressure sensation. As shown in Figure 5.13, the Affective Sleeve has a longer felt fabric area to accommodate the longer SMA wires than the non-felt fabric without SMA wires. My first replication attempt used 10 cm long SMA wires as it covered roughly half of my wrist (Figure 5.14- A). However, the Affective Sleeve seemed to have used longer SMA wires that go past the wrist's halfway point, so I also created 16cm long SMA wire prototypes (Figure 5.14- B). Despite using longer 0.5mm diameter SMA wires, this still did not yield enough noticeable pressure sensation around my wrist especially with the simultaneous heat buildup.

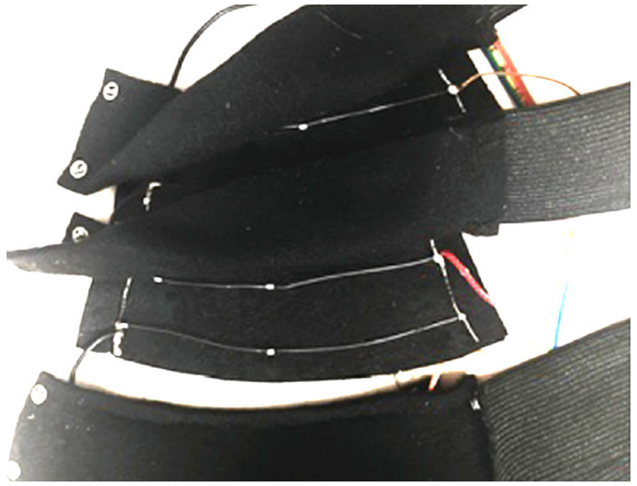


FIGURE 5.12: PHOTO OF SMA WIRE ACTUATOR MECHANISM FOR AFFECTIVE SLEEVE (PAPADOPOULOU ET AL., 2019)

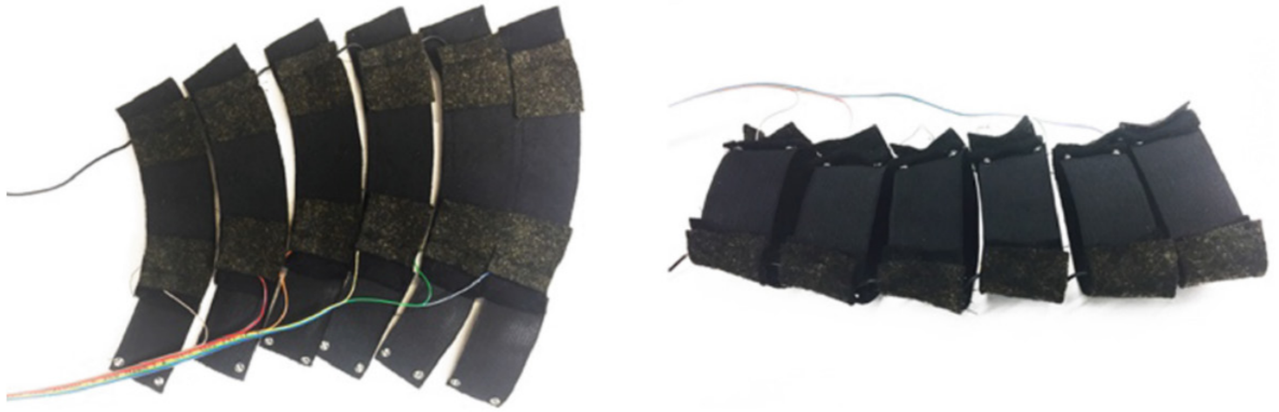


FIGURE 5.13: PHOTOS OF AFFECTIVE SLEEVE IN OPEN (LEFT) AND CLOSED (RIGHT) POSITIONS (PAPADOPOULOU ET AL., 2019)

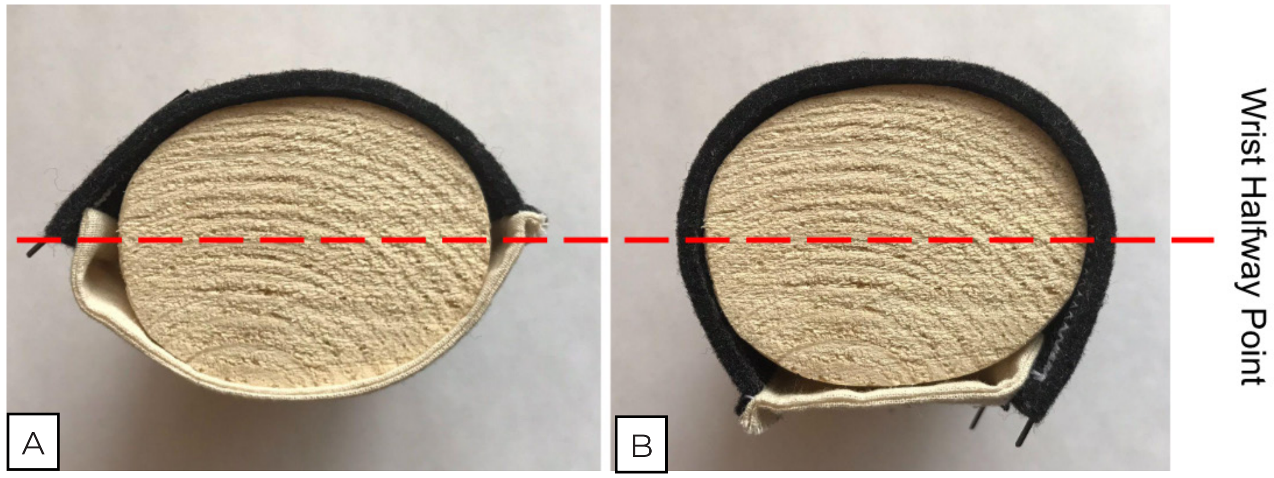


FIGURE 5.14: CROSS-SECTIONAL VIEW OF A WRIST SHAPE MOCK-UP WITH [A] 10CM PROTOTYPE AND [B] 16CM PROTOTYPE

ELECTRICAL CONNECTIVITY CHALLENGE

To establish electrical connection over two straight SMA wires, I first tried to solder them to a piece of regular electrical wires. But SMA wires are notoriously difficult to solder (Chapter 2.5-A), so to bypass that difficulty, a regular electrical wire was wrapped tightly around the SMA wires and covered with a bead of solder (Figure 5.15- A). That method worked initially, but the electrical connection stopped working after about a week. As an alternative, I tried to wrap a regular wire even more tightly and with more loops (Figure 5.15- B), but this still resulted in subpar electrical connection and melting of the rubbery electrical wire insulation housing. Using an infrared thermal camera, I realized there were localized heat build-ups on regular electrical wires that are far greater than the SMA wire thermal readings that were taken further away from the source of localized heat (Figure 5.16). This is likely due to lack of conductive surface area contact between the alligator clips and the SMA wires, resulting in higher localized resistance and heat build up similar to the wire wrap method in Figure 5.15- B.

There were two different methods used to overcome this electrical connectivity challenge: training an SMA wire into a U shape, or using electrical crimps. As shown in Figure 5.17, a long piece of SMA wire can be bent and heat trained into a U shape; essentially using the SMA wire

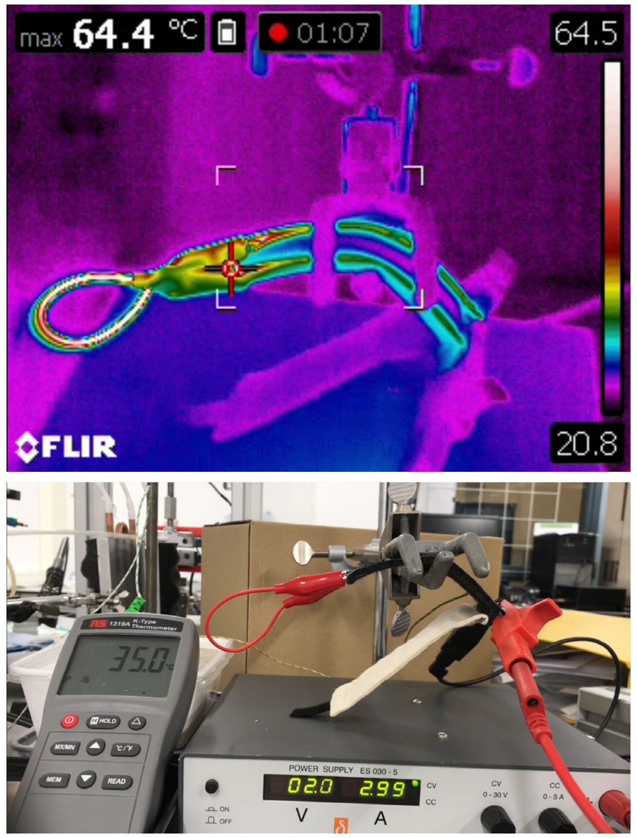


FIGURE 5.16: [TOP] IR THERMAL CAMERA READING 64.4°C ON THE ELECTRICAL ALLIGATOR CLIPS/WIRE WHEN [BOTTOM] THERMOMETER READING ON THE SMA WIRE WAS 35°C

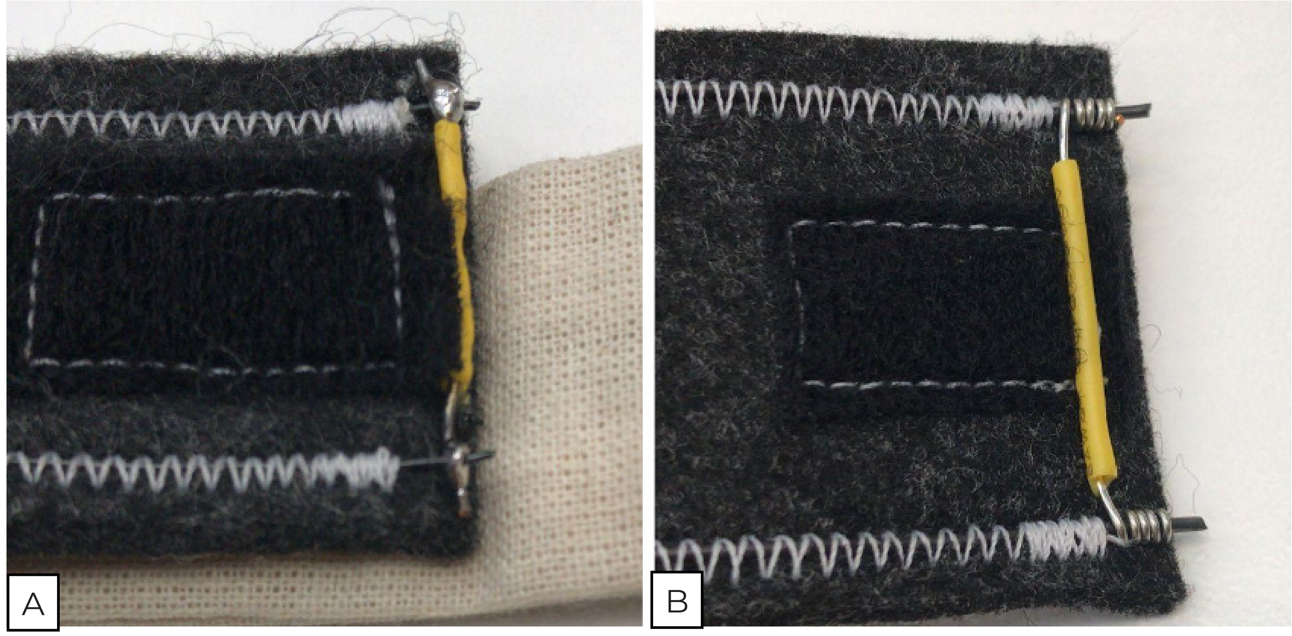


FIGURE 5.15: ATTEMPTS AT MAKING ELECTRICAL CONNECTIONS ON TWO SEPARATE SMA WIRES. [A] REGULAR WIRE WRAP + SOLDER METHOD, [B] TIGHTER AND MORE WRAPS WITH REGULAR WIRE

itself to establish electrical connection between two straight SMA wires. Approximately 3cm of additional SMA wire length was required to act as a bridge between the two “straight” SMA wires for my wrist prototypes. So a 10cm prototype required approximately 23cm SMA wire, whereas a 16cm prototype required approximately 35cm SMA wire to form the U shape.

This U shape method worked as a temporary solution for the wrist prototype iterations; however, this still doesn’t resolve the connectivity issue for connecting to a power source without bulky alligator clips for an embodied working prototype. On the other hand, the use of electrical crimps eliminated localized heat build up as shown in Figure 5.18. Using electrical crimps does not require heat training the SMA wires like the U shape method. The U shape method was used for the majority of wrist prototype iterations, while the crimp method was used for the sleeve prototypes (Chapter 6).

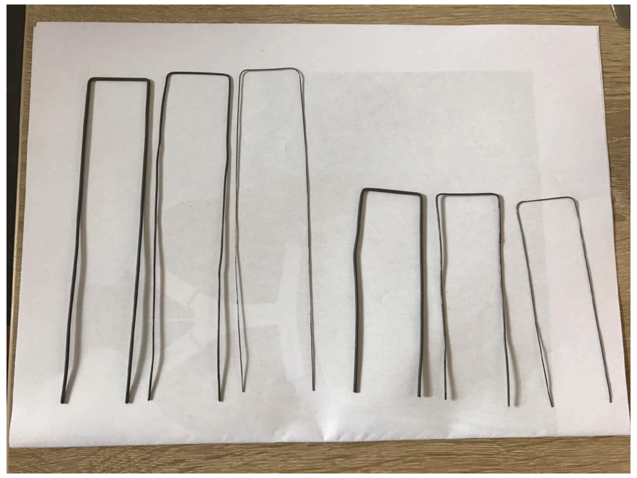


Figure 5.17: Different diameter “straight” SMA wires formed and trained into U shapes for electrical connectivity

WRIST PRESSURE SENSING DEVICE

Since pressure or force discrimination thresholds are subjective and different based on body location, the 0.5mm diameter wires could be exerting some pressure but not enough to be noticeable on the wrist. To assess the pressure levels objectively, I fabricated a wrist pressure sensor device (Figure 5.19) with two force sensitive resistors (FSR) sensors, foam pads cut to the size of the FSR sensing area (approx. 1.75in x 1.5in), and a wooden block sanded down to a shape similar to my wrist. This device connects to an Arduino to get FSR analogue readings and gives a better understanding of the pressures felt on the top and bottom of the wrist.

Unfortunately, it is not possible to get accurate force readings in Newtons using an FSR sensor since it outputs “variation of its electric resistance” (Sadun et al., 2016). Attempts to establish certain weights to the readings by placing a known weight on the FSR sensors did not result in consistent values even with a foam pad to evenly distribute the known weight’s force. Instead, the difference in FSR sensor values can be used as a relative measurement to see if there were changes in pressure from before and during SMA wire activation. The changes in average FSR sensor values for four different wrist prototypes (16cm and 10 cm long prototypes with 0.5mm diameter SMA wires, 16 cm and 10cm long prototypes with 1mm diameter SMA wires) are shown in Figure 5.20. The blue bars indicate the value changes on the FSR sensor placed on the side without SMA wires while the red bars are the changes on the side with SMA wires.

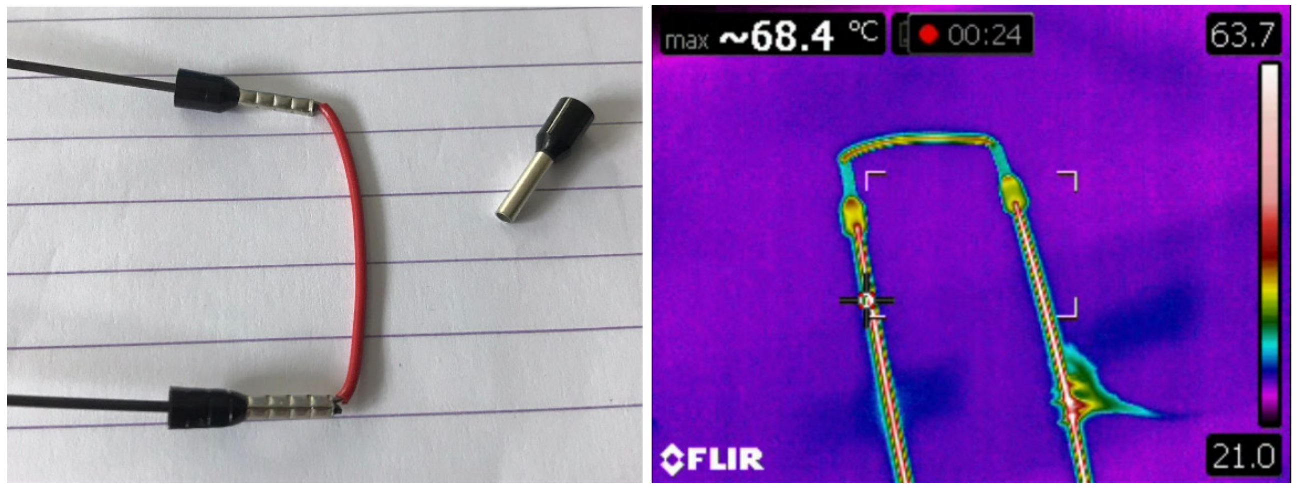


Figure 5.18: [Left] Two 1mm diameter SMA wires connected with a regular electrical wire using electrical crimps and [right] the IR thermal camera reading demonstrating more evenly distributed heat across all types of wires

It is important to note that the 16cm SMA wire prototypes had a decrease in FSR readings on the SMA side, while all other readings increased during the SMA wire activations. Additionally, the 1mm diameter wires showed greater changes in pressure compared to 0.5mm diameter wires. So 0.5mm diameter SMA wires may not be able to produce enough bending force to apply notable enough pressure on the wrist. Therefore, different diameter SMA wires may be more effective at generating the pressure sensations, which resulted in wrist prototype iterations that deviated from the Affective Sleeve’s actuator mechanism.

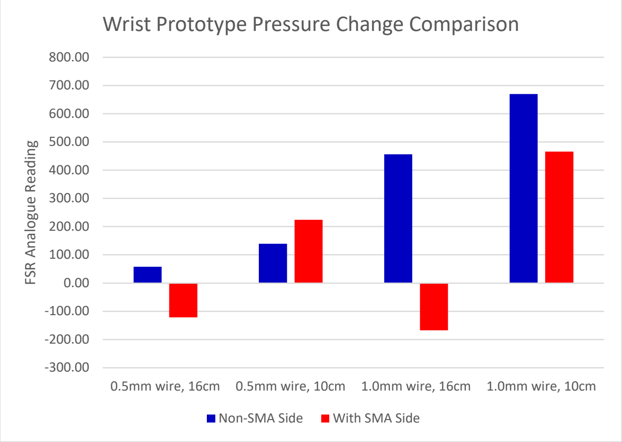


Figure 5.20: Changes in average FSR sensor values for four different wrist prototypes

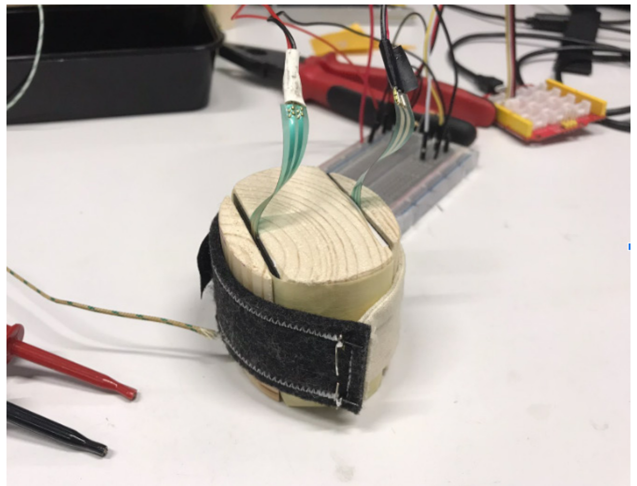


Figure 5.19: Wrist pressure sensing device with two force sensitive resistors (FSR), foam pads cut to the size of the FSR sensing area (approx. 1.75in x 1.5in), and a wooden block shaped similarly to my wrist

B. Deviating Wrist Prototype Iterations

Based on the previous explorations on trying to recreate the Affective Sleeve actuator mechanism, it was evident that larger diameter SMA wires are likely necessary to create noticeable pressure sensations on the wrist over the heat build up occurring simultaneously. This section goes into further detail on the changes in SMA wire diameters and other design deviations from the Affective Sleeve actuator mechanism.

SMA WIRE DIAMETER EXPLORATIONS

Changes to the SMA wire diameter was the first design deviation explored for the wrist prototypes. Because both the 16cm and 10cm long prototypes with 0.5mm diameter SMA wires did not produce noticeable pressure sensation around the wrist, I explored using 1mm and 1.5mm diameter SMA wires as well. 1mm diameter wire has an activation temperature range of 45 - 50°C while 1.5mm diameter wire has an activation temperature of 35 - 40°C. Both of those SMA wires were bought from Nanografi.com. As shown in Figure 5.33, the 1mm and 1.5mm diameter wires were also trained into straight U shapes to each make 16cm and 10cm long prototypes.

<u>Wrist Testing 10cm & 16cm Prototypes</u>: When the thicker wire prototypes of different lengths were tested on my wrist, they generated enough pressure sensations to be slightly more noticeable over the warmth sensation than the 0.5mm diameter prototypes. However, only the first activation generated enough noticeable pressure while the follow up consecutive activations generated comparatively subpar pressure sensations. This is mainly due to the thicker diameter SMA wires not fully returning (Figure 5.21& 5.22- B) to the wrist wrapped initial position (Figure 5.21& 5.22- A) after they’ve been activated once and cooled down to room temperature.

The 1mm and 1.5mm diameter SMA wires were not returning fully to their initial bent shape

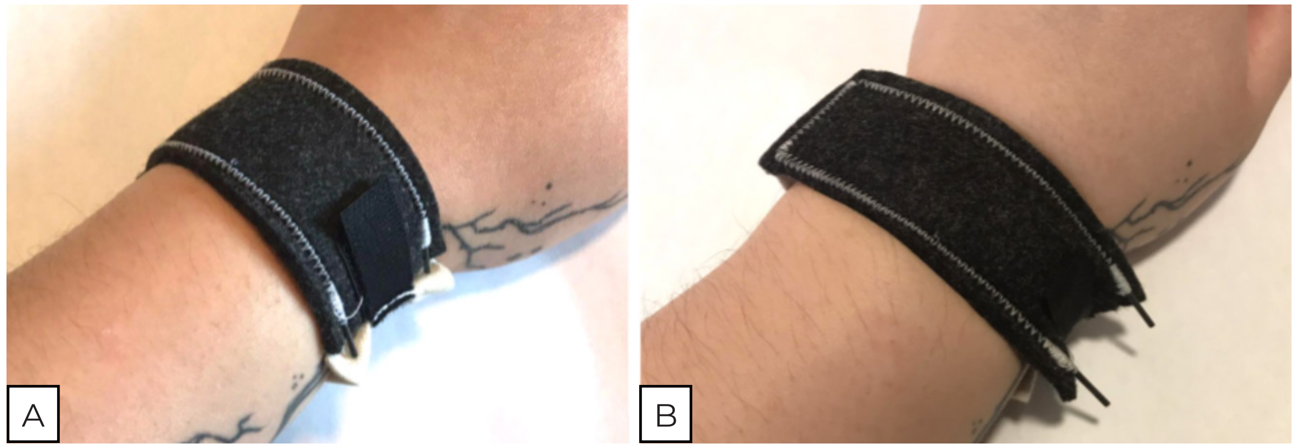


Figure 5.21: 1.5mm diameter 10cm prototype [A] before activation; [B] after activating & cooling down not returning back to initial bent shape

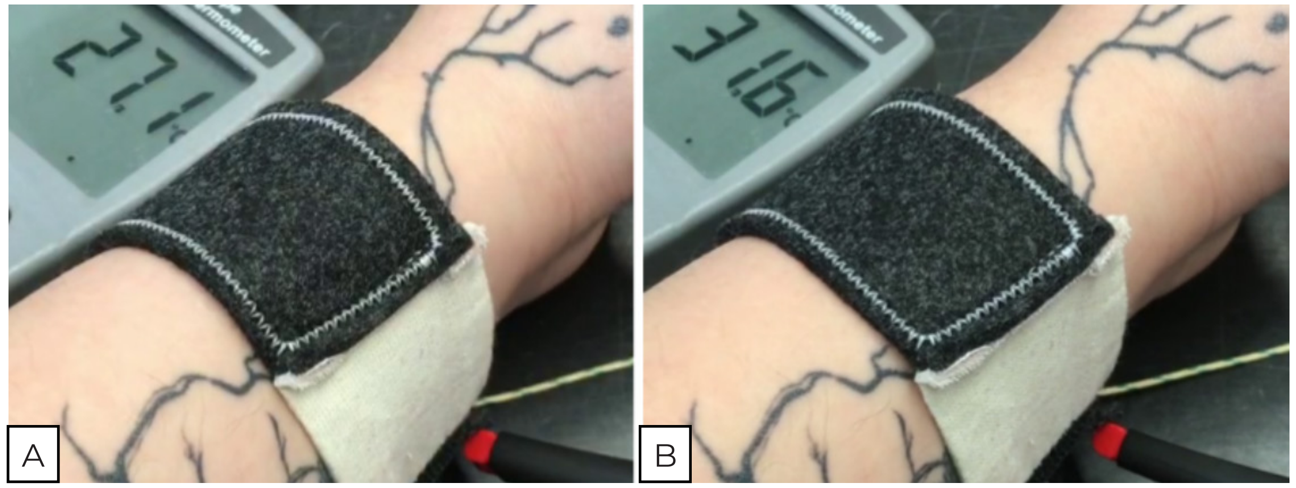


Figure 5.22: 1mm diameter 16cm prototype [A] before activation; [B] after activating & cooling down not returning back to initial bent shape

because the non-stretch fabric and velcro straps could not provide enough counter force to bend and wrap the SMA wires back around the wrist. This was especially evident for the 10cm prototype with 1.5mm diameter SMA wire, since the 1.5mm diameter SMA wire requires the highest amount of force to deform out of the three different wire diameter prototypes. For 16cm prototypes, it was evident that the ends of the SMA wires remained straight after activating and cooling down as shown in Figure 5.22- B.

FSR Testing 10cm Prototypes: The FSR pressure sensing device was used to monitor the relative pressure changes between before, during, and after activation for two consecutive activation cycles of 10cm prototypes with 1.5mm or 1mm SMA wires. The SMA wires were cooled down to room temperature between the two activation cycles using natural convection. As shown in Figure 5.23 and 5.24, the pressure levels did not return back to the initial starting pressure.

For the 1mm diameter 10cm prototype, the non-SMA side did get close to returning to its starting pressure compared to the SMA side. However, for the 1.5mm diameter 10cm prototype, it maintained about the same pressure levels for both sides once it reached its first activation even when the SMA wire was cooled to room temperature. Therefore, even though the actual applied pressure force was higher in the subsequent activation cycles, I only felt the changes in pressure likely due to pressure habituation.

FSR Testing 16cm Prototypes: The readings from the FSR pressure sensing device for 16cm prototypes were not as clear cut as the 10cm prototypes. The 16cm prototype with 1mm diameter SMA wire also underwent two consecutive activation cycles and natural convection cooling. The non-SMA side showed

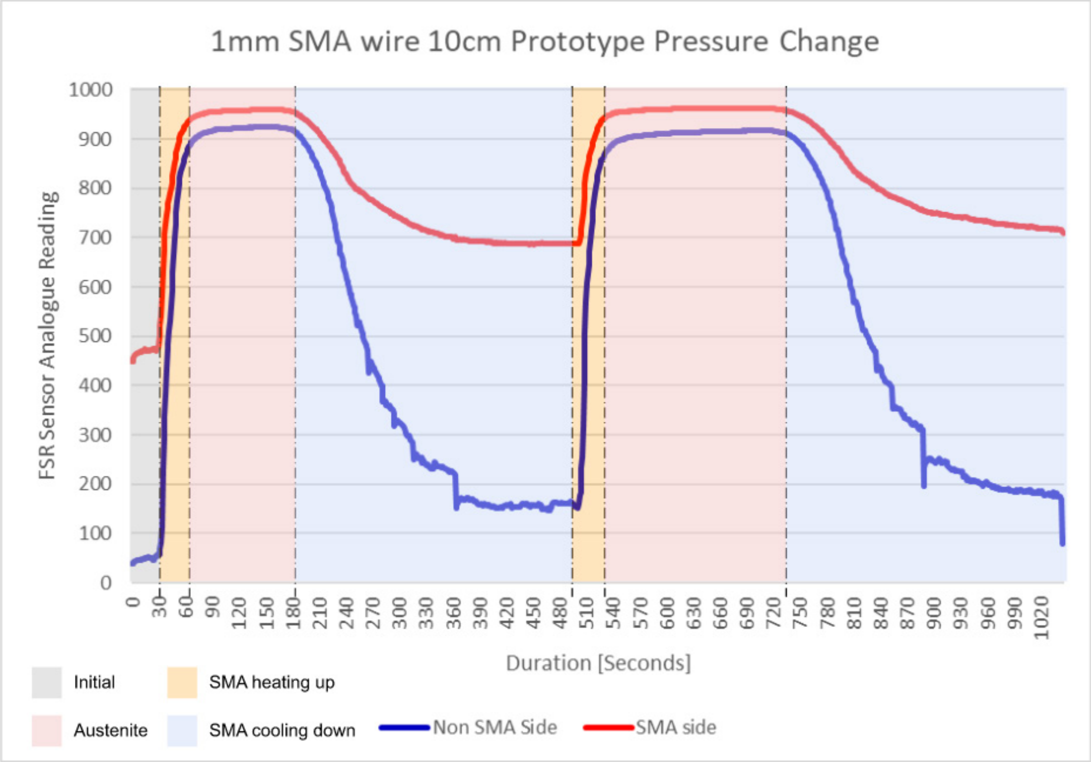


Figure 5.23: FSR sensor readings of 10cm wrist prototype with 1mm diameter SMA wire undergoing 2 consecutive activation cycles.

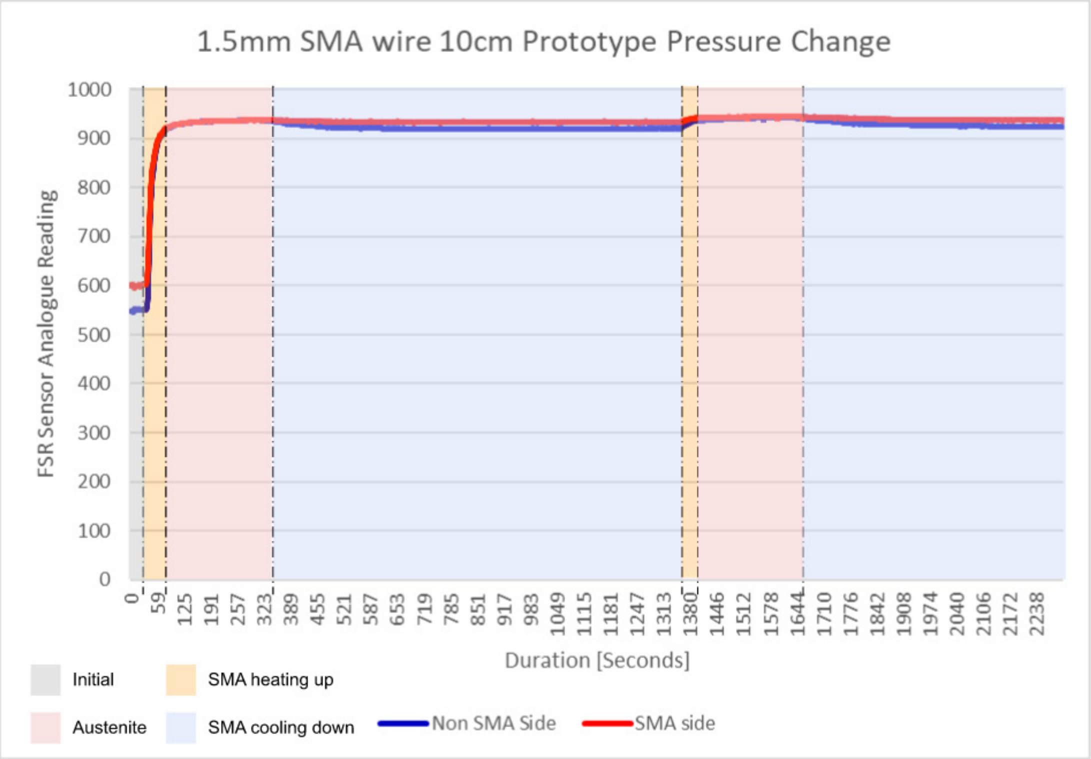


Figure 5.24: FSR sensor readings of 10cm wrist prototype with 1.5mm diameter SMA wire undergoing 2 consecutive activation cycles.

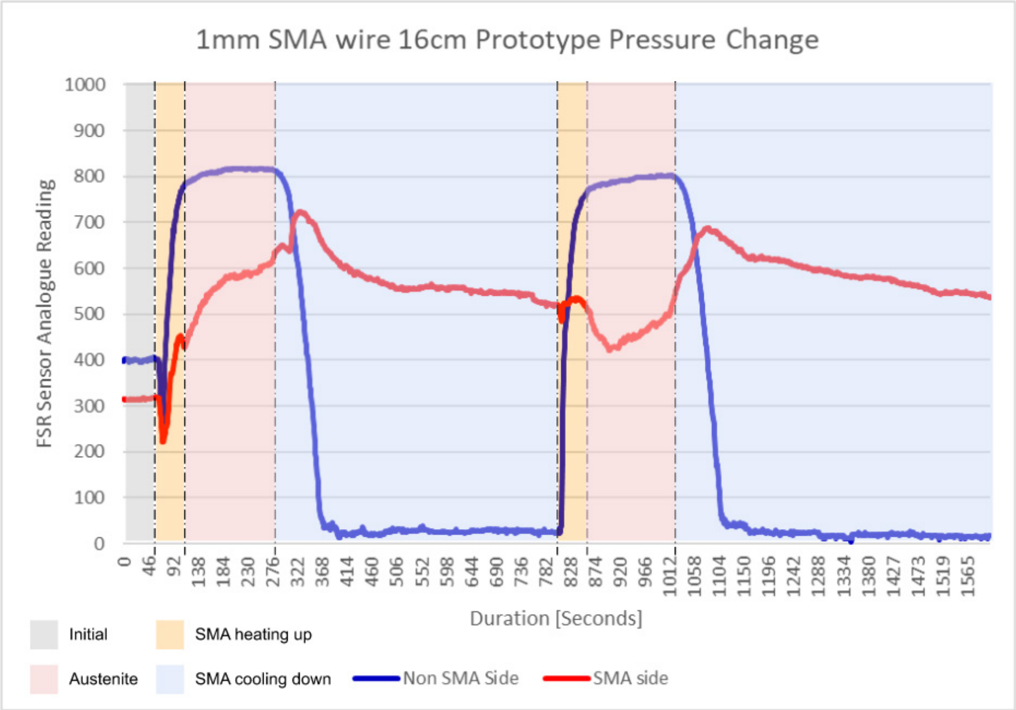


FIGURE 5.25: FSR SENSOR READINGS OF 16CM WRIST PROTOTYPE WITH 1MM DIAMETER SMA WIRE UNDERGOING 2 CONSECUTIVE ACTIVATION CYCLES.

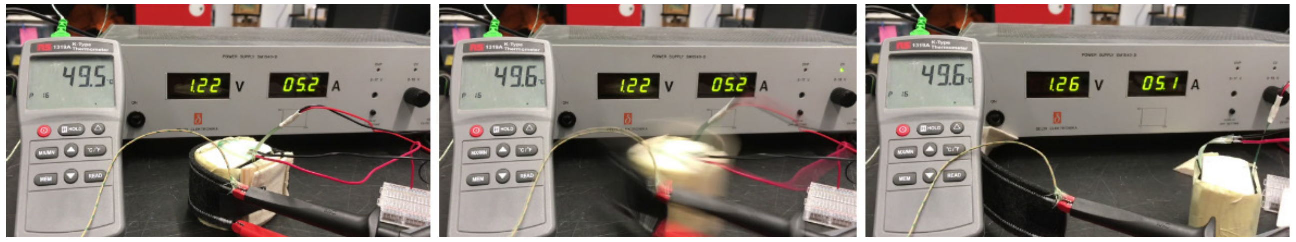


FIGURE 5.26: 16CM PROTOTYPE WITH 1.5MM DIAMETER SMA WIRE OVERCOMING THE VELCRO STRAPS AND EXPLOSIVELY PEELING OFF OF THE FSR PRESSURE SENSING DEVICE BETWEEN 49.5°C AND 49.6°C

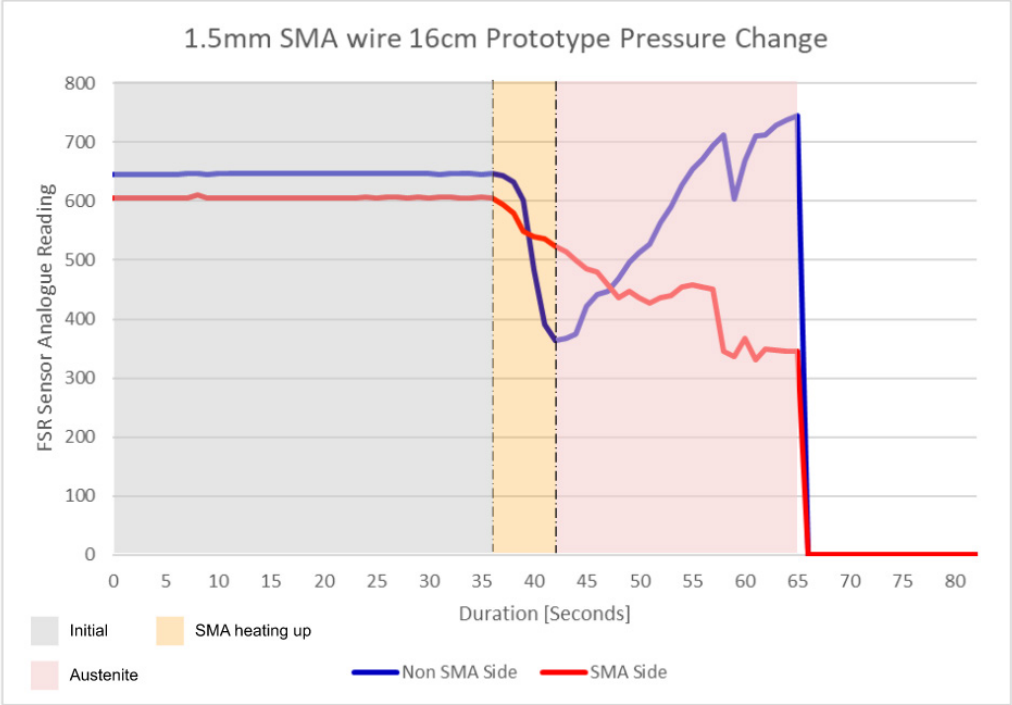


FIGURE 5.27: FSR SENSOR READINGS OF 16CM WRIST PROTOTYPE WITH 1.5MM DIAMETER SMA WIRE WHEN THE PROTOTYPE EXPLOSIVELY PEELED OFF AROUND 65 SECONDS

two distinct plateaued peaks similar to the 10cm prototype (Figure 5.25); however, the FSR reading dropped below the initial reading during the cooling phases. Conversely, the SMA side did not have plateaued peaks but stayed consistently higher than the initial reading.

On the other hand, the force of the activated 16cm prototype with 1.5mm diameter SMA wire occasionally overcame the velcro straps as the SMA wire tried to return to its trained straight shape. This resulted in the prototype explosively peeling off of the FSR pressure sensing device between 49.5°C and 49.6°C (Figure 5.26) at around 65 second duration on Figure 5.27. Although this did not happen when I tested the prototype on my own wrist, similar instances occurred when tested on the FSR pressure sensing device. Thus, the 16cm prototype with 1.5mm diameter SMA wires was deemed to be unsafe, so further testing was not conducted.

INTERIM OBSERVATIONS

1.5mm Diameter Wire's Superelastic Behavior:
In general, the 1.5mm diameter prototypes caused minor discomfort on my wrists when they did not return to their initial wrist wrapped position, since the SMA wires were pressing onto my bones. Compared to the 1mm diameter prototypes, the 1.5mm diameter prototypes were difficult to even bend around my wrist at room temperature. They had to be bent with both hands into arbitrary curvatures to be put on my wrist, since the SMA wires would exhibit superelastic behaviors causing difficulty when bending them against my wrist.

Conversely, the untrained 1.5mm diameter wires were not exhibiting similar superelastic behaviors. The development of superelastic behavior could be a result of the activation temperature changing from 35 - 40°C to below room temperature during the annealing process. Annealing temperature and duration can change the nickel to titanium ratio from oxidation, which then changes the activation temperature (Satoh et al., 2008). According to Aura Design (another SMA wire supplier), the annealing temperature should be around 500°C, but the annealing duration has to be determined experimentally since it depends on the wire diameter (n.d.).

Because the U shaped wires were trained at 550°C for 30 minutes, there is a likely possibility that the activation temperature changed. However, given how the 16cm prototype with 1.5mm diameter wire was deemed to be a safety hazard, the 1.5mm wire was no longer a viable candidate for this project. Instead, 1mm wire's ideal annealing temperature and duration was experimentally determined to be at 500°C for 15 minutes since the wire retained its original 45 - 50°C activation temperature range.

Insufficient Perceived Pressure Sensation:
When the prototypes were tested on my wrist, I observed that the 1mm diameter prototypes produced slightly more noticeable pressure sensations compared to the 0.5mm diameter counterparts. However, the pressure sensations were still not significant enough to be considered as DTP, as they were overshadowed by the heat buildup. At first, I thought increasing the amount of SMA wires would increase the felt pressure sensation. So I created new 10cm and 16cm prototypes to have essentially four lines of active SMA wires by sewing an untrained 1mm diameter wire into a W shape (Figure 5.28). Although the W shape prototypes did produce more noticeable pressure sensations compared to the U shape trained prototypes, they still had difficulty returning to the initial wrist wrapped position after one activation cycle. So far all the wrist prototypes explored used straight SMA wire's bending SME force combined with non-stretchy fabric to create the pressure sensation.

FIGURE 5.28: 1MM DIAMETER WIRE PROTOTYPES [LEFT] W SHAPE, [RIGHT] U SHAPE

CURLED U SHAPE TRAINED SMA WIRES

A different SMA mechanism approach was necessary since the straight SMA wire approach was not producing satisfactory enough pressure sensation for a DTP wearable. Because the straight wire approach faces challenges in returning to a wrist-wrapped position, a more effective solution would be to utilize a curled shape trained wire approach, which can improve consecutive activation cycles. 1mm diameter SMA wire was trained into a curled U shape (Figure 5.29) by using a bolt jig similar to Figure 4.2. Instead of wrapping the SMA wire along the grooves of a bolt, the wire was kept straight to maintain the straight bridge between the two curled ends. M12 threaded rod was used to create the curled shapes at the wire ends, which resulted in uneven and overlapping circles with approximately a maximum of 2cm diameter.

The curled U shape trained SMA wire was then flattened out and sewn onto a 16cm felt fabric strap similar to the other wrist prototypes. The prototype was then tested on my wrist as shown in Figure 5.30, and it produced a more noticeable pressure sensation than the straight wire prototypes. When the curled U shape prototype activates, it applies radial pressure by tightening around my wrist. However, the most noticeable pressure was applied by the straight bar at the end of the prototype, since the ends of the prototype had the most visually noticeable range of motion.

Figure 5.29: Curled U shape trained 1mm diameter SMA wire

Despite the curled U shape not completely returning to its original wrist-wrapped position after a single activation cycle, it still loosened around my wrist as the SMA wire cooled down to room temperature. This allowed for more effective felt pressure sensations for consecutive cyclic activations compared to the straight wire wrist prototypes, because the baseline starting pressure for the consecutive activation cycles were closer to the original wrist-wrapped position. The FSR pressure sensing device's readings also verified this phenomenon as shown in Figure 5.31. Additionally, the curled U shape prototype was tested over six rapid consecutive activation cycles (Figure 5.32). A hand fan was used as a forced convection method to reduce the cooling duration between each activation cycle. Based on the FSR readings, it was evident that the curled U shape prototype is able to reproduce similar pressure sensations over multiple cycles.

Figure 5.30: Curled U shape 16cm prototype with 1mm diameter SMA wire tested on my wrist. [From left to right] Before activation (27.4°C), austenite state (71.5°C), and cooled after activation (33.0°C)

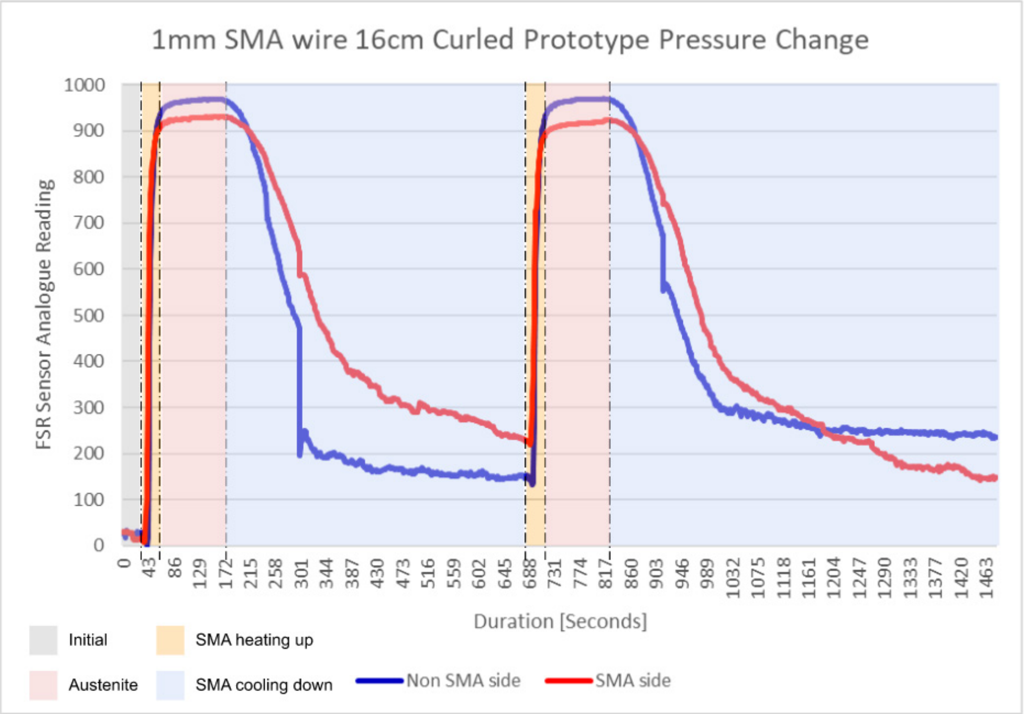


Figure 5.31: FSR sensor readings of 16cm wrist prototype with 1mm diameter SMA wire trained into a curled U shape undergoing 2 consecutive activation cycles.

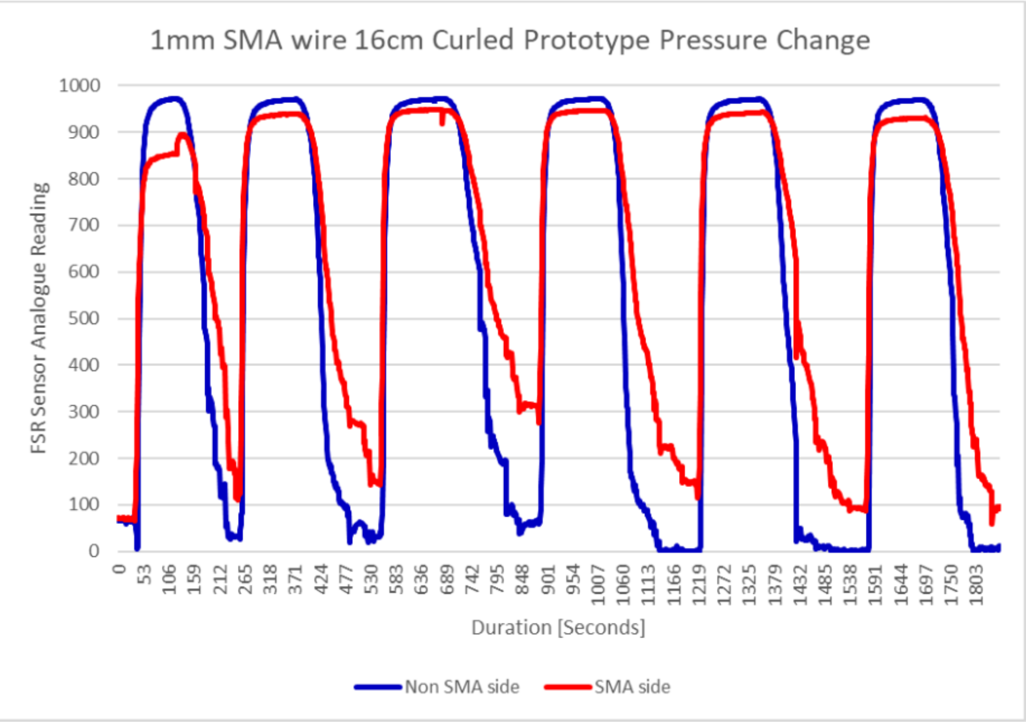


Figure 5.32: FSR sensor readings of 16cm wrist prototype with 1mm diameter SMA wire trained into a curled U shape undergoing six rapid consecutive activation cycles. The SMA wire was cooled using forced convection between each activation cycle.

C. Overall Wrist Prototypes Evaluations

The wrist prototypes were initially developed to replicate the Affective Sleeve's SMA actuator mechanism, but over time, design deviations were made to increase the perceived pressure sensation. The wrist prototype iterations are shown in order in Figure 5.33 starting from the left. The list of insights gathered from each iterations are as follows:

1. 10cm prototype; single straight untrained 0.5mm diameter wire: Single 0.5mm diameter SMA wire is not strong enough to produce any perceived pressure sensation.

2. 10cm prototype; two separate straight untrained 0.5mm diameter wires: It is difficult to solder SMA wires. Wrapping a regular electrical wire around the SMA wires and covering with solder works temporarily, but the electrical connection degrades and stops over time.

3. 10cm prototype; U shape straight trained 0.5mm diameter wire [top]: little to no perceived pressure sensation. May require a longer SMA embedded fabric strip.

4. 16cm prototype; U shape straight trained 0.5mm diameter wire [bottom]: little to no perceived pressure sensation even with longer SMA embedded fabric strip. Requires larger diameter SMA wires. Discontinue using 0.5mm diameter wire.

5. 10cm prototype; U shape straight trained 1mm diameter wire [top]: some noticeable perceived pressure sensation, but reduced for consecutive activation cycles from insufficiently returning to initial wrist-wrapped position.

6. 16cm prototype; U shape straight trained 1mm diameter wire [bottom]: same insights from #5.

7. 10cm prototype; U shape straight trained 1.5mm diameter wire [top]: same insights from #5. Formation of superelastic behavior from annealing setting, so it's difficult to deform around the wrist.

8. 16cm prototype; U shape straight trained 1.5mm diameter wire [bottom]: same insights from #7. SMA wire force overpowered the velcro strap several times during activation. Discontinue using 1.5mm diameter wire.

9. 10cm prototype; W shape straight untrained 1mm diameter wire [top]: more noticeable perceived pressure sensation than U shape counterpart, but has more difficulty returning to initial wrist-wrapped position after first activation

10. 16cm prototype; W shape straight untrained 1mm diameter wire [bottom]: same insights from #9

11. 16cm prototype; U shape Curl trained 1mm diameter wire: significantly noticeable perceived pressure sensation than the straight prototypes. Acceptable return to initial wrist-wrapped position after each activation cycle. Some radial pressure, but mainly from the connector bar curling into the wrist since the ends/shorter edges of the SMA strap had the most visually noticeable movement.

All the prototypes were tested on my own wrist to evaluate the subjective haptic experience, but the majority of the prototypes could not produce adequate perceivable pressure sensations over the heat buildup. To get objective insights into the pressure changes, I fabricated a FSR sensor based pressure sensing device that approximated the shape of my wrist. While the FSR pressure sensing device provided valuable insights into the relative pressure changes that the wrist prototypes generated, it is important to note that the sensor results do not fully capture the haptic experience perceived by humans. Because the FSR sensors were placed only on the locations related to the top and bottom areas of my wrist, the device could not record pressures applied radially or to the sides of the wrist. This is likely the reason behind the unclear SMA side sensor reading patterns for 16cm prototypes in Figure 5.25.

To give a better insight into the haptic experience, a visual representation of the perceived pressure locations for different prototypes are shown in Figure 5.34. This visual representation is based on my own subjective experience, so I can only provide the general locations of the primary and secondary perceived pressure sensations.

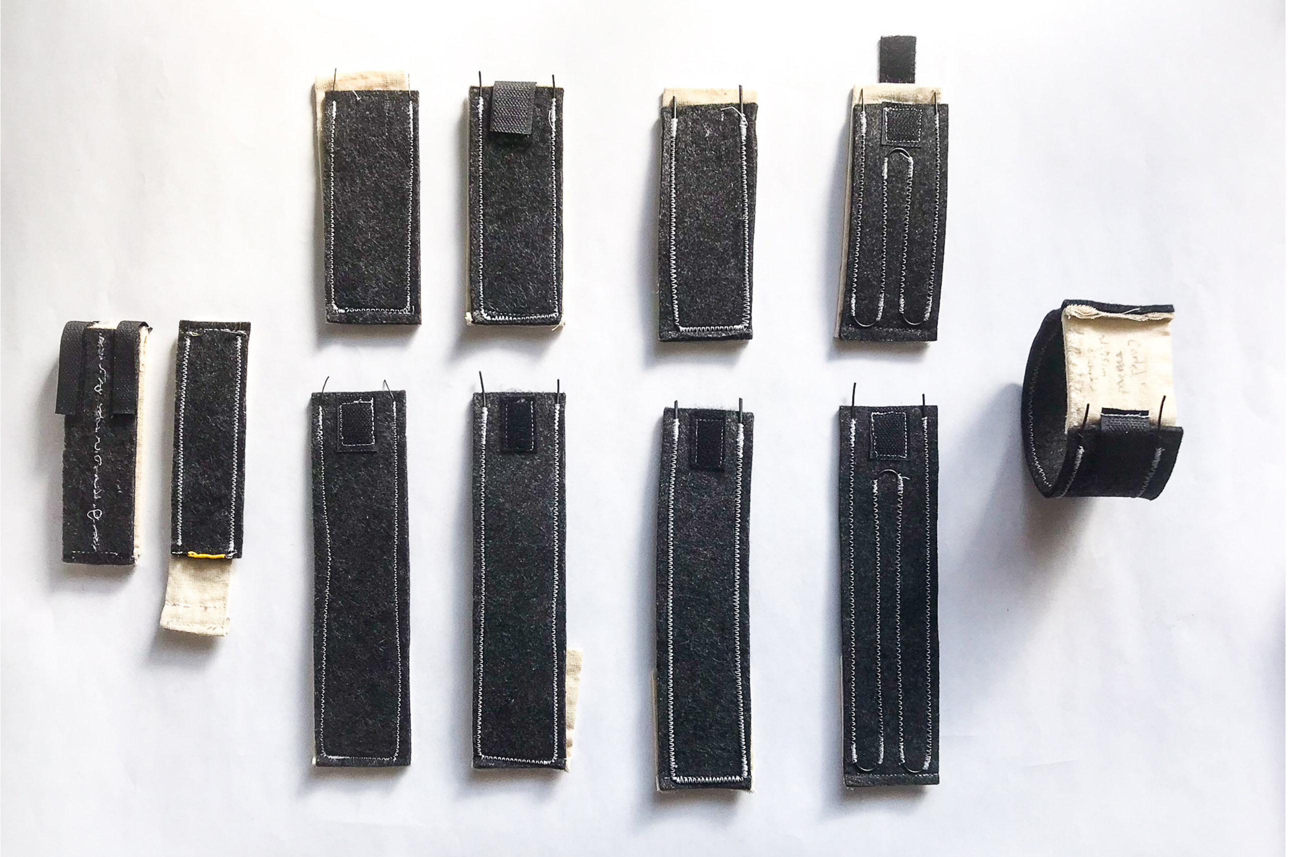


Figure 5.33: Wrist prototype iterations in chronological order from left to right. Some of the prototype's velcro fasteners were removed to be reused in sleeve prototypes.

The 10cm straight wire prototypes produced a clamping pressure applied to the top and bottom of my wrist. The 16cm straight wire prototypes produced some clamping pressure, but the main perceived pressures were on the sides of my wrist. Lastly, the 16cm curled wire prototypes produced some radial pressure only along the SMA embedded felt strap, but the main perceived pressure was from the short connector bar that was being pushed into my wrist.

Based on the various insights, it was evident that the curled prototype was producing the most noticeable DTP sensations and desirable SMA cyclic activation behavior compared to the straight wire prototypes. However, the curled U shape is difficult to train because of its complex geometry. Instead of the U shape, using electrical crimps and regular electrical wires as the connecting bar simplifies the SMA wire training process. The shape of the curled wires were also further iterated to improve the haptic experience.

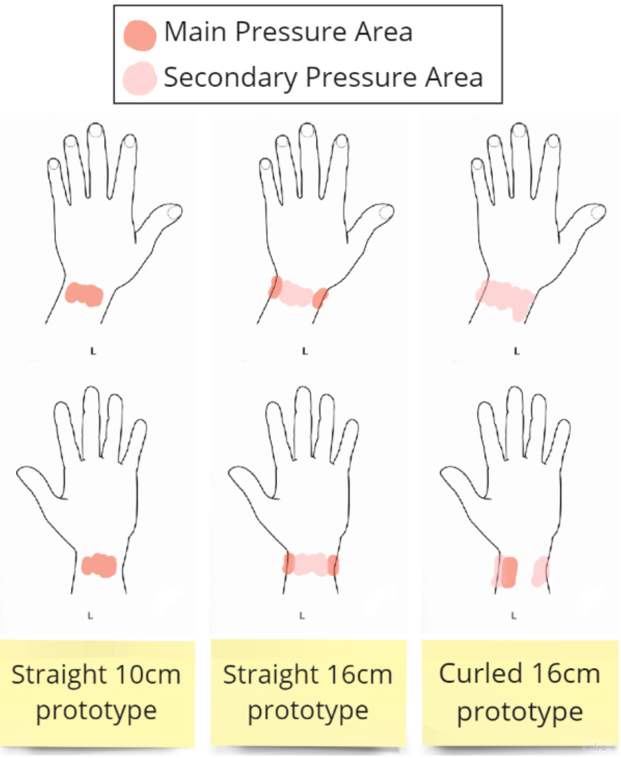


Figure 5.34: Perceived pressure areas from different wrist prototypes

D. Final Wrist Prototype Iteration Based on Evaluation

As discussed in previous sections, the U shape curl trained wrist prototype had the most promising results out of all wrist prototypes. This section covers the final wrist prototype iteration done to further improve the curled SMA wire actuator mechanism. By iterating on the SMA trained shape, two main issues from the U shape curl prototype were addressed: enhancing the consistency of the perceived pressure distribution to eliminate any hotspots and streamlining the SMA training process.

NEW SHAPE FOR CURLED SMA ACTUATOR

Although there was radial pressure all along the SMA embedded strap when the curled U shape trained prototype was activated, the U shape connector bar (Figure 5.35- A) created a pressure sensation hotspot. This was likely due to the ends of the SMA embedded strap having the most amount of visually observable movements compared to the middle of the SMA strap (Figure 5.35- B). Additionally, the curls of the trained U shape were uneven spiraling circles stacked on top of each other (Figure 5.29) resulting in accidental wire overlaps during the annealing process. The accidental overlaps caused the SMA wire to flatten and alter its cross-sectional shape and diameter. This inconsistency along the SMA wire could result in potentially unforeseen issues, and the differing circle diameters could alter the haptic experience. Therefore, a different curled shape approach than the U shape is necessary to improve the functionality and user experience of the wrist prototype.

One possible solution is to train the SMA wires to be a smaller ellipse than my wrist as shown in Figure 5.36. Since the SMA wires would be trained to a smaller ellipse, they could create compression sensations by tightening around the wrist when activated. However, this would not be effective for users who have wrists smaller than the SMA trained shape, which means that multiple sizes of the prototype would need to be fabricated for user tests. Additionally, shorter SMA wires generate less force than longer SMA wires in general, so it would be beneficial to find a different shape that can accommodate longer wires.

Instead of the elliptical shape, an inverted heart shape (Figure 5.37) uses a longer SMA wire and promotes further movement at the wire ends. Although the wire ends with a connector bar produced the pressure hotspot for the curled U shape prototype, increasing the number of hotspot sources can distribute the pressure evenly and instead turn them into a design feature. For instance, having a series of the heart shaped SMA wires would create two lines of closely distributed connector bars with regular electrical wires on each end of the SMA embedded fabric strip. This method also simplifies the SMA training process, since the heart shapes can be affixed between two perforated metal sheets similar to the zigzag springs rather than trying to modify the bolt jig for the curled U shape.

Figure 5.35: [A] Shorter ends of the SMA embedded strap with U shape connector bar highlighted [B] Middle of the SMA embedded strap

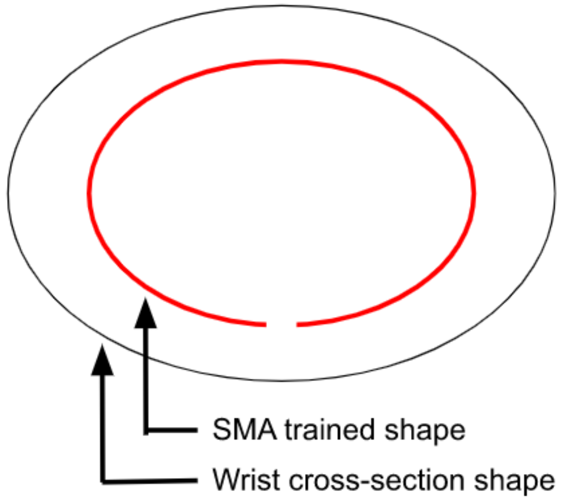


Figure 5.36: Elliptical shape for a potential curled SMA actuator

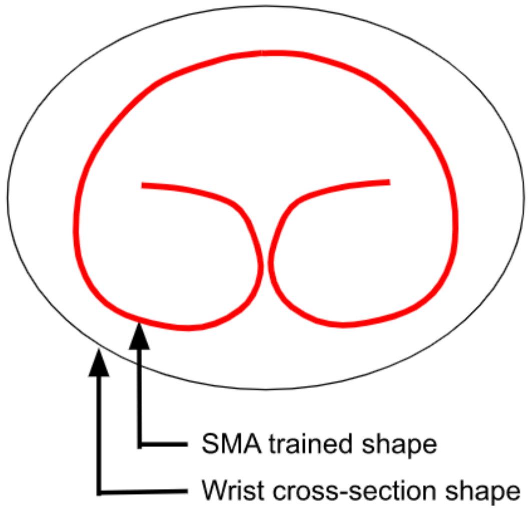


Figure 5.37: Inverted heart shape for curled SMA actuator

FABRICATING THE FINAL WRIST PROTOTYPE ITERATION

Since the objective is to create two lines of closely distributed connector bars, it was necessary to use four SMA wires to have connector bars on each end of the SMA embedded strap. The heart shape (Figure 5.38) was used as a template to shape four segments of 14.5cm long 1mm diameter SMA wires. Once the SMA wires were heat trained at 500°C for 15 minutes, they were connected using segments of 22 AWG solid single core electrical wires and electrical crimps as shown in Figure 5.39. The plastic protector caps on the electrical crimps (Figure 5.18) were removed and only the metal tubing was used to connect the electrical wires and SMA wires. Additionally the longer segments of the same type of electrical wire were connected to the SMA wire ends that do not have connector bars so that power supply clips can be connected to the wrist prototype further away from my wrist.

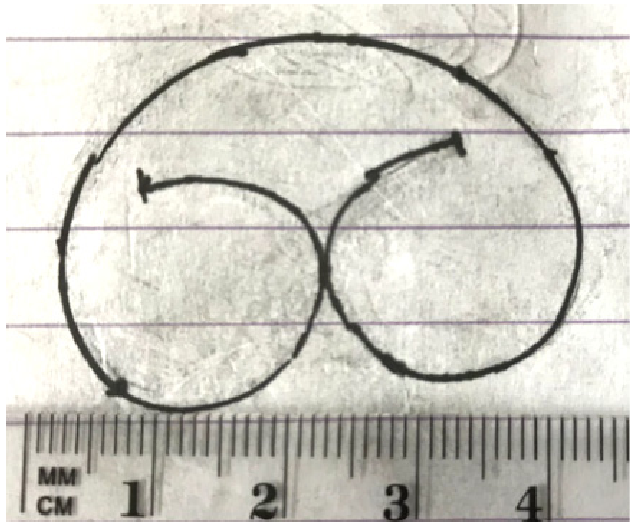


Figure 5.38: Inverted heart shape template used for the final wrist prototype iteration

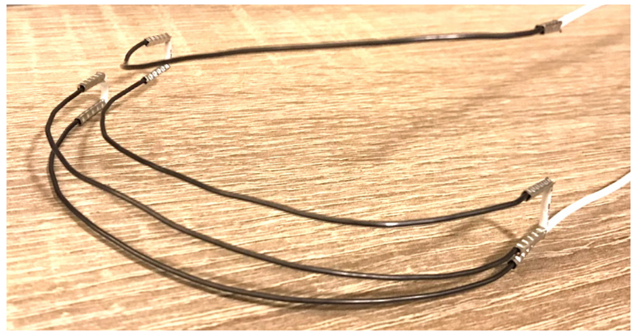


Figure 5.39: Four heart shaped trained SMA wires straightened out and connected using electrical crimps and solid core electrical wires

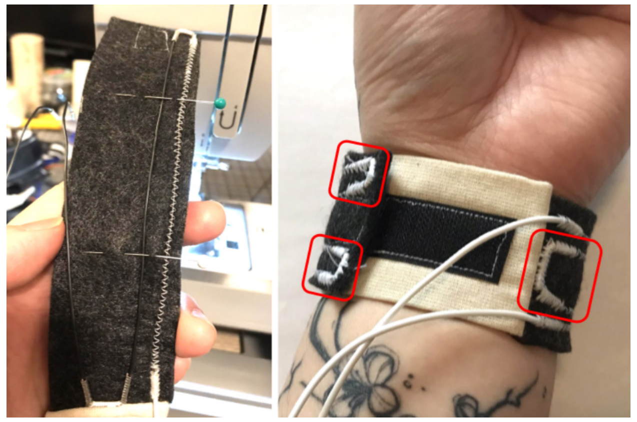


Figure 5.40: [Left] Sewing process for [Right] the final wrist prototype. Three of the solid core electrical wire connector bars are emphasized.

The assembled SMA wires were sewn onto a blank wrist prototype fabric strap (Figure 5.40). The two connector bars placed on one side of the SMA embedded strap had to be shorter than the one connector bar on the other side to accommodate for the velcro strip. Despite the uneven lengths of the connector bars and the gap to accommodate the velcro strip, the perceived pressure sensation felt evenly distributed on both ends of the SMA embedded strap when the final prototype was tested on my wrist. The final wrist prototype iteration also had evenly distributed and more noticeable radial pressure sensation along the middle of the SMA embedded strap. Therefore, the heart shape SMA actuator mechanism is able to create the desired DTP sensations and will be used for the final sleeve concept.

5.4 Insights from Working Prototypes

The following list summarizes the insights gathered from working prototypes development and evaluations:

1. Stroking prototype's SMA actuator mechanism is bulky and requires a lot of space for a relatively small amount of movement displacement.

2. Stroking prototype can be improved to increase its displacement and stroking sensations, but it was not further iterated due to the time constraints.

3. Wrapping a regular electrical wire around a SMA wire with or without solder does not establish proper electrical connection. Small contact area results in localized heat build up from increased resistance. Electrical crimps provide proper mechanical and electrical connection between SMA wires and regular wires.

4. Replication attempts of Affective Sleeve's straight SMA wire actuator mechanism with 0.5mm diameter SMA wire resulted in little to no pressure sensation on the wrist especially with the simultaneous heat buildup.

5. Using 1mm or 1.5mm diameter SMA wires for the straight wire actuator resulted in slightly more noticeable pressure sensation than 0.5mm diameter wires, but the prototypes had difficulty returning to the initial wrist wrapped position with the wrist and non-stretch fabrics acting as the bias force.

6. Curled trained SMA actuators provided DTP sensations and returns to initial position for consecutive activation cycles better than the straight wire actuators.

7. Heart shape for the curled SMA actuator simplifies the SMA training process and resulted in the strongest perceived pressure sensation on my wrist.

6. SERENISLEEVE, DEVELOPMENT, AND USER TEST

6.1 Sleeve Prototype Development

Based on the wrist prototype development iterations, it was concluded that the SMA actuator with heart shape training provided the most noticeable pressure sensation on my wrist. A longer version of the final wrist prototype was developed as a sleeve that covered my entire forearm for the sleeve concept (Chapter 5.1-B). Creating a longer version of the wrist prototype involved further trial and error iterative prototyping process that is described in this section. The three main challenges involved with the sleeve prototype development are as follows:

1. Adjusting the wrist prototype's heart shape template to accommodate for changes in forearm dimensions

2. Finding a method to easily separate SMA actuators and other electronic components from the fabric sleeve for washability

3. Implementing some form of safety mechanism to prevent the SMA wires from overheating and causing skin damages

A. Sleeve Prototype Development

Unlike the wrist prototype, the sleeve prototype covers the full forearm and has to accommodate for the arm dimensional variation from the wrist to the elbow. For instance, my wrist circumference is approximately 17cm whereas the forearm circumference near my elbow is approximately 29cm. The heart shape template used for the final wrist prototype (Figure 5.38) used 14.5cm SMA wire which went past my wrist's midway point similar to Figure 5.14- B. However, the same template would not work for the elbow end of my forearm since 14.5cm SMA wire would only reach the midway point similar to Figure 5.14- A. Therefore the heart shape template needed to be scaled up to accommodate the size changes throughout the forearm. To do so, a fabric sleeve that can cover my forearm was created to act as an approximate shape to work from. First, a truncated paper cone was fitted around my forearm by wrapping a sheet of printer paper, trimming and taping on paper scraps. Then the truncated paper cone was cut

Figure 6.1: Truncated paper cone wrapped around my forearm with desired seam lines drawn in black dashed lines

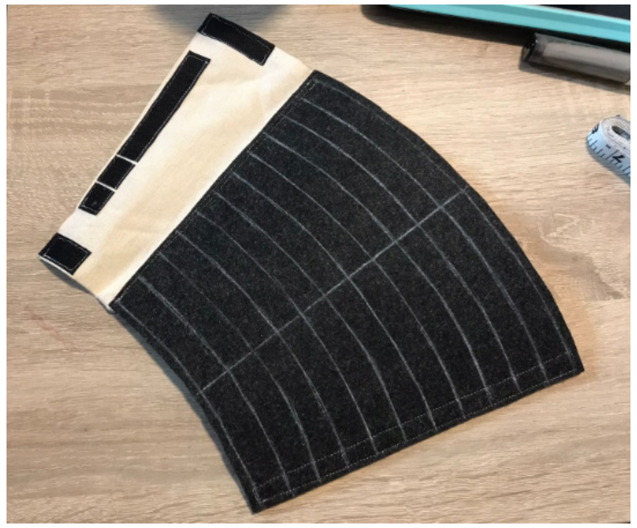


Figure 6.2: Felt and muslin fabric sleeve with approximate locations for the SMA wires drawn with white caulk

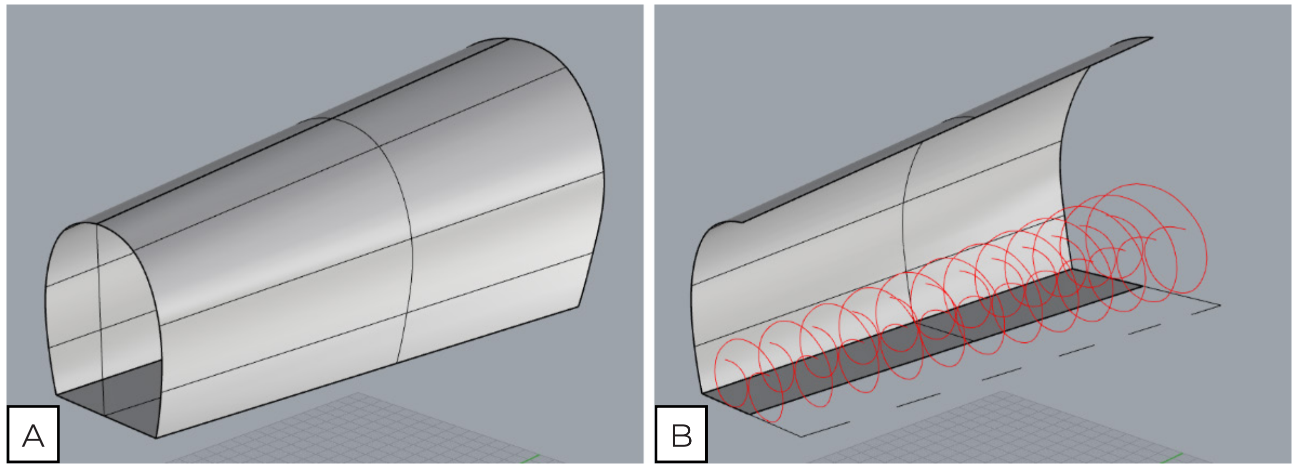


Figure 6.3: [A] Fabric sleeve modeled in Rhino 7 [B] Cross section of the modeled sleeve and the 12 scaled and interpolated heart shape curves shown in red

Figure 6.4: Felt fabric sleeve prototype

along the desired seam lines down the length of my forearm (Figure 6.1) and traced onto a different sheet of paper. The traced lines were smoothed out and adjusted as needed for a better and comfortable fit. Afterwards, they were turned into sewing pattern pieces with 1cm seam allowance as shown in Appendix F.

Using the drafted pattern pieces, a felt and muslin fabric sleeve was made (Figure 6.2). As mentioned in Chapter 5.3-D, a minimum of four SMA wires were needed to have a line of connector bars on each side. Additionally, when using an even number of SMA wires, the SMA wire ends without connector bars are positioned on the same side. This arrangement consolidates the power supplying electrical wires onto one side. Since the sleeve is much longer than the wrist prototype, it requires more than four SMA wires to create two lines of closely distributed connector bars and to create a noticeable pressure sensation over a larger surface area. Therefore, 12 SMA wires were used and resulted in ~1.5cm connector bars that are close in length to the longest connector bar (~1.3cm) for the wrist prototype.

The fabric sleeve was then modeled in Rhinoceros 7 (Figure 6.3- A) as well as the final wrist prototype's heart shape template using Figure 5.38 as a photo reference. The heart shape curve was placed at the wrist end of the sleeve and a copy of it was scaled up accordingly for the elbow end of the sleeve. Using the two curves and the sleeve model, 10 additional heart shape curves were interpolated (Figure 6.3- B). The resulting 12 curves were printed and used as a guide to handform the SMA wires. After training the 12 SMA wires at 500°C for 15 minutes, they were connected and sewn onto the felt fabric using the same methods as the final wrist prototype (Figure 6.4).

INTERIM EVALUATION

Haptic sensations: Interestingly, when I was wearing the felt fabric sleeve prototype, the SMA wire temperature readings went up to around 28°C to 30°C from my body heat compared to approximately 22°C when the prototype was left on the lab counter. When the prototype was tested on myself (Figure 6.5), it produced significantly noticeable pressure sensation over the heat buildup. Similar to the final wrist prototype, I experienced the felt sleeve prototype's primary pressure sensation at the connector bars and secondary radial pressure sensation along the SMA wires.

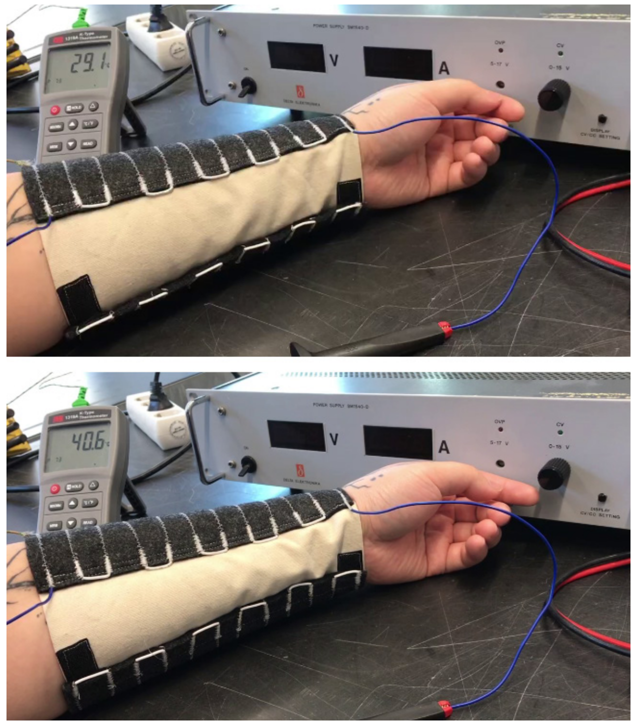


Figure 6.5: [Top] Felt sleeve prototype before activation and [Bottom] after reaching 40°C

It was difficult to determine exactly at what temperature the pressure sensation started since the SMA wires gradually increased the pressure rather than a sudden squeeze, but the pressure seemed to stop increasing and stayed constant at around 70°C. The pressure could be slightly increasing still at that temperature; however, the warmth became much more noticeable at 70°C and could be overpowering the pressure sensation. When the power supply was turned off and the sleeve prototype was cooled with natural convection, the pressure sensation didn't ease up completely until around 32°C even though the activation temperature for the SMA wires was 45-55°C.

Felt fabric issues: During tests, I noticed that the felt fabric retained a lot of the residual heat from the SMA wires, so my arm became warm and sweaty after a few activation cycles. Additionally, the stiffness of the felt fabric made it feel like I was wearing a piece of armor or protective gear, causing difficulty in rotating my arm or bending my wrist. Based on the textile temperature test results (Chapter 4.3-B), another sleeve prototype was created using the COOLMAX 3D mesh fabric instead of the felt fabric to reduce heat buildup (Figure 6.6).

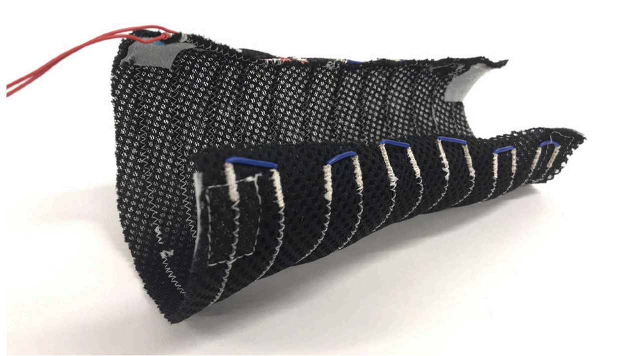


Figure 6.6: COOLMAX 3D mesh fabric SMA actuator insert

The change in fabric also increased flexibility, which improved the overall wearability comfort. On the other hand, the loss of rigidity meant that the 3D mesh prototype would easily stretch in different directions, making it difficult to use it directly as a sleeve. Instead, attaching the 3D mesh prototype to a different piece of fabric helped reduce stretching and warping. Furthermore, treating the 3D mesh prototype as a detachable SMA actuator insert for a fully removable fabric sleeve cover is beneficial for the wearable garment's washability.

SMA wire lengths: While assembling the felt fabric sleeve prototype, I observed that the length of the SMA wires exceeded the span of the felt fabric, causing certain connector bars to extend beyond its edges. In order to ensure that the connector bars were positioned within the heat insulating fabric, I adjusted the heart shape curves in Rhinoceros 7 to shorten the overall linear length. From using approximately 2.4m of SMA wire for the felt fabric sleeve prototype, I managed to reduce down to 2.0m for the 3D mesh fabric SMA actuator insert. Reducing the overall length of the SMA wires also helped reduce the power consumption of the sleeve prototype (Chapter 6.1-C). The printable guide sheet template of the reduced length heart shape curves with the corresponding calculated lengths can be found in Appendix G.

B. Sleeve Cover Development

Washability is an important factor to consider (Chapter 2.5-C) for hygiene since wearable garments need to be closely attached to the user's body to receive the haptic sensations. Having a fully detachable fabric sleeve cover not only facilitates washability but helps prevent the 3D mesh fabric SMA actuator from warping or stretching in undesirable directions. Without the need to embed electronics, manufacturing sleeve covers in various styles becomes simpler and more cost-effective. This would allow users to own multiple sleeve covers for outfit coordination or customization based on their preferred style.

To isolate the SMA actuator from the environment and from the user's skin, a double layered sleeve cover was designed using my left hand and arm dimensions (Figure 6.7). The double fabric layers also extended into the palm area as a small pocket for a 5mm diameter FSR sensor to slide into. The FSR sensor acts as a noiseless button to activate the SMA actuator. To prevent the FSR sensor's plastic membrane from creasing, it was taped to a 1cm wide flexible plastic strip cut out from a takeout container lid (Figure 6.8). The plastic strip also makes it easier to insert the sensor into the designated small pocket. Furthermore, the sleeve cover was intentionally designed without a lengthwise opening down the forearm to eliminate the need for extra velcro straps or other fasteners. Use of additional fasteners would either result in a bulkier sleeve prototype or contain rigid components that could cause discomfort. Instead, the sleeve cover design utilizes the fabric's stretchiness to slide on or off the arm. The sleeve cover's various design features are explained in detail in Chapter 6.2-A, and the sewing patterns in two different sizes are in Appendix H.

It is important to note that the sleeve cover's sewing patterns need to be adjusted to accommodate differences in arm and hand sizes. Even though the elastic cords help tighten around the user's arm, they are ineffective if the sleeve cover is too small or too big for the user. The sewing patterns also need to be adjusted based on the type of fabric and its stretchiness. The first version of the sleeve cover was made with a polyester stretch fleece fabric, but the fleece trapped a lot of my body heat and caused sweating even without the additional heat from the SMA actuator. But when a second version was constructed using a thinner breathable eyelet lining fabric, the resulting sleeve cover was too tight for my arm. Because the eyelet lining fabric does not stretch as much as the fleece fabric, the sewing patterns had to be scaled up and adjusted to accommodate the difference in fabric stretchiness.

Figure 6.7: Double layered sleeve cover design

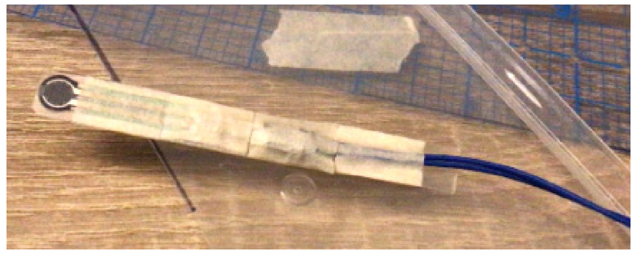


Figure 6.8: 5mm diameter FSR sensor taped to a 1cm wide plastic strip cut from a takeout container lid

Additionally, it is imperative to use a zigzag stitch rather than a straight stitch at the locations where the sleeve cover stretches significantly during don or doff. By using straight stitches, the sleeve's stretch is constrained to the overall stitching thread length, preventing it from reaching the fabric's maximum stretch capacity. This is especially relevant around the wrist area since the hand is generally wider than the wrist.

C. SMA Temperature Control Exploration

Although using breathable fabrics can help reduce heat buildup, the SMA wires can heat up well beyond the temperature safe for human skin contact depending on the duration and amount of current traveling through the wires. Using a combination of a microcontroller and a temperature sensor could inhibit users from accidentally burning themselves. However, I wanted to minimize the number of electronic components to prevent bulkiness, so I looked into possible ways to control the SMA temperature without the use of sensors.

LIMITING THE MAXIMUM STEADY STATE TEMPERATURE

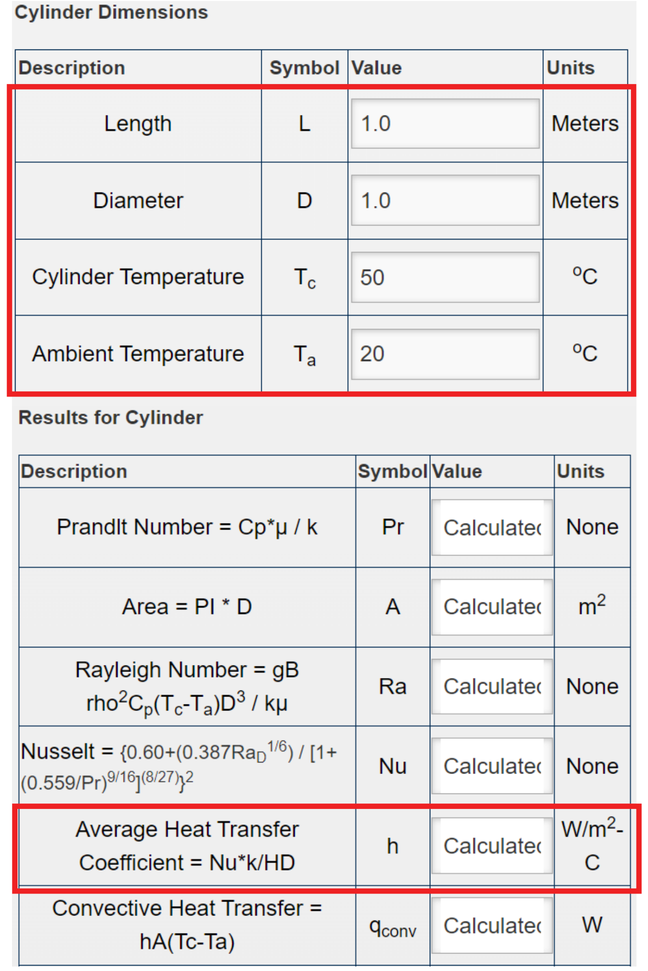
First, I tried to limit the SMA actuator's maximum temperature by calculating the approximate current necessary to reach a specific target temperature. SMA wires can reach a steady state temperature by balancing the heat generated from joule heating and the heat loss to the ambient surroundings (Rao et al., 2015). Under the assumption that the heat loss transfer only occurs through natural convection, Rao et al. used (2) to estimate the current needed to reach a target steady state temperature where T is the target temperature, T_{amb} is the ambient temperature, ρ is the resistivity, d is the wire diameter, h is the heat transfer coefficient, and I is the current (2015). Of these, the resistivity and heat transfer coefficient values are difficult to get.

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

There are materials databases that list the resistivity value of the nitinol wires; however, it should be noted that the resistivity values vary between SMA wires from different manufacturers. It also differs between martensitic and austenitic phases because resistivity depends on the material composition and the temperature (Britannica, 2023). The resistivity of the SMA wire can be calculated using (3) where l is the wire length, and R is the resistance at either martensitic or austenitic phase. I decided to also calculate my SMA actuator's resistance based on the voltage and current input readings from the lab power supply when the SMA wire was at its martensitic phase.

$$\rho = \frac{R\pi d^2}{4l} \qquad (3)$$

Unlike the resistivity value, the heat transfer coefficient is difficult to calculate and "only very approximate values are available" because the value depends on the vertical or horizontal orientation of the wire and whether free or forced convection is used (Rao et al., 2015). Rao et al. used the "thermal wizard" website's Natural Convection around a Horizontal Cylinder page (Maya HTT, 2014) to estimate the heat transfer coefficient by inputting the length, diameter, cylinder temperature, and ambient temperature values (Figure 6.9) (2015). Because equation (2) uses estimated resistivity and heat transfer coefficient values, the calculated current is also an estimation. It is recommended to use a thermocouple wire and a feedback control system to achieve a very specific final temperature rather than relying on the calculated current (Rao et al., 2015).



Cylinder Dimensions

Description	Symbol	Value	Units
Length	L	1.0	Meters
Diameter	D	1.0	Meters
Cylinder Temperature	T_c	50	°C
Ambient Temperature	T_a	20	°C

Results for Cylinder

Description	Symbol	Value	Units
Prandlt Number = Cp*μ / k	Pr	Calculatec	None
Area = PI * D	A	Calculatec	m^2
Rayleigh Number = gB $rho^2C_p(T_c-T_a)D^3$ / kμ	Ra	Calculatec	None
Nusselt = $\{0.60+(0.387Ra_D^{1/6}) / [1+(0.559/Pr)^{9/16}]^{(8/27)}\}^2$	Nu	Calculatec	None
Average Heat Transfer Coefficient = Nu*k/HD	h	Calculatec	W/m^2-C
Convective Heat Transfer = hA(Tc-Ta)	q_{conv}	Calculatec	W

Figure 6.9: Screenshot of the "thermal wizard" website used to calculate heat transfer coefficient (Maya HTT, 2014)

Nevertheless, I still tried to experiment with a 10cm long, 1mm diameter SMA wire with activation temperature of 45-50°C to see if the calculated necessary current would result in the target steady state temperature. For that particular piece of wire, the calculated resistivity value was 1.4E-6 Ωm. With a target temperature of 100°C and 22°C ambient room temperature, the heat transfer coefficient was estimated to be 27.9 W/m2C, and the calculated necessary current was 2.0 Amps. However, with 2.0 Amps current input, the SMA wire temperature reading stagnated at maximum temperature of 55.6°C after approximately 2.5 minutes and fluctuated between 54.7°C and 55.6°C afterwards.

I also conducted the steady state temperature experiment using the felt fabric sleeve prototype that was placed on the lab counter. It is important to note that using the calculated resistivity rather than a value from a materials database is especially relevant for the prototype since it uses a mix of regular electrical wires and SMA wires. The calculated resistivity of the felt fabric sleeve prototype was 8.5E-7 Ωm, and the heat transfer coefficient was estimated to be 24.3 W/m^2C with a target temperature of 45°C and 22°C ambient room temperature. Similar to the single wire experiment, the felt fabric sleeve prototype's temperature readings stagnated around 35.3°C with the calculated current of 1.3 Amps even after leaving the power supply on for 40 minutes. Therefore, it was confirmed that the calculated current from equation (2) should only be used as an approximate starting reference point for future experiments rather than an exact value to reach the target steady state temperature.

FLASHING THE SMA WIRES

Based on the steady state temperature experiment results, it was evident that the SMA wires needed higher current than the amount calculated from (2) to reach the actual target steady state. Additionally, the response time to reach a steady state temperature of 55°C for a 10cm long, 1mm diameter SMA wire was approximately 2.5 minutes. A response time in the order of minutes is too slow for haptic feedback especially when the prototype is meant for anxiety modulation in real-time. Instead of limiting the maximum temperature, "flashing" or exposing the SMA wires at high current for a limited duration would reduce the activation response time. Equation (4) can be used to estimate the amount of time it would take for the SMA wires to heat up based on the current input where ρ_m is the density, C_p is the (assumed constant) specific heat capacity, L is the latent heat, and Tavg is the average temperature at which the heat transfer occurs (Rao et al., 2015).

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

Equation (4) was rearranged into (5) since the goal was to figure out the necessary current to reach the activation temperature within a desired response time.

$$I = \sqrt{\frac{\pi^2 d^3}{4\rho} \left[\frac{\rho_m d \, (C_p \Delta T + L)}{4 \Delta t} + h \Delta T \right]} \tag{5}$$

The values used for the constant variables in (5) are listed below:

Specific heat capacity (C_p) = 837 J/Kg°C
Latent heat (L) = 24200 J/Kg
Density (ρ_m) = 6450 Kg/m^3

For the same 10cm long, 1mm diameter SMA wire used in the steady state temperature experiment, the calculated resistivity was 1.4E-6 Ωm, and the heat transfer coefficient was estimated to be 25.7 W/m2C with a target temperature of 60°C and 22°C ambient temperature. The calculated current necessary to reach 60°C in 10 seconds was 4.2 Amps. When I ran 4.2 Amps of current through the wire, it took approximately 13 seconds for the wire to reach the target temperature. The measured response time was about 3 seconds over the target response time, but this discrepancy could be influenced by human error since the power supply was manually switched on and off. Alternatively, the thermometer may also have a slight lag since the temperature reading continued to increase for 2 seconds by about 7°C after the power supply was switched off.

Nonetheless, the measured response time for the single SMA wire was close enough to the target response time, so I decided to conduct a few more current flashing experiments using the felt fabric sleeve prototype. The results from those experiments are shown in Table 5. Two of the experiments were done with the prototype placed on the lab counter by its own, and the other two experiments were done with the prototype worn on my arm. The target temperature for all of the current flashing experiments involving the sleeve prototype was 50°C. Interestingly, due to my body heat, the initial starting temperatures of the SMA wires were elevated to around 28 to 30°C rather than the 22°C ambient room temperature when the felt fabric sleeve prototype was worn around my arm. Because of the higher starting temperature, the calculated necessary current for the worn prototype was lower (4.7 Amps) than the prototype placed on the lab counter (5.0 Amps) even though the target response times were both 10 seconds.

Based on the felt fabric sleeve prototype experiment observations, it seems the calculated currents using (5) consistently yielded measured response times that were within a few seconds of the target response times as long as the target response time was 20 seconds or below. For the target response time of 40 seconds, the measured response time was 11 seconds shorter. This significantly shorter duration is likely due to reduced natural convection heat loss from the SMA wires being partially covered by the felt fabric. However, this greater discrepancy in duration for target response time longer than 20 seconds is not applicable for this project, because response time greater than 10 seconds seemed too slow when I wore the sleeve prototype.

On the other hand, response time shorter than 10 seconds required higher current and voltage that small portable batteries may not be able to provide. For instance, the felt fabric sleeve prototype requires 17V or 6.4Amps to reach 50°C from 28°C in 5 seconds. Given how Lithium-Polymer (LiPo) batteries used for typical RC cars are commonly sold in configurations of 7.4V with 2-cell packs or 11.1V with 3-cellpacks (RCCarAction.com, 2018), keeping the voltage requirement to be 11.1V or lower would allow the prototype to be powered by portable batteries. The felt fabric sleeve prototype still required 12.2V for 10 second response time. However, a smaller amount of SMA wire length was used for the 3D mesh SMA actuator insert from 2.4m to 2.0m (Chapter 6.1-A).

CALCULATING 3D MESH SMA ACTUATOR INSERT ENERGY CONSUMPTION

With the reduced SMA wire length amount, the SMA actuator insert requires 4.6 Amps and 10.5V to reach 50°C from 28°C in 10 seconds. With a 11.1V powersource, the actuator insert has a calculated current draw of 4.8 Amps and would reach 55°C from 28°C in 10 seconds. Assuming that the SMA actuator insert's current draw is constant throughout the 10 seconds, the sleeve prototype consumes 0.15 Watt-hours per activation since energy consumption = voltage x current x duration.

A 11.1V LiPo rechargeable battery with a 2300 mAh capacity takes an hour to completely discharge when a current of 2.2 Amps is drawn constantly (crazyFPV, 2021). With a current draw of 4.8 Amps, the LiPo battery would last about 28.75 minutes of continuous activation or 172 activation cycles for 10 second durations. Since the lower compression settings for the final prototype (Chapter 6.2-B) has shorter durations and less current draw, the total number of possible activation cycles with the LiPo battery would be greater than 172 assuming that the user would not use the highest compression settings for all the activations.

Table 5:

	Calculated Current	Required Voltage	Target Time	Measured Time
Felt fabric sleeve placed on lab counter	4.9 Amps	13.0 V	10 sec	12 sec
	3.6 Amps	9.5 V	20 sec	21 sec
Felt fabric sleeve worn on arm	4.6 Amps	12.2 V	10 sec	10 sec
	2.6 Amps	6.7 V	40 sec	29 sec

* Target temperature = 50°C

** Starting temperature = 22°C (placed on lab counter), 28°C (worn on arm)

6.2 SereniSleeve: The Final Sleeve Prototype

After gathering insights from iterating on several wrist and sleeve prototypes (Figure 6.10), the final sleeve prototype, dubbed as SereniSleeve (Figure 6.11), was fabricated and used for user tests. SereniSleeve consists of a double layered fabric sleeve cover with fully detachable 3D mesh SMA actuator insert and 5mm diameter FSR sensor. The double layer sleeve cover design allows to house the electronic components while simultaneously protecting them from the environment and keeping them out of sight. The electronic components are fully detachable from the sleeve cover, allowing for washability and customizability that are otherwise difficult to achieve for wearable garments with embedded electronics.

The FSR sensor is placed in the middle of the palm and acts as a button to activate the SMA actuator. The placement of the sensor button allows the user to trigger the activation by forming a fist when they are tense from anxiety. When SereniSleeve is activated, the SMA actuator creates DTP sensations in the form of warmth and pressure around the user's forearm. Depending on how strongly the user holds down on the sensor button, one of three pressure settings (low, medium, and high) is activated. To prevent SereniSleeve from activating accidentally, the user has to continuously hold down the sensor button for two seconds for it to be registered as an intentional press. Once the sleeve is activated, the SMA actuator undergoes different heating and cooling duration depending on the pressure setting.

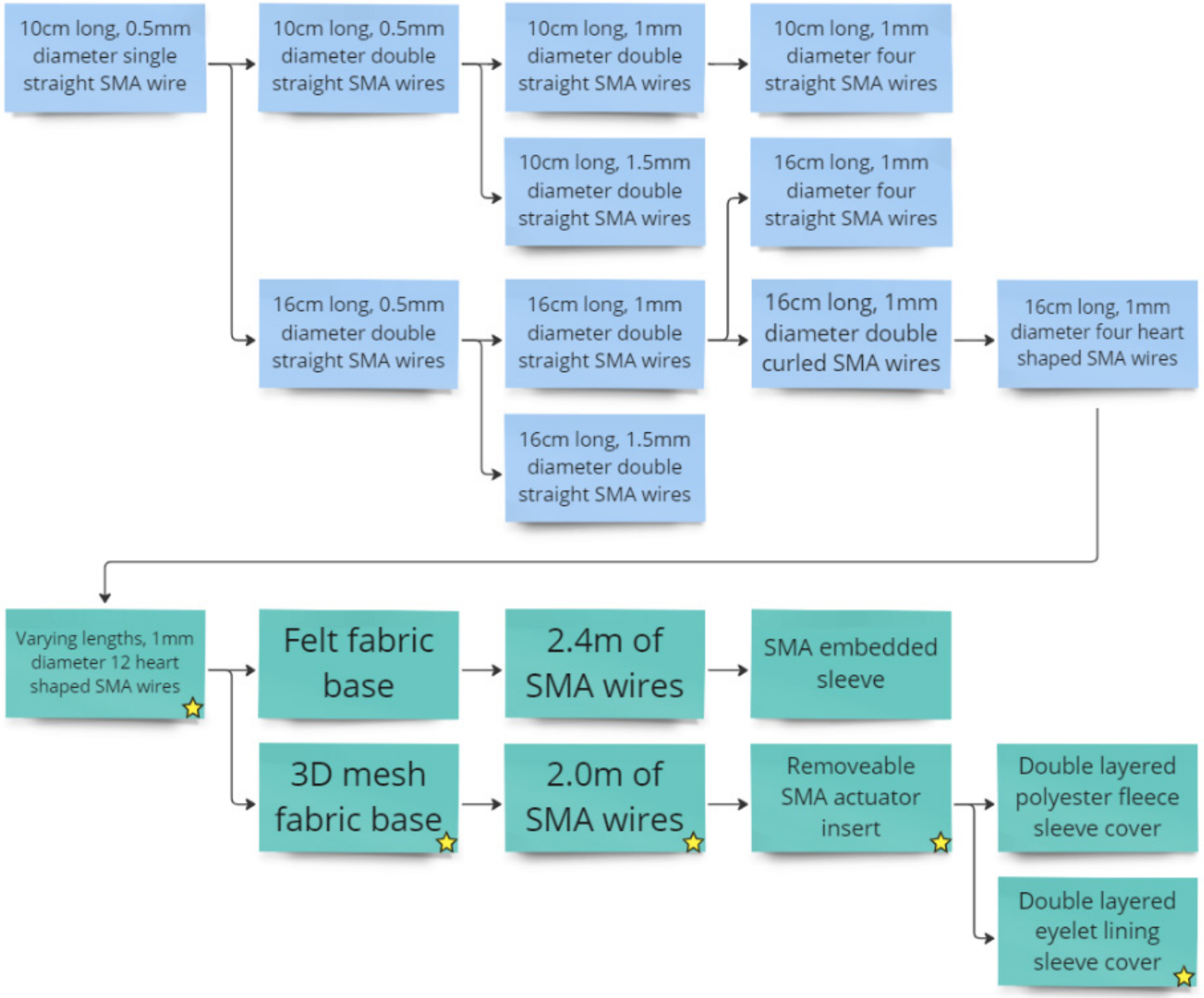


Figure 6.10: Visual flow chart of the wrist (blue) and sleeve (green) prototype iterations. The design decisions applied for SereniSleeve are highlighted with stars

Figure 6.11: SereniSleeve with double layered sleeve cover and 3D mesh SMA actuator insert

A. SereniSleeve Design Features

The step-by-step process involved in putting together SereniSleeve is shown to highlight the different design features and components.

Figure 6.12 : The double layered sleeve cover is slipped on like a regular fingerless glove.

Figure 6.13 : The elastic cord can be used to tighten the inner layer around to ensure a good fit

FIGURE 6.14 : 3D MESH SMA ACTUATOR INSERT AFFIXES TO THE INNER LAYER OF THE SLEEVE COVER WITH VELCRO STRIPS. THE INNER LAYER ALSO ACTS AS A MOISTURE WICKING FABRIC BETWEEN THE ACTUATOR INSERT AND THE USER'S SKIN.

FIGURE 6.15 : 5MM DIAMETER FSR SENSOR ATTACHED TO A STRIP OF FLEXIBLE THIN PLASTIC IS SLIPPED INTO THE POCKET ON THE PALM AREA.

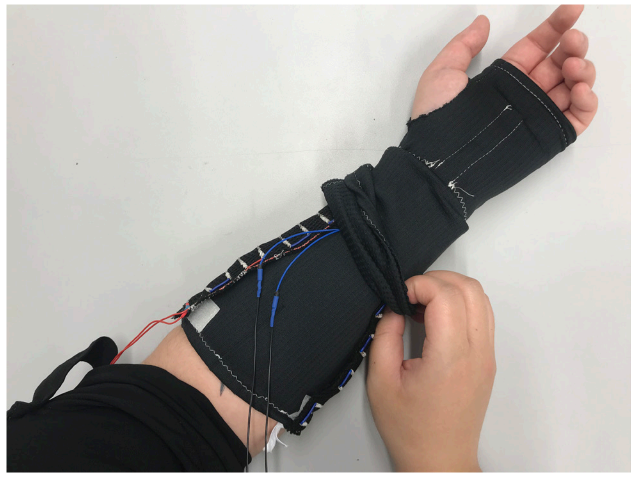


FIGURE 6.16 : THE OUTER LAYER HIDES THE SMA ACTUATOR AND THE FSR SENSOR WIRES, SO THE OVERALL WEARABLE IS DISCREET, AND THE ELECTRONIC COMPONENTS ARE PROTECTED FROM THE ENVIRONMENT.

FIGURE 6.17 : THE OUTER LAYER ALSO HAS AN ELASTIC CORD THAT CAN BE USED TO TIGHTEN AROUND THE FOREARM.

FIGURE 6.18 : SERENISLEEVE IS ACTIVATED BY MAKING A FIST AND HOLDING DOWN THE FSR SENSOR BUTTON FOR A FEW SECONDS.

It is possible to slide the fully assembled SereniSleeve on and off the arm without having to go through each step; however, the current choice of fabric is not stretchy enough to easily do so. Due to the project's time constraints, this limitation could not be addressed. Nonetheless, a few changes to the sleeve cover should enhance the sleeve's ease of don and doff (Chapter 6.4-B).

B. SereniSleeve Electronics

Since SMA actuator insert is activated through resistive heating, its temperature is regulated by limiting the amount of current and flow duration through a combination of Seeeduino Lotus V1.1 microcontroller, Grove MOSFET, 5mm diameter FSR sensor, and 47kΩ resistor (Figure 6.19). The user has to continuously hold down on the FSR sensor for 2 seconds to activate the SMA actuator. This was implemented to prevent SereniSleeve from accidentally activating when the user is holding objects in their hands.

FSR sensors are composed of a polymer film with a conductive surface, a second polymer film with printed electrodes, and an adhesive spacer layer with an opening for the sensor's active area (Figure 6.20). When the two polymer layers come in contact through applied force on the active area, "conductive layer of the printed electrodes short circuit to reduce the electric resistance" (Sadun et al., 2016). Because the FSR sensor used for SereniSleeve has a small 5mm circle active area, objects that come in contact with the sensor beyond the active area would be pressing on the spacer layer, which results in a reduced or no force reading.

SereniSleeve is unlikely to accidentally get activated by holding items, since the user has to precisely hold down the FSR sensor for 2 seconds at its small 5mm diameter active area for it to be registered as an intentional press. Additionally, the microcontroller is programmed (Appendix I) to take the average FSR sensor reading over 2 seconds to average out sensor noise. Based on the average sensor reading, one of the three different predetermined compression settings is activated:

1. Low compression:

1a. - Activated at average FSR sensor reading from 100 to 499

1b. - Heating duration of 5 sec at 0.6 of max current

1c. - Cooling duration of 20 sec

2. Medium compression:

2a. Activated at average FSR sensor reading from 500 to 699

2b. Heating duration of 8 sec at 0.8 of max current

2c. Cooling duration of 30 sec

3. High compression:

3a. Activated at average FSR sensor reading of 700 and higher

3b. Heating duration of 10 sec at max current

3c. Cooling duration of 40 sec

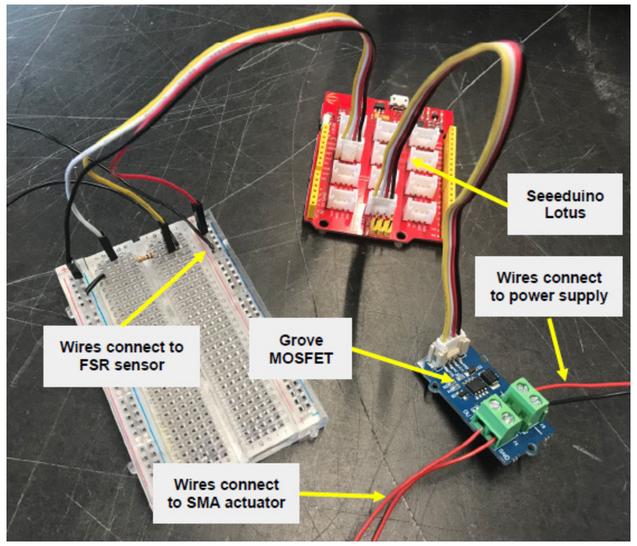


FIGURE 6.19: MICROCONTROLLER ASSEMBLY FOR SERENISLEEVE

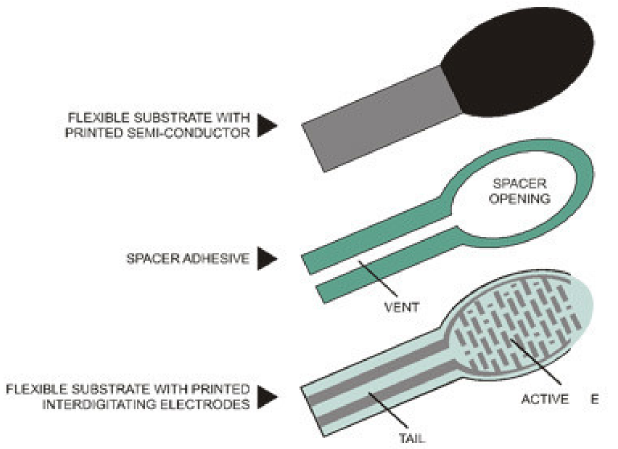


FIGURE 6.20: FSR SENSOR CONSTRUCTION (ADAFRUIT, 2012)

With the use of a 47kΩ resistor, the thresholds for the three different settings were determined based on the sensor values that my hand could generate. For the highest compression setting, the SMA wires would get a maximum of 4.8A at 11.1V for 10 seconds, which results in the SMA wires heating up to approximately 55°C. It is important to note that the 55°C temperature reading was measured by attaching a thermocouple wire directly to the surface of the SMA wire rather than over the fabric insulations. When the thermocouple wire was placed between my skin and the inner layer of the fabric sleeve cover, the maximum temperature reading did not exceed 38°C even after multiple activation cycles at the high compression setting in rapid succession with a shorter cooling duration than 40 seconds. Since "[skin] burns will not occur if the temperature is below 44°C", and tissue injury only occurs at 44°C after being exposed to the heat for several hours (Ong & Milne, 2016), the user would not be exposed to high enough heat from the SMA actuator with the aforementioned heating and cooling duration settings.

Once the 10 second heating duration is over, 40 seconds of cooling duration is enforced. During the cooling phase, the microcontroller does not register any FSR sensor values as intentional button presses to prevent the users from reactivating the SMA actuator. Rather than cooling down the SMA actuator completely to room or body temperature, the cooling durations for the different pressure settings are only long enough for the SMA actuator to cool down to a temperature where it would alleviate some of the pressure sensation. Because the actual duration required for the SMA actuator to cool down to the user's body temperature would take several minutes, the enforced cooling durations are meant to prevent users from rapidly reactivating the SMA actuator that would cause uncomfortable heat build up.

6.3 User Tests

Although an autobiographical design method was used to base the iterative design decisions, user tests were still conducted to get unbiased opinions about the haptic sensations and the overall experience of using SereniSleeve. I've recruited participants consisting of 15 TU Delft students and recent graduates through personal connections or advertisements in various TU Delft student online group chats. The user test method was approved by TU Delft Human Research Ethics Committee in March 2023.

A. User Test Method

The one-on-one individual user test took about 45 minutes and consisted of three parts: online questionnaires, experiencing SereniSleeve, and a semi-structured interview (Figure 6.21). Participants were informed verbally and through an informed consent form (Appendix J) of the user test process and the type of haptic sensations they would feel from SereniSleeve. However, they were not informed of the desired anxiety reducing effect of the haptic sensations or the main goal of the project until after the user test was over to prevent biased responses. Each participant was assigned a randomly generated participant number to keep their responses as anonymous as possible.

QUESTIONNAIRES

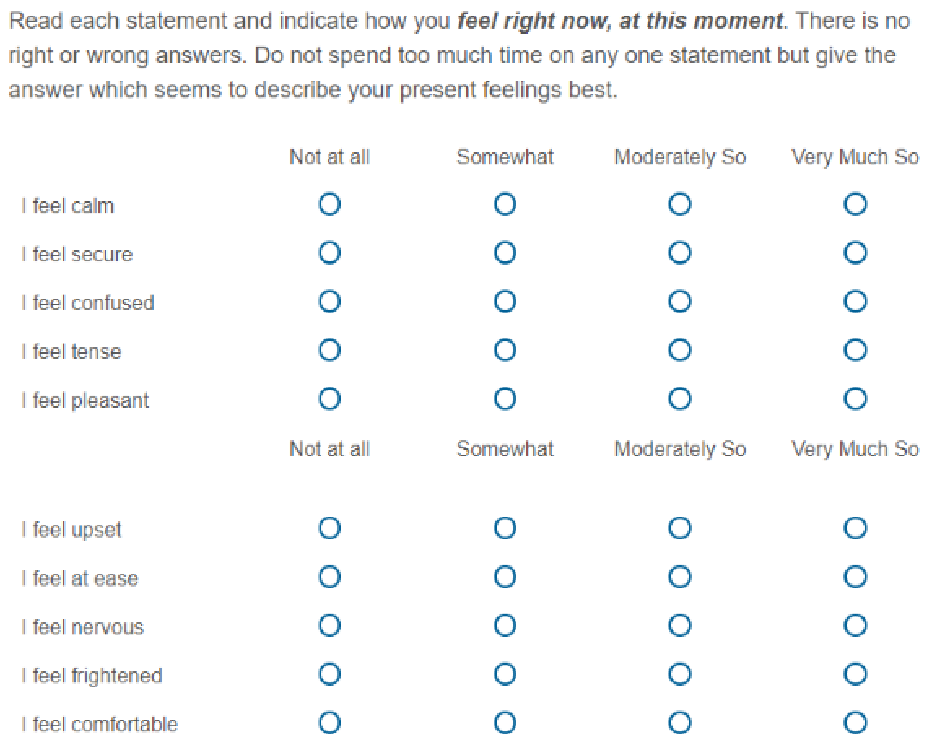
There were two instances when the participants filled out the online questionnaires on an iPad: before and after trying out SereniSleeve. Except for the first questionnaire's demographic questions about gender and age range, the two questionnaires used a nearly identical simplified Spielberger State-Trait Anxiety Inventory (STAI) with 5 positively and 5 negatively valenced statements. The first questionnaire asked the participants to "indicate how [they] ***feel right now, at this moment***" on a four point Likert scale of "Not at all", "Somewhat", "Moderately So", and "Very Much So" (Figure 6.22). The second questionnaire used the same 10 statements but with a different prompt asking to "indicate how ***the sensations from the wearable device make [them] feel*** right now" after the participants had some time to freely explore each of the three different pressure settings.

TRYING ON SERENISLEEVE

Since I only had one working SereniSleeve for the user test, I decided to put it on the participants with their consent to ensure that it would not be accidentally damaged. The participants were provided with either the small or large fabric sleeve cover depending on their forearm size in comparison to mine. Once the SMA actuator insert and FSR sensor button were properly affixed to the sleeve cover, the participants were informed about the three different pressure settings, respective heating and cooling durations, and how to activate SereniSleeve. They were given some time to practice pressing on the FSR sensor button without the power supply that activates the SMA actuator. During the button pressing exercises, the participants were able to see the Arduino serial monitor on my laptop screen that indicated the pressure setting type, as well as the heating and cooling durations (Figure 6.23). This gave them an initial sense of the different force thresholds required to activate each of the three pressure settings. Once they were accustomed to the FSR sensor button thresholds, the power supply was turned on for the participants to freely explore the haptic sensations from SereniSleeve. The participants were encouraged to activate the sleeve whenever they desired during the user test.

	User Test Methods	Type of Information gathered
Start	Welcome, brief introduction, assign participant ID #	Informed consent form
Stage 1	1st online questionnaire	Demographics, simplified STAI questionnaire about the participant's current emotion state
Stage 2	Trying on and freely exploring SereniSleeve	Observations on participant's initial reaction
Stage 3	2nd online questionniare	Simplified STAI questionnaire about the participant's emotion state after experiencing the haptic sensation
Stage 4	Semi-structured interview	In-depth discussion about the participant's opinion on the prototype

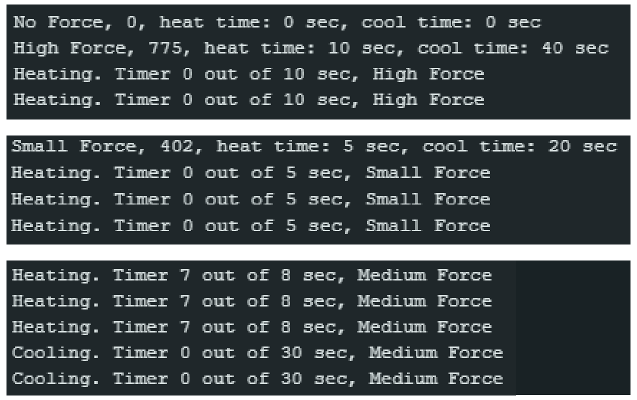
Figure 6.21: Overall flow of the user test



Read each statement and indicate how you ***feel right now, at this moment***. There is no right or wrong answers. Do not spend too much time on any one statement but give the answer which seems to describe your present feelings best.

	Not at all	Somewhat	Moderately So	Very Much So
I feel calm	○	○	○	○
I feel secure	○	○	○	○
I feel confused	○	○	○	○
I feel tense	○	○	○	○
I feel pleasant	○	○	○	○
	Not at all	Somewhat	Moderately So	Very Much So
I feel upset	○	○	○	○
I feel at ease	○	○	○	○
I feel nervous	○	○	○	○
I feel frightened	○	○	○	○
I feel comfortable	○	○	○	○

Figure 6.22: Simplified STAI questionnaire used for the user test questionnaire before trying on SereniSleeve



```
No Force, 0, heat time: 0 sec, cool time: 0 sec
High Force, 775, heat time: 10 sec, cool time: 40 sec
Heating. Timer 0 out of 10 sec, High Force
Heating. Timer 0 out of 10 sec, High Force
```

```
Small Force, 402, heat time: 5 sec, cool time: 20 sec
Heating. Timer 0 out of 5 sec, Small Force
Heating. Timer 0 out of 5 sec, Small Force
Heating. Timer 0 out of 5 sec, Small Force
```

```
Heating. Timer 7 out of 8 sec, Medium Force
Heating. Timer 7 out of 8 sec, Medium Force
Heating. Timer 7 out of 8 sec, Medium Force
Cooling. Timer 0 out of 30 sec, Medium Force
Cooling. Timer 0 out of 30 sec, Medium Force
```

Figure 6.23: Example screenshots of Arduino serial monitor indicating the pressure setting type and heating/cooling duration

SEMI-STRUCTURED INTERVIEW

The semi-structured interview was conducted after the participants finished filling out the second questionnaire. The interview focused on the participants to "think out loud" or to talk about their opinions on SereniSleeve and the haptic sensations it provided. Because the simple online questionnaire alone cannot capture the participants' nuanced changes in emotional state, the interview is also conducted for a holistic overview. To help prompt the discussion, some or all of the questions in the following list were asked:

1. Do you normally wear any form of wearable tech or regular accessories on a daily basis?

2. What kind of physical sensations do you feel from the sleeve and where?

3. How does the sensation from the wearable make you feel?

"It reminds me of ______"
"It feels similar to ______"
"It makes me feel similar to when I ________"

4. Do you feel in control when using the sleeve?

5. When or what do you think this could be used for? Either for yourself or in general.

6. Besides the haptic sensations, what do you like or dislike about SereniSleeve overall and why? What would you change about it to make it better?

B. User Test Results

Out of the 15 user test participants, the majority of them were industrial design students or recent graduates, while two were non-design students at TU Delft. Among the participants, four fell within the age range of 26 to 35, while 11 participants were between the ages of 18 and 25. Additionally, 10 participants identified as female and 5 participants identified as male. The results from the user tests are categorized based on four themes: the haptic sensations' emotional effect, potential use case scenarios, usability, and general perception of SereniSleeve.

EMOTIONAL EFFECTS OF SERENISLEEVE'S HAPTIC SENSATIONS

To get a general quantitative overview of the participants' perception on the emotional effects of SereniSleeve's haptic sensations, I used a similar method as the Spielberger STAI questionnaires to score the questionnaire results. As shown in Figure 6.24, the positively valenced statements were given 4 points for "not at all" to 1 point for "very much so", whereas the negatively valenced statements were given 1 point for "not at all" to 4 points for "very much so". Based on this scoring system, the minimum score possible is 10 indicating that the participant was likely in a low anxiety state. On the other hand, the maximum score possible is 40 indicating that the participant was likely in a high anxiety state.

It is important to note that the score values from this questionnaire do not correspond with the full Spielberger STAI's actual scoring system that is used to evaluate participant's potential clinical level of anxiety. Instead, the questionnaire scores for the user tests were used to compare the self-reported anxiety levels before and after the participants had time to experience SereniSleeve's haptic sensations. 10 participants experienced a potential decrease in anxiety level after trying out SereniSleeve with the largest score difference of -11 points, while five participants experienced a potential increase in anxiety level with the largest score difference of +5 (Figure 6.25). Of the five participants who experienced an increase in anxiety level, three were male and two were female.

	Not at all	Somewhat	Moderately So	Very Much So
I feel calm	4	3	2	1
I feel secure	4	3	2	1
I feel confused	1	2	3	4
I feel tense	1	2	3	4
I feel pleasant	4	3	2	1
	Not at all	Somewhat	Moderately So	Very Much So
I feel upset	1	2	3	4
I feel at ease	4	3	2	1
I feel nervous	1	2	3	4
I feel frightened	1	2	3	4
I feel comfortable	4	3	2	1

miro

Figure 6.24: Questionnaire score chart

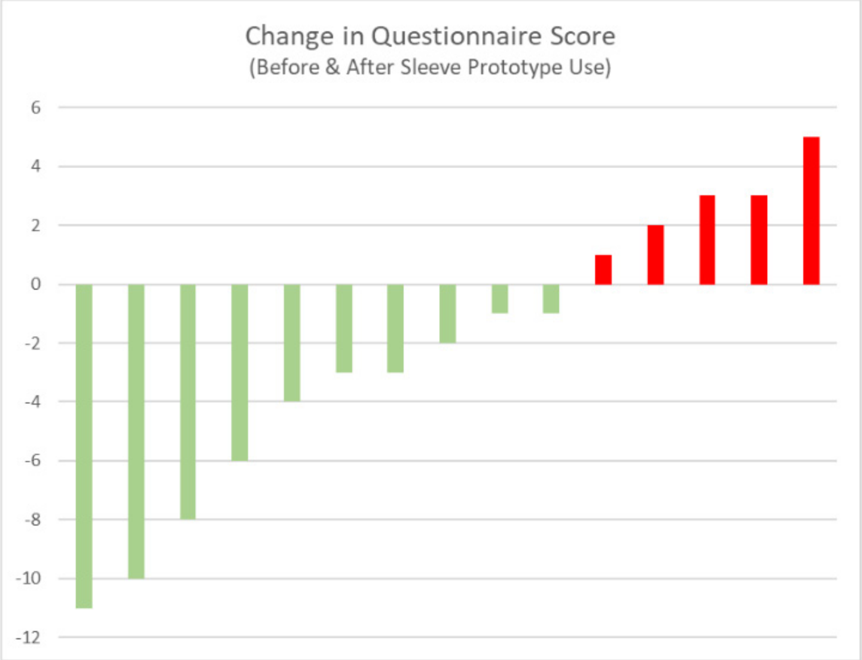


Figure 6.25: Changes in the user test participants' self-reported anxiety state before and after trying out SereniSleeve. Green indicates possible decrease in anxiety level and red indicates possible increase in anxiety level.

The interview responses were used to get qualitative analysis and an in-depth view of the participants' perception on the emotional effects of SereniSleeve's haptic sensations. During the interview phases, many of the participants expressed how they were initially concerned about trying out the sleeve. Although few expressed excitement and curiosity, the participants generally had concerns centered around the novelty of SereniSleeve's actuator mechanism, such as being nervous about the anticipatory unknown haptic experiences, potential physical harm or discomfort, and perceived fragility of the sleeve. However, participants also stated that they became less nervous overall about the haptic sensations throughout the user test as they had more time to explore and activate SereniSleeve.

Some commonly used positive descriptors for the haptic experience were comforting, cozy, calming, and relaxing, whereas the negative descriptors were constricting, restrictive, intense, and stiff.

9 out of 10 participants whose questionnaire score decreased mentioned that SereniSleeve's haptic sensations are helpful for reducing stress or managing anxious thoughts. The other participants stated that they were unsure about the stress- or anxiety-reducing effects of the haptic sensation, because they strongly disliked the highest pressure setting or were concerned about the heat buildup. However, they also stated that the smallest pressure setting still gave them a sense of comfort and calmness especially after getting used to the new haptic sensations.

When the participants were asked to describe the feelings that they get when using SereniSleeve, there were some interesting descriptions or analogies to portray the haptic experience. For example, participants described their positive haptic experience as similar to putting on warm socks during winter time, taking a vacation in a warm igloo, comforting touch from someone, getting a hug or a massage, or "stress ball for the arm". On the other hand, the negative experiences were described as something growing around the arm, or someone grabbing the arm in a pressuring or demanding manner especially at the highest pressure setting.

The participant with the highest increase in questionnaire scores provided the most polarizing description stating that the sensation felt like an inescapable "warm hug… from a teddy bear that's stuck around your arm." Based on the various descriptions and statements, the majority of the participants either felt like they had partial control (n=8) or felt like the haptic sensations were coming from someone else (n=4) even if they knew they were triggering the activation. Despite only a few participants feeling like they were in full control when using SereniSleeve, participants still expressed feelings of relaxation or stress reduction.

POTENTIAL USE CASE SCENARIOS

The participants' ideas and suggestions about the potential use case scenarios for SereniSleeve fell under four different categories. The specific examples within each of the categories are listed below:

1. Coping strategies:

- Situation dependent stress or anxiety management (n=7)
- Grounding technique (n=5)
- Meditation/mindfulness exercises (n=5)
- Breathing exercises (n=3)
- Tool for therapy sessions (n=3)
- Self-care reminder/notification to take breaks (n=2)
- Fidgeting device for focus improvement (n=2)

2. General relaxation:

- Relaxation routine/ritual at the end of the day (n=9)
- Spa treatment at home (n=1)

3. Physical health:

- Physical therapy (n=8)
- Pre/post workout or physical activity (n=3)
- Massage (n=1)

4. Miscellaneous tools:

- Communication/social touch device (n=5)
- Portable heater (n=2)
- Gentle alarm for end of meditation session (n=1)
- Additional haptic experience for escape rooms (n=1)

The most popular potential use case scenarios were general relaxation routine or ritual at the end of the day (n=9), physical therapy for muscle pain or injury (n=8), and situation dependent stress or anxiety management (n=7). Additionally, participants stated that SereniSleeve would be useful for grounding techniques, breathing exercises, and mindfulness or meditation sessions because the haptic feedback would help "get [them] out of [their] head" and provide physical bodily sensations that are easier to focus on. Interestingly, four out of the five participants with increased questionnaire scores still gave example use case scenarios relating to the coping strategies or general relaxation categories. Those participants clarified that they personally would use the lower pressure settings for the calming effects or recognized the potential emotional benefits for other users who enjoy strong, deep pressure sensations.

It is also worth noting that two participants specifically mentioned SereniSleeve's effects on improving focus and reducing mind-wandering. The repetitive and cyclic nature of the sleeve interaction and haptic feedback reminded them of using a "calmer fidget spinner." Additionally, few participants (n=3) stated that the haptic sensations either were subtle background sensations or positive distractions from anxious spiraling thoughts. On the other hand, five participants expressed that the sensations could be negatively distracting or demanding, so there wasn't a clear consensus on the implicit nature of SereniSleeve's haptic sensations.

For its emotional benefits, seven participants expressed interest in using a commercial version of the fully SereniSleeve. However, they also stated that they would only use it under specific circumstances rather than daily use, such as when they expect to be in exceptionally distressing situations, at therapy sessions, or only at home as an end of the day relaxation ritual. Whereas five participants stated that they are not interested in using any wearables for emotional benefits because of the social stigma associated with mental health or they did not feel the need for additional help in regulating their anxiety and stress.

USABILITY

Unfortunately, SereniSleeve's had usability issues that persisted throughout the user tests. The three main contributing factors to poor usability had to do with the sleeve's activation system, the sleeve cover design, and SMA actuator stiffness.

Activation system: All the participants struggled with using the FSR sensor button because of the button placement and difficulty applying the correct amount of force to activate the desired pressure setting. Participants had varying hand dimensions, such as palm size, finger lengths and locations, that impacted how well they could accurately press on the FSR sensor's active area (Figure 6.26). The 5mm diameter circle at the very tip of the button pocket was the only active area, which required precise placement of a finger for the FSR sensor to register the pressing force. For instance, if the sensor's active area lay between two fingers, it would either not register the press at all or register the press at a lower force than what the participant was applying. Because the FSR sensor button location was chosen based on the shape of my hands, it was unsuitable especially for participants who had smaller palms or longer fingers.

Figure 6.26: Example photos of users having difficulty pressing the FSR sensor button

Even if they managed to activate SereniSleeve by making a fist or using the other hand's fingers, participants struggled to trigger the correct pressure setting that they were aiming for. The participants would either miss the intended activation thresholds or had difficulty reaching the FSR sensor's force threshold for the highest pressure setting. In one instance, the thresholds had to be adjusted because the participant simply did not have enough finger strength to activate the highest pressure setting. The struggle with the activation system frustrated the participants or made them nervous about triggering the incorrect pressure setting.

Moreover, I observed that many participants would continue to press down on the FSR sensor button even after the SMA actuator activated or tried to reactivate before the cooling duration was over. Even though the participants were always able to see the Arduino serial monitor indicating SereniSleeve's activation status (Figure 6.23) on my laptop screen, many participants had difficulty knowing when to press the button to reactivate the sleeve. Although many participants became accustomed to activating the desired pressure settings by the end of the user test or stated that the activation system was "intuitive", some participants expressed the need for some sort of supplementary cues representing the activation status, an instruction manual listing the different heating and cooling durations, or to reduce the number of pressure settings to two. Instead of having preset pressure settings, some participants even suggested using a "one-to-one" response that only activates while the FSR sensor button is being held down and provides a pressure sensation directly corresponding to the force input.

Sleeve Cover Design: Similar to the benchmarking research projects, the improper fit of the sleeve cover influenced the participant's SereniSleeve experience. When the hand portion of the sleeve cover was too big for the participant, they had further difficulties with the FSR sensor button since the button placement would shift as they moved their fingers. In two instances, the incorrectly sized sleeve cover was put on the participants' arms, which resulted in an increasing sensation of tightness and discomfort by the end of the user test. For example, one participant had difficulty differentiating the three pressure settings because of the overall tightness of the sleeve cover. Interestingly, the participants who had slightly loose fitting sleeve covers around their forearm did not experience compromised pressure sensations nor difficulty differentiating between the three pressure settings.

Even though the majority of the participants were fitted properly with the correct sleeve cover sizes for their forearms, participants expressed that the sleeve is cumbersome to don and doff. Some stated that the sleeve cover fabric isn't stretchy enough for it to easily slide on and off over their hands. However, the glove portion of the sleeve cover was the main contributing factor to the perceived annoyance in don and doff of SereniSleeve. Those who disliked the glove portion (n=8) were concerned about maintaining hand cleanliness for daily use in certain situations, such as during cooking, working in a machine shop, using the toilet or washing their hands afterwards. For one participant, she found the fabric covering her hands to be distracting similar to any sort of accessories on or around her hand.

Although the glove portion of SereniSleeve was generally disliked, the participants were also unsure about where to place the FSR sensor button without it. Some participants suggested placing the button on the side of the index finger (Figure 6.27- A) or on top of the thumb (Figure 6.27- B). Additionally, there were disagreements over the fist making user interaction to activate the sleeve; one participant believed it to be intuitive since she makes a fist when she is stressed and angry, whereas another participant expressed that she would prefer to have a more gentle and "self-compassionate" interaction like a self-hugging motion (Figure 6.28).

SMA actuator stiffness: Stiffness of the SMA actuator was another usability issue that persisted throughout the user tests since participants felt restricted in their range of motion after activating SereniSleeve. The majority of the participants talked about how the sleeve's stiffness made it difficult for them to rotate (pronate and supinate) their arm (Figure 6.29) or reduced the range of their wrist movements. One participant explained that while the stiffness wasn't an issue for large, general movements, it significantly restricted small delicate movements.

However, it was difficult to discern whether the participants felt that SereniSleeve was stiff and inflexible before activating the SMA actuator. Due to the residual warmth after activation, the SMA actuator continues to remain stiff and inflexible until the wires cool down sufficiently. As discussed further in Chapter 6.2-B, the enforced cooling durations for the different pressure settings are meant to prevent users from rapidly reactivating the SMA actuator, which would cause uncomfortable heat buildup, rather than ensuring the actuator has cooled down completely to the user's body temperature. Since all participants were initially worried about potentially breaking SereniSleeve with their movements, they left their arms resting on the table (Figure 6.30) and rarely moved them once the sleeve was put on their arms. They only began to move their arms after they activated the sleeve several times and became more comfortable, at which point the SMA actuator already had lingering residual heat that stiffened up the sleeve.

The connection between the initial stationary arm behavior and participants' complaints about SereniSleeve's stiffness was overlooked until the last user test, so participants' opinions about their physical comfort and sleeve stiffness before activation were not inquired. But the last user test participant was asked to massage the sleeve while it was cooling down to deform the SMA wires to the shape of her forearm (Figure 6.31). After doing so, the participant stated that although "it's still not the same as being 100% free, but [the arm movements are] more doable," as SereniSleeve's stiffness reduced, and her previously restricted mobility range had increased.

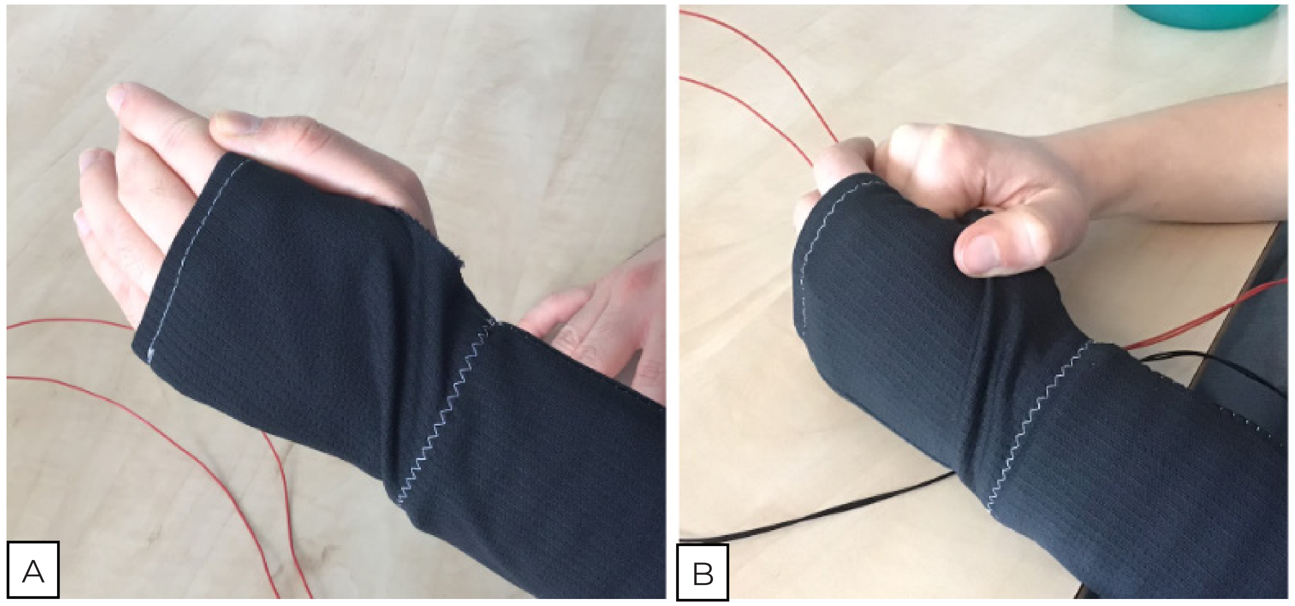


Figure 6.27: Participants' suggestions on alternative button locations, such as [A] on the side of the index finger or [B] on top of the thumb

Figure 6.28: Participant's suggestion for gentler, self-hugging user interaction to activate SereniSleeve

Figure 6.29: A participant demonstrating difficulties in rotating his arm

GENERAL PERCEPTION OF SERENISLEEVE

Haptic sensations: Overall, the participants had generally positive perceptions towards SereniSleeve's haptic sensations the more they

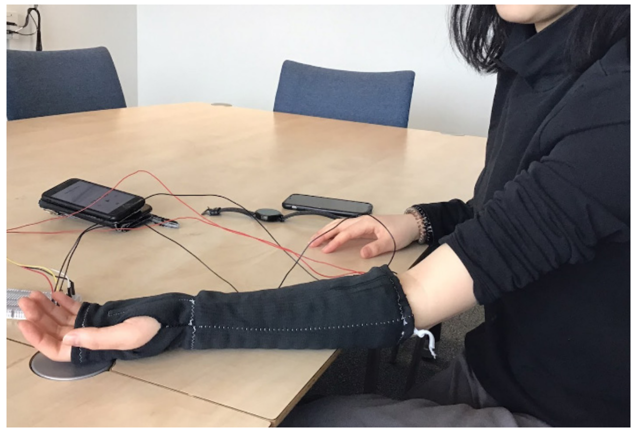


Figure 6.30: Participants' typical arm position resting on the table during the user tests

Figure 6.31: A participant massaging SereniSleeve while it was cool down to conform the SMA wires to her forearm shape

got used to the novel sensations. Regardless of their opinion on the sleeve's effectiveness in reducing stress or anxiety, the participants found the pressure and warmth sensations at varying degrees to be pleasant and comforting. All participants mentioned that the sleeve's haptic sensations reminded them of hug-like interactions or DTP related products like weighted blankets. Two participants even felt like SereniSleeve "became part of [them]" or an extension of their own body after prolonged use. Unfortunately, eight participants were also reminded of blood pressure cuffs especially during the highest pressure setting. However, they clarified that the two haptic experiences were not quite the same because of the presence of warmth and less restrictive pressure sensation. The combination of warmth and gradual wave-like pressure changes made them perceive SereniSleeve's haptic sensations and movement as "more organic" than blood pressure cuffs' mechanical movements.

Although participants generally attributed the feelings of coziness and nonmechanical movements to the presence of warmth, some also stated that they felt nervous about the heat build up. Especially during the first few activations, they were unsure if the heat would continue to rapidly increase for all subsequent activation cycles. One participant described the warmth sensation as being closer to a car seat heater than a human touch, since he felt like the heat was not subtle and increased at an unnatural rate. Fortunately, the participants became less nervous about the heat build up once they realized that the changes in temperature became more subtle with the presence of lingering residual heat. Nevertheless, it was evident that the participants did not envision using SereniSleeve during warmer seasons.

Sleeve cover aesthetic: Majority of the participants appreciated the removable fabric sleeve cover for its washability and potential for customizability. One participant compared the sleeve covers to socks, as users could purchase multiple sleeve covers in various styles and colors to coordinate with their daily outfits. Another participant stated that the sleeve cover was "sleek" since the electronic components were hidden in the double layer design, which would help reduce drawing unwanted attention from other people.

Although the sleeve cover helps to disguise the electronic components, participants disagreed on the discretion of the overall sleeve design. Some believed that SereniSleeve is discreet because it doesn't look like a wearable device and the SMA actuator movements are not visible. However, other participants thought that the sleeve could still attract unwanted attention because it looked like a broken arm splint especially if it's only worn on one of the arms. The six participants, who were reminded of arm splints, pointed out certain aspects that contributed to this image, such as the hand portion of the sleeve cover, the black fabric color, the SMA actuator's motion restricting stiffness, and the sensation of the small plastic strip with FSR sensor going over the palm and wrist area. On the other hand, some participants thought the sleeve cover design would be a bold fashion statement. Especially with the hand portion, participants associated the sleeve design with alternative, anime, or skater culture; whereas without the hand portion, some associated the design with basketball compression sleeves or long sleeved Under Armour shirts typically worn underneath regular clothes. Therefore, getting rid of the hand portion of the sleeve cover seemed to be the general consensus among the participants' responses and suggestions for improvement.

Participant suggestions: There were several suggestions from the participants about the current SereniSleeve and potential additional features that can improve the overall user experience. The following list compiled the recurring or interesting participant suggestions including the ones that were already discussed in more detail earlier in this chapter.

1. Usability improvements - user interaction

- Changing the FSR sensor button placement
- One-to-one pressure sensation response corresponding to the user's FSR sensor force input
- Reducing the number of preset pressure settings
- Supplementary cue to indicate SMA activation
- Self-compassionate gesture or interaction to activate

2. Usability improvements - sleeve cover

- Omitting the sleeve cover's hand part
- Use of stretchier fabrics
- Opening with velcro straps for easier don/doff
- Options for different sleeve sizes and lengths

3. Additional features - user interaction

- Automatic anxiety or stress detection to alert the user
- Two sleeves to wear on both arms

4. Additional features - Haptic sensation

- Activating different segments of the sleeve in a sequence for stroking sensation
- Option to adjust SMA actuator placement
- Option for preprogrammed pressure patterns
- Option to adjust the pressure output for the preset settings

6.4 Discussions, Limitations, and Concluding Remarks

A. Discussions and Limitations - User Tests

FACTORS POTENTIALLY INFLUENCING PARTICIPANT RESPONSES

The user test participants felt generally nervous about trying on SereniSleeve at the start of their user tests either because they were unsure about the sleeve's safety or the novel haptic experience. All of the participants were hesitant to move their arms because they were concerned about potentially damaging the sleeve and the electrical wires connected to it. Majority of them became more comfortable after wearing and activating the sleeve for some time before filling out the second questionnaire. On the other hand, few participants took longer to get used to the novel haptic sensations and still had strong dislike towards the highest pressure setting.

It was interesting to observe how polarizing the participants' opinions were towards the highest pressure setting. One participant excitedly stated that "[she] wants high force immediately", whereas another participant stated that he was a "bit frightened" of the high pressure setting as he associated the squeezing sensation to someone grabbing his arm in a demanding or angry manner. The participants, who strongly disliked the high pressure setting, became more open to the haptic sensations at the lower pressure settings by the end of the user test. This phenomena could be due to certain people generally having adverse opinions towards on-body haptic experiences (Foo et al., 2020).

The gender of the participants could also influence the perceived stress or anxiety-reducing effects of DTP sensations. According to Berretz et al., their research results suggest that women had reduced cortisol response when embraced shortly prior to stressful social situations, whereas stress-buffering effect could not be observed in men (2022). This aligns with how 3 out of 5 male participants had increased questionnaire scores when only 2 out of 10 female participants had similar increases in scores. However, further user tests with a larger participant pool are necessary to confirm such hypotheses.

These aforementioned factors likely influenced the participants' questionnaire responses, so the changes in questionnaire scores may not accurately represent SereniSleeve's anxiety reducing effect on the participants. Nonetheless, considering that a majority of the participants suggested use case scenarios involving general relaxation routines or popular coping strategies for self-regulating anxiety and stress levels, it was evident that SereniSleeve had a stress- or anxiety-reducing effect on different participants to varying degrees.

PARTICIPANT SUGGESTIONS: ANXIETY DETECTION FEATURE

As listed in the previous section, participants had various suggestions regarding the current SereniSleeve and additional features to enhance the overall user experience. Contrary to the insights gathered from the literature review, many participants expressed a desire for the sleeve to detect potentially elevated anxiety or stress levels through the use of physiological signal sensors. Those participants stated that they would benefit from having a wearable device that alerts them to take breaks or practice self-care, as they had difficulty noticing when they needed intervention for their anxious thoughts or breaking out of stress-induced bad habits.

On the other hand, one of the users who brought up the detection feature also stated that she wasn't sure if she would want the sleeve to break her stress-induced hyperfocus, even if doing so is better for her mental health in the long run. With these contradictory suggestions and literature review insights, it is difficult to discern if the automatic anxiety or stress level detection feature for anxiety modulating wearable devices is indeed necessary or helpful. Especially given how participants generally viewed SereniSleeve as a product they would typically use at home as part of their nighttime relaxation routine, the anxiety detection feature would only be useful when potential users would consider wearing the sleeve on a daily basis outside of their homes. Therefore, further iterations on SereniSleeve's embodiment is necessary to encourage daily use outside of the user's homes even before considering adding the anxiety detection feature.

B. Discussions and Limitations - SereniSleeve

ELECTRONICS AND DISCRETION

Unlike the commercially available DTP wearable garments that use inflatable mechanisms or added weights, the SMA actuator based SereniSleeve is noiseless, lightweight, and mostly discreet. Since SereniSleeve is at a proof-of-concept level, the SMA actuator itself is discreet as part of a wearable garment, but other electronic components involved have yet to be fully incorporated, such as the microcontroller, MOSFET, and powersource. A custom made PCB could consolidate the microcontroller and MOSFET into a compact form; however, it is still a rigid electronic component that would impact the user's comfort if it were to be affixed to the sleeve. Moreover, the typical Lithium-Polymer battery required to power SereniSleeve is too bulky to fit a sleeve. For instance, the Tattu 11.1V Lithium-Polymer rechargeable battery with minimum 2300 mAh capacity (Figure 6.32) is approximately 10.6cm long, 3.6cm wide and 2.3 tall (GensTattu, n.d.) which would not fit onto the sleeve without drawing attention.

Figure 6.32: 11.1V Lithium-Polymer rechargeable battery (GensTattu, n.d.)

With the current design, both the battery and the custom-made PCB would have to be tethered to SereniSleeve and carried in the user's jacket or pants pocket. Embedding fewer SMA wires in the sleeve actuator insert could help reduce the overall energy required to activate SereniSleeve and allow for the use of a smaller battery, but doing so would compromise the intensity of the haptic sensations. Regardless of the battery size, this arrangement is less likely to be as discreet nor comfortable for the user because of the electrical wires running from their pocket to SereniSleeve.

Some user test participants suggested modifying SereniSleeve's embodiment from a glove-like detached sleeve to one connected to regular clothing, such as on jacket sleeves or long sleeved T-shirts. This would certainly allow the electrical wires connecting SereniSleeve's electronic components to be embedded or affixed to the garment; however, the entire shirt or jacket would have to be redesigned so that all the electronic components and wires are easily attachable and removable for maintenance and washability. Additionally, many user test participants thought that the fingerless glove portion of the sleeve cover negatively impacted the sleeve's discretion because it resembled an arm splint that could draw unwanted attention from others. Getting rid of the glove portion can improve SereniSleeve's discretion as well as its general hygiene for daily use.

USABILITY: ACTIVATING SERENISLEEVE

The primary purpose of the glove portion in SereniSleeve is for affixing the FSR sensor button, which users can utilize to activate the sleeve by clenching their fist during anxious moments. Because the sensor button's location was determined based on my hand dimensions, all user test participants struggled to press on the sensor in the intended manner. The FSR sensor requires that the user place one of their finger tips precisely on its 5mm diameter active area to register the full force. If the sensor is pressed partially on the edge of the active area, the force is registered at a reduced amount. Due to the varying palm sizes and finger lengths, the sensor button placement did not align well for the participants.

In two separate instances, the participants managed to trigger SereniSleeve by holding onto items, even though the microcontroller was programmed to only register intentional activations based on the average sensor reading over a span of 2 seconds. In the first instance, the participant accidentally pressed against the FSR sensor with the corner of the iPad used to fill out the online questionnaire. In the second instance, a different participant was intentionally attempting to trigger the button by holding on to various objects. The majority of his attempts did not activate the sleeve except for when he pushed hard against the edge of a table with his hands.

Although holding onto larger surfaces does not accidentally trigger SereniSleeve, the current FSR sensor button location needs to be changed to improve the usability. However, the sensor would have to be placed somewhere on the main body of the sleeve if the glove portion is to be omitted. This may result in difficulty for the user to access the button in an intuitive motion or interaction especially during a high anxiety state. Some possible locations to place the sensor button are on top of the wrist or on a small fabric tag that could be tucked away into the sleeve. These new sensor button locations would also need to undergo user testing to determine if they are indeed easier to intuitively activate.

In addition to the difficulties associated with the FSR sensor button, some participants continued to hold down the button even after SereniSleeve activated or tried to reactivate the sleeve before the end of the enforced cooling duration. These behaviors could be attributed to the participants' unfamiliarity with SereniSleeve and may resolve once they become accustomed. Nonetheless, implementing other supplementary cues besides the DTP sensations could improve SereniSleeve's usability and help the users realize when and how long they should be pressing the button. For example, a small piece of thermochromic fabric on the sleeve cover can be utilized to subtly indicate the SMA actuator's temperature. Using a small, low noise vibrotactile motor can also provide short vibration patterns to indicate the beginning and end of an activation cycle. However, adding supplementary cues could further decrease the sleeve's discretion, so it should be cautiously utilized in moderation.

USABILITY: CUSTOMIZING HAPTIC SENSATIONS

Because of the usability issues related to the FSR sensor button, participants often had difficulty with reaching the correct sensor reading thresholds to activate the desired pressure setting out of three preset options. Reducing the number of preset pressure settings from three to two can help resolve difficulties regarding threshold levels. Doing so eliminates the guesswork involved in pressing the sensor button with an arbitrary force to activate the middle pressure setting out of three. Thus having three preset settings was useful for demonstrating SereniSleeve's pressure range ability but caused usability complications for the participants.

Additionally, participants generally had one pressure setting that they enjoyed the most, while feeling ambivalent towards the other two settings or expressing strong dislike towards one of them. Since different participants had varying preferences to the different haptic sensation intensities, giving them the option to adjust the intensity could improve the overall SereniSleeve usability and user experience. Participants' suggestions regarding haptic sensation customizations generally fell into three different categories: adjustable preset settings' intensities, option for preprogrammed patterns, and one-to-one sliding scale of pressure response.

Adjusting the preset pressure settings intensities and having the option to use preprogrammed patterns can be addressed by developing a mobile app that connects wirelessly to SereniSleeve. It is important to note that the SMA actuator's lengthy cooling durations restrict the possible types of preprogrammed patterns to slow, undulating changes in pressure as it cannot respond in quick successions similar to pulsing patterns. Finding the right balance between heating and cooling durations could result in slow pressure changing patterns that can be useful for breathing exercises. Faster changing patterns or creating sensations akin to stroking could be achieved by dividing the SMA actuator into different segments that can be individually activated, similar to Papadopoulou et al.'s Affective Sleeve (2019).

On the other hand, providing a one-to-one sliding scale of pressure sensation based solely on the live force readings while the user is holding down the FSR sensor button is not as straightforward as it may seem. Due to heat buildup, if the user does not release the button in time, the SMA actuator could cause potential skin damage from overheating. Using a temperature sensor could help prevent the SMA actuator from overheating and provide valuable feedback data for fine-grained pressure control. However, without a forced cooling method, the pressure sensation would still continue to persist after the user releases the button because of the residual heat. Adding these extra electronic components would result in a bulkier, non-discrete sleeve and higher energy consumption. Therefore, creating an app for adjusting the intensity of the preset pressure settings and providing options for preprogrammed patterns would be the more reasonable approach for individual user haptic sensation customization.

Sleeve Cover Wearability

Lastly, the fabric sleeve cover could be further iterated to improve the overall SereniSleeve's wearability. The sleeve cover was intentionally designed to not have a lengthwise opening along the arm to eliminate bulky and uncomfortable velcro straps or other rigid fasteners. The current sleeve cover design does allow SereniSleeve to slide on and off the arm with all the electronic components still in place, but it requires a lot of effort to do so.

Repeatedly assembling and disassembling the overall SereniSleeve resulted in the regular electrical wires breaking at two different locations during the user tests. The breakages happened at the connection points where the electrical wire and SMA wire are held together with electrical crimps. The electrical wires could have been serrated and weakened from using a wire stripper. Reinforcing the connection points with heat shrink tubing (Figure 6.33) would certainly help with durability; however, improving the overall sleeve cover's wearability can reduce the wear and tear of the actuator insert since it would not have to be removed each time the user don and doff the sleeve.

To enhance the wearability of the sleeve, it would be beneficial to replace segments of both the inner and outer sleeve cover layers with a stretchier fabric or a wide fabric elastic band. Specifically, the fabric replacement should be done along the inner forearm where the SMA actuator insert does not come into contact, since the actuator insert would impede the fabric from stretching effectively. Not only would this make donning and doffing easier for the fully assembled sleeve, but it would also help achieve a better fit as this method is more accommodating of different forearm thicknesses compared to elastic cords that tighten around the elbow end of the forearm.

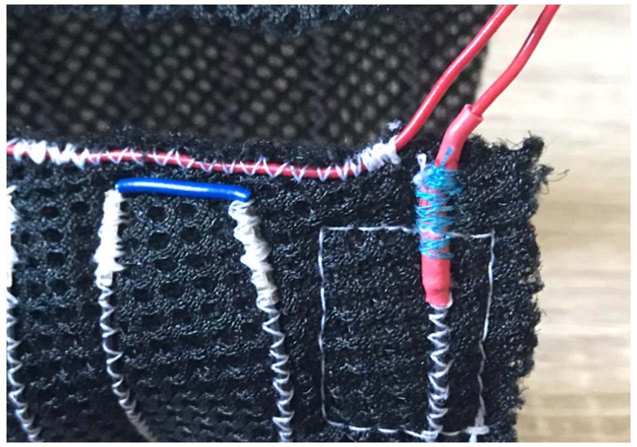


FIGURE 6.33: ELECTRICAL CRIMP CONNECTION POINTS WITH (RED, ON THE RIGHT) AND WITHOUT (BLUE, ON THE LEFT) HEAT SHRINK TUBING

C. Conclusion and Future Recommendations

The main goal of this graduation project was to develop a discreet and comfortable SMA based DTP wearable device that helps reduce daily anxiety levels in non-clinical settings. Through insights gathered from iterative design, rapid prototyping, and autobiographical design, the final sleeve prototype, or "SereniSleeve" was fabricated to apply DTP sensations to the user's forearm in the form of warmth and pressure. The DTP haptic sensations provide physical body grounding sensations that users can utilize to redirect their mind and break out of their spiraling thoughts. Unlike therapy sessions or mindfulness mobile apps, SereniSleeve can be used as a real-time and implicit intervention during anxiety or stress inducing situations.

SereniSleeve consists of a fabric SMA actuator insert, a 5mm diameter FSR sensor, and a double layered fingerless glove sleeve cover The actuator insert has 12 differently sized heart shape trained 1mm diameter NiTI SMA wires with activation temperature range of 45 - 50 °C embedded onto 3D mesh fabric to promote airflow. The FSR sensor is used as a button to activate the SMA actuator insert. The actuator insert affixes to the sleeve cover's inner layer with velcro strips, and the FSR sensor slides into a pocket so that it is positioned on the user's palm. Users can activate one of the three compression settings by clenching their fist during their anxious moments. The electronic components are completely detachable from the fabric sleeve cover for ease of maintenance and washability. Without embedded electronics, the fabric sleeve cover can easily be customized based on the user's personal style and outfit coordination.

User tests were conducted to collect unbiased opinions about the haptic sensations and the overall experience of using SereniSleeve. In general, participants found varying degrees of the pressure and warmth sensations to be pleasant and comforting. The participants suggested that SereniSleeve can be used for various purposes, including but not limited to night-time relaxation routines, physical therapy, and situation dependent stress or anxiety management. Since SereniSleeve is still at a proof-of-concept prototype level, participants faced some difficulties with its usability, especially related to the FSR sensor activation method. Nonetheless, further design iterations can improve its overall usability, wearability, and user haptic experience.

Future recommendations to improve SereniSleeve:

1. Omit the fingerless glove portion of the sleeve cover to improve discretion and hand hygiene.

2. Replace segments of both the inner and outer sleeve cover layers along the inner forearm with a wide fabric elastic band to improve the ease of don and doff.

3. Find a new location for the FSR sensor button that can be activated in an intuitive and self-compassionate user interaction rather than clenching fists.

4. Integrate a small piece of thermochromic fabric

or a low noise vibrotactile motor as supplementary cues to indicate the Sleeve's activation status.

5. Divide the SMA actuator insert into different segments that can be individually activated for stroking-like sensations or for complex preprogrammed pressure patterns.

6. Develop a mobile app for users to customize the intensities of preset compression settings and to provide options to use preprogrammed pressure patterns.

7. Use custom PCB to consolidate the micro-controller and related electronic components.

8. Find a discreet method to store or affix the powersource, custom PCB, and electrical wires that connect to SereniSleeve.

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7.2 Figures

Figure 2.2 - Reproduced from “Emotion Regulation: Conceptual Foundations,” by J.J. Gross and R.A. Thompson, 2007, in J.J. Gross (Ed.), Handbook of Emotion Regulation, p. 10, Guilford Press. Copyright 2007 by Guilford Press. Accessed through https://psu.pb.unizin.org/psych425/chapter/process-model-of-emotion-regulation/

Figure 2.7 - Screenshot taken on March 2023 https://www.schoolspecialty.com/flag-house-weighted-vest-4-pounds-medium-2121274

Figure 2.8 - [A] https://otvest.com/ , [B] https://www.squeasewear.com/squease-kids/

Figure 3.1 - Different types of hugs; Illustration from https://www.mindbodygreen.com/articles/types-of-hugs

Figure 3.6 - Photo of a boy covering his head with a blanket by Mikhail Nilov from https://www.pexels.com/photo/photo-of-a-boy-covering-his-head-with-a-blanket-8654433/

Figure 4.1 - Diagram indicating the pitch of a bolt. Image from https://u-bolts-r-us.co.uk/blog/2_metric-thread-pitch-dimensions.html

Figure 4.10 - Product listings on Nexmetal's website; Screenshot taken on 15-April 2023 from nexmetal.com https://nexmetal.com/collections/wire?view=list

Figure 5.1 - NeatTimes reflective harness vest with LED lighting for running at night https://www.amazon.in/NeatTimes-Reflective-Harness-Rechargeable-Adjustable/dp/B0832JQCHR

Figure 5.4 - [A] Sports compression sleeve https://www.bauerfeind-sports.com/nl/Productlijnen/Mouwen/Sports-Compression-Sleeves-Arm/p/YPBF_SPA_SCSLEEVA , [B] Fashion statement fingerless glove sleeve https://www.asos.com/collusion/collusion-unisex-long-sleeve-knitted-fingerless-gloves-in-green-space-dye/prd/203346701

8. APPENDIX

Appendix A: Correlation Between DTP and Social Touch

Touch is an inherent and important form of social interaction that is used to communicate emotions and build interpersonal connections (Eid & Osman, 2016). Even at our earliest stages in life, touch plays an important role in regulating people's physical and emotional well-being as observed by Spitz in 1945 on how infrequently touched human infants exhibited "developmental arrest and depression" (Wilhelm et al., 2001). Additionally, the importance of touch was further demonstrated in Harlow and Zimmerman's 1959 experiment on how baby monkeys would prefer to be with a soft cloth surrogate mother that could provide comforting physical contact over a hard wire surrogate mother that provided milk (Grandin, 1992). Affective haptic technologies essentially tries to emulate aspects of human touch by applying force and warmth (Huisman, 2017), which leads to an important question of "do affective wearable devices need to have a social aspect for it to have anxiety reducing effect?"

While there are numerous studies showcasing the physiological and psychological benefits of non-noxious human touch delivered in appropriate social contexts (Haynes et al., 2022), it is still largely inconclusive if social touch technology (STT) has evidence of stress reducing effects on a physiological level (Huisman, 2017). There are conflicting research outcomes surrounding this topic because the perceived sensory and emotional attributes of touch can be influenced by the study settings and delivery method, such as self-directed, mechanically applied, or from another person (Guest et al., 2010). For instance, Case et al. argues that "deep pressure remains pleasant even when applied mechanically, in the absence of a social interaction" based on self-reported participant ratings and MRI scans (2021). On the other hand, positive effects of STT were still observed even if the haptic stimuli, such as vibrotactile feedback, emulated only limited aspects of sensations that an actual human touch can provide. This implies that the STT haptic stimuli were effective in eliciting calming sensations because those stimuli were associated as coming from another human being remotely through the use of technology (Huisman, 2017).

Although using mechanical haptic feedback can lead to losing the social aspect of touch, decoupling the tactile sensation from social context could be beneficial for wearable devices when the device's desired outcome is explicitly for anxiety regulation rather than emulating natural touch experiences. For instance, the Huggy Pajama project by Teh et al. (Figure A.1) was developed so that parents can remotely give their children the hugging sensation through a haptic jacket (2009). In this context, being able to feel physical hugging sensations for the child can certainly improve parent-child interaction during phone or video calls. However, having to rely on another person's input to initiate the tactile haptic feedback may not be ideal for wearable devices meant to provide real-time intervention for anxiety modulation, since the other person may not be available to respond in a timely manner.

Additionally, the degree and type of social touch as well as the associated meaning varies across different cultures (Suvilehto et al., 2015). Depending on their cultural background and personal circumstances, some individuals may either not rely on others or lack close relationships necessary for emotional support through social touch. Thus implementing a social aspect of touch into real-time anxiety modulation wearable devices could restrict when and by whom they can be used.

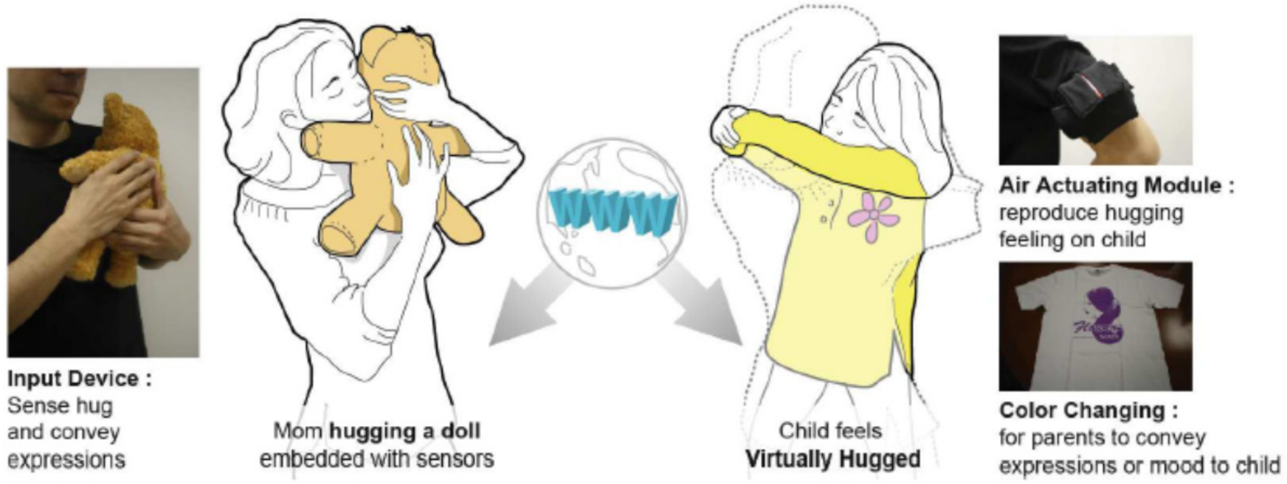
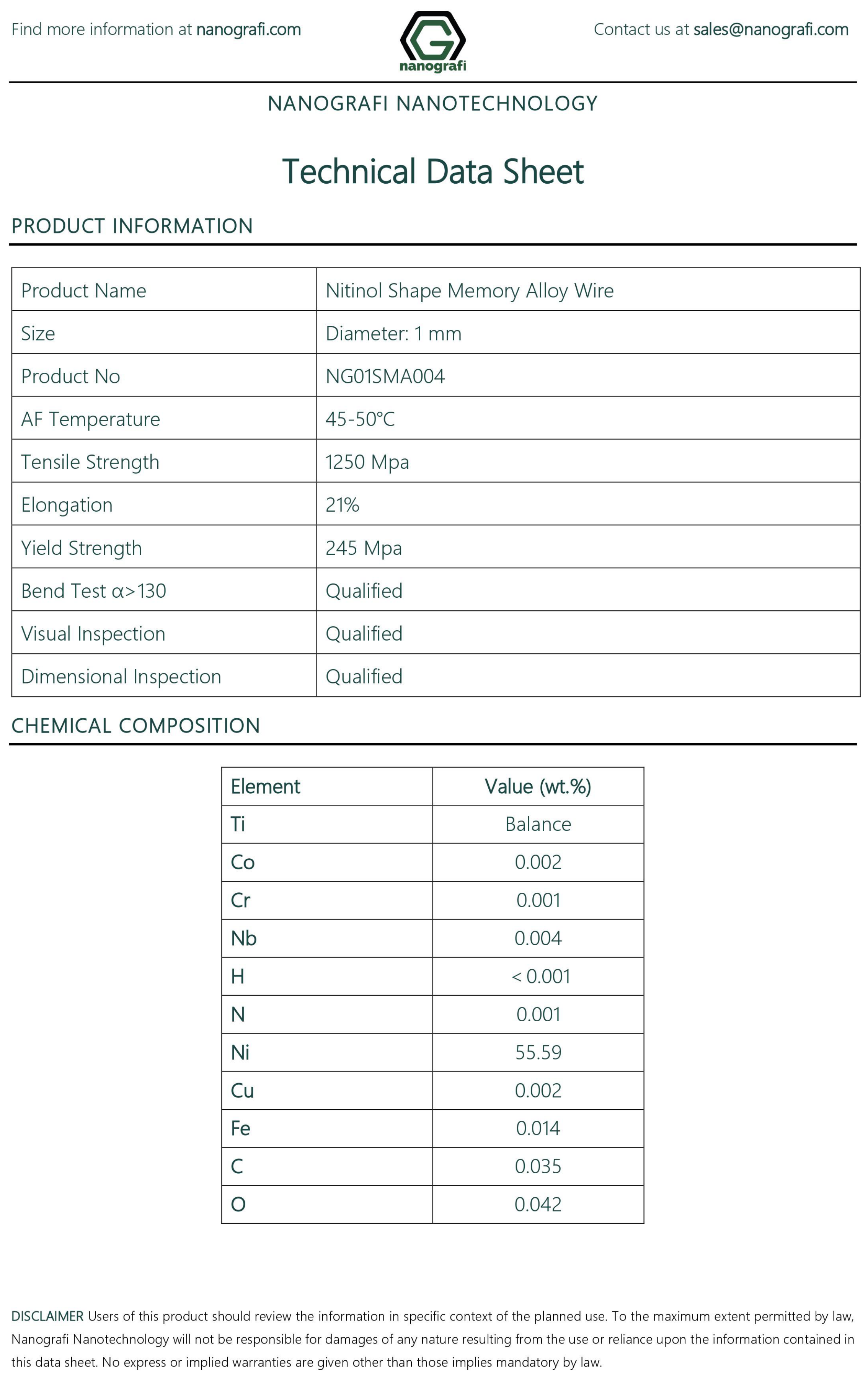


Figure A.1: Overview of the Huggy Pajama interaction (Teh et al., 2009)

Appendix B: Nanografi SMA Tech Data Sheet



Find more information at nanografi.com

Contact us at sales@nanografi.com

NANOGRAFI NANOTECHNOLOGY

Technical Data Sheet

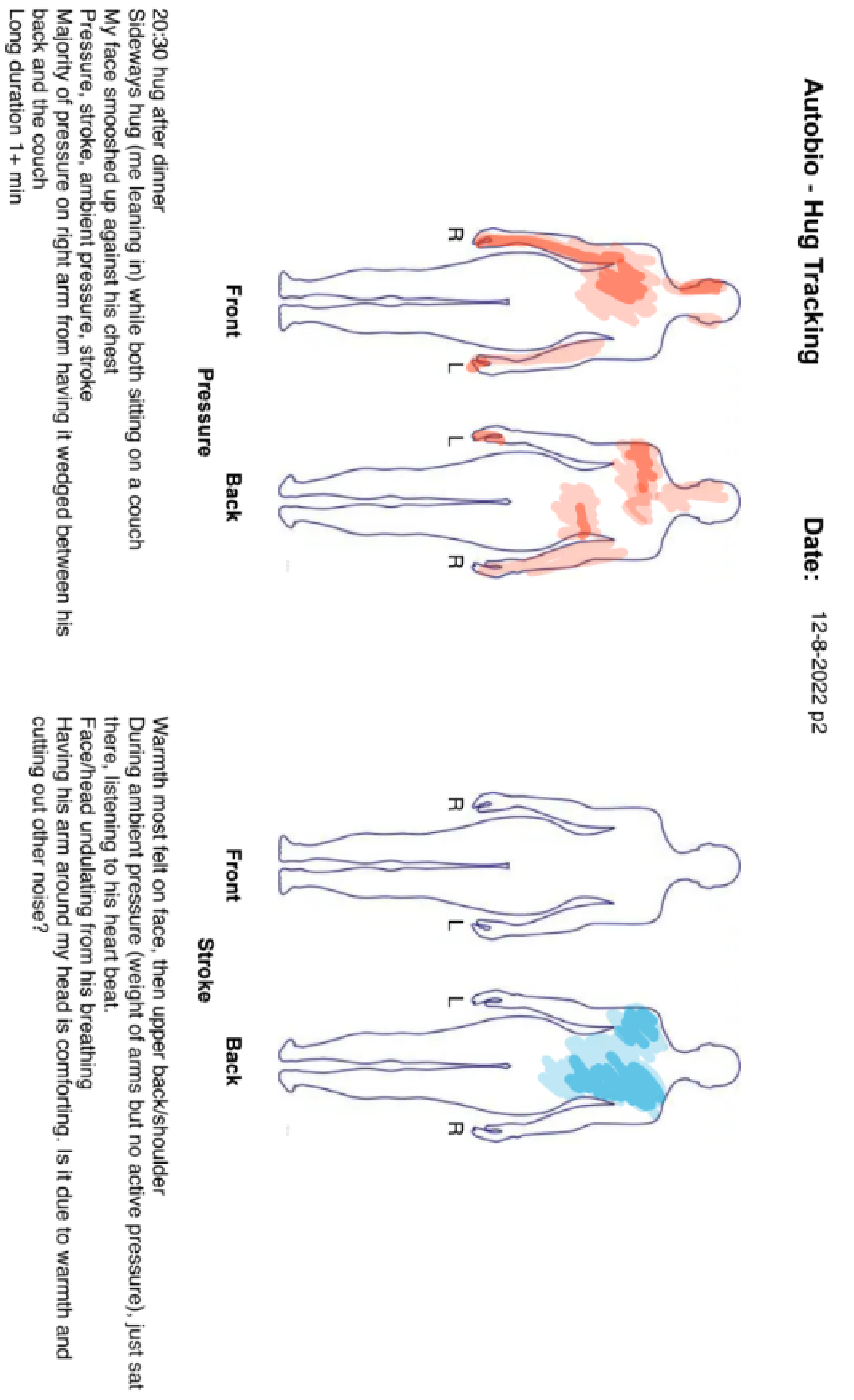
PRODUCT INFORMATION

Product Name	Nitinol Shape Memory Alloy Wire
Size	Diameter: 1 mm
Product No	NG01SMA004
AF Temperature	45-50°C
Tensile Strength	1250 Mpa
Elongation	21%
Yield Strength	245 Mpa
Bend Test α>130	Qualified
Visual Inspection	Qualified
Dimensional Inspection	Qualified

CHEMICAL COMPOSITION

Element	Value (wt.%)
Ti	Balance
Co	0.002
Cr	0.001
Nb	0.004
H	< 0.001
N	0.001
Ni	55.59
Cu	0.002
Fe	0.014
C	0.035
O	0.042

Appendix C: Autobiographical Hug Tracking Diary



Autobio - Hug Tracking

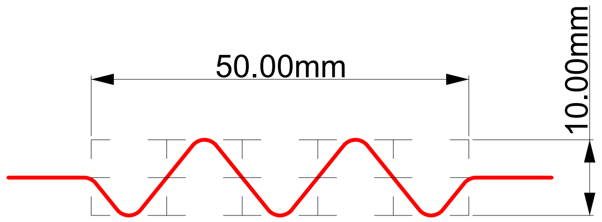
Date: 12-8-2022 p2

20:30 hug after dinner
Sideways hug (me leaning in) while both sitting on a couch
My face smooshed up against his chest
Pressure, stroke, ambient pressure, stroke
Majority of pressure on right arm from having it wedged between his back and the couch
Long duration 1+ min

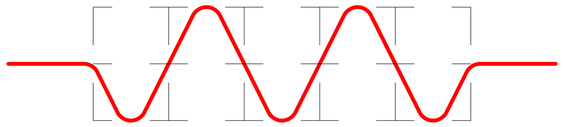
Warmth most felt on face, then upper back/shoulder
During ambient pressure (weight of arms but no active pressure), just sat there, listening to his heart beat.
Face/head undulating from his breathing
Having his arm around my head is comforting. Is it due to warmth and cutting out other noise?

Appendix D: Zigzag Spring Guide Sheet

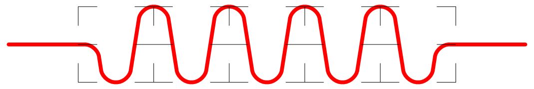
Total wire length: ~95mm
Radius curvature: 2mm
Height: 10mm
Zigzag displacement
(1st valley to last valley): 40mm
Valley to peak displacement: 10mm
Number of peaks: 2



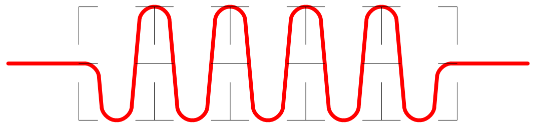
Total wire length: ~115mm
Radius curvature: 2mm
Height: 15mm
Zigzag displacement
(1st valley to last valley): 40mm
Valley to peak displacement: 10mm
Number of peaks: 2



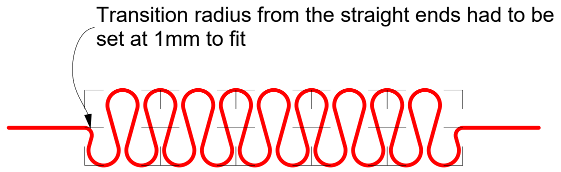
Total wire length: ~135mm
Radius curvature: 2mm
Height: 10mm
Zigzag displacement
(1st valley to last valley): 40mm
Valley to peak displacement: 5mm
Number of peaks: 4



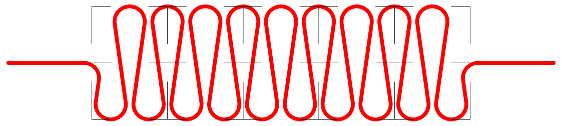
Total wire length: ~180mm
Radius curvature: 2mm
Height: 15mm
Zigzag displacement
(1st valley to last valley): 40mm
Valley to peak displacement: 5mm
Number of peaks: 4



Total wire length: ~260mm
Radius curvature: 2mm
Height: 10mm
Zigzag displacement
(1st valley to last valley): 45mm
Valley to peak displacement: 2.5mm
Number of peaks: 9



Total wire length: ~355mm
Radius curvature: 2mm
Height: 15mm
Zigzag displacement
(1st valley to last valley): 45mm
Valley to peak displacement: 2.5mm
Number of peaks: 9



Appendix E: Initial Elongating Behavior Investigations

To investigate this strange elongating behavior formation on an one-way SMA wire, a spiral spring was made using 0.5mm Nexmetal NiTi wire with 50°C activation temperature in an M4 bolt jig and annealed for 30 minutes at 550°C. The resulting M4 spring had 4.32mm outer diameter and 16.06mm length excluding the excess wire ends that were not formed into a spiral spring. The M4 spring was stretched to approximately 10 cm in length for each stretch cycle. The stretched spring was then placed in a bowl of boiling water and the spring length at its heated "activated" state was measured using digital calipers while it was still in the water (Figure E.1- A). Afterwards, the spring was then taken out of the water and placed on a counter to cool down to room temperature. Once the spring reached room temperature and stopped expanding, the spring length at its cooled state was also measured using digital calipers (Figure E.1- B). This was repeated over 10 stretch cycles and the resulting data is shown in Figure E.2 as a scatter plot.

Both the heated and cooled lengths of the M4 spiral spring were steadily increasing each time the spring underwent a stretch cycle (Figure E.2). The black dot on stretch cycle 0 represents the initial trained spring length before undergoing the stretch cycles. Interestingly, the heated spring length did not return back to the initial trained shape either and exhibited decreased shape recovery. Additionally, the difference between cooled length and the heated length of the spring increased for each stretch cycle as well. After this test was conducted, I was informed that stretching a 16.06mm SMA spring to 10 cm would be well beyond the recommended 4% strain level as the stretch length percentage is roughly 6 times its original length (or 600%).

So the follow up test with a zigzag spring was revised to stretch the spring to a length that is approximately twice (200%) its room temperature length rather than the original trained length. Except for the first 200% stretch length that was calculated based on the original trained length, the subsequent 200% stretch lengths for each stretch cycle were recalculated based on the low temperature shape length from the previous stretch cycle. As shown in Figure E.3, a hand formed zigzag spring (Figure 4.9- B) made by following the Rhinoceros 7 generated guidelines was used for this test. Since the zigzag spring lost its uniformity during the annealing process, it was difficult to consistently measure its length from the same reference points. However, using Figure E.3 as the reference photo, the zigzag spring's lengths were measured with digital calipers from the same reference points to the best of my ability.

Although the target stretch length for the zigzag spring was 200% its room temperature length, the actual stretch length varied from 200% because the springs were stretched by hand and were difficult to consistently reach the right stretch amount. So the actual calculated stretch percentage is shown above the scatter plots (Figure E.4). Similar to the M4 spiral spring, both the heated activated length and cooled room temperature length of the zigzag spring gradually deviated and increased after each stretch cycle compared to the initial trained length despite being only stretched to 200% of its length rather than 600%.

To make sure that the length deviation was not increasing without stretching, the zigzag spring, displaying two-way SME behavior after the 10 stretch cycles, underwent four non-stretch cycles. The zigzag spring was not stretched during these non-stretch cycles and was only heated up beyond its activation temperature in a bowl of boiling water and cooled down to room temperature similar to the stretch cycle's heating/cooling method. The zigzag maintained its established heated and cooled length during its four non-stretch cycles and the difference between the two lengths also stayed the same (Figure E.5).

At this point in the SMA tinkering and exploring phase, the springs made of Nexmetal's SMA nitinol wires with 40°C activation temperature did not display a visibly noticeable elongating behavior. Despite numerous attempts at contacting Nexmetal through emails and phone calls, the seller did not respond to any questions nor send any technical data sheets for either of the purchased wires. There is a possibility that Nexmetal could have accidentally sent their two-way SMA wire instead of the standard one-way SMA wire, since their two-way SMA wire has an activation temperature (55°C) similar to the 50°C one-way SMA wire activation temperature. These similarities in activation temperatures may have caused confusion during warehouse organization or during the shipment packaging for my order. On the other hand, the elongating behavior could be an aggregation of residual stress and plastic deformation within the SMA wires as they are stretched beyond recommended 4% strain level

Regardless, the initial tests proved that the 50°C activation temperature wire formed different heated and cooled temperature shapes deviating from the intended trained shape. This deviation in length could result in SMA actuators losing their effectiveness over time especially since the heated spring lengths at their activated state were also elongating compared to the trained shape. Because the zigzag spring continued to deviate from its original trained shape even when it was stretched less than twice its length (below 200% stretch length), SMA actuators made with this particular SMA wire would result in limited displacement. Unless there is a mechanical limiter in the actuator to prevent the SMA springs from stretching beyond their recommended strain level at all times, the actuators can accidentally and easily be stretched beyond 200% stretch length especially in a wearable context where rigid structures and parts can be uncomfortable for the user. Moreover, the continued elongation of the springs' heated and cooled temperature shapes would further complicate the integration method to embed the SMA actuators onto fabric. Therefore, only the 40°C activation temperature SMA Nexmetal wire was used for the remainder of the SMA tinkering and exploration phase.

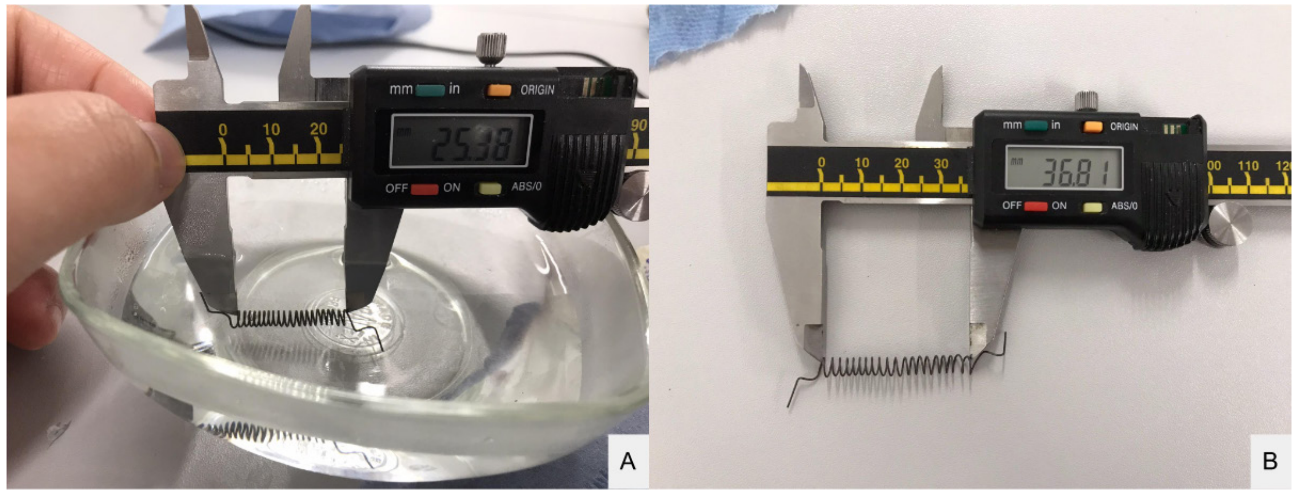


Figure E.1: [A] SMA spring's heated length being measured with digital calipers while in a bowl of hot water [B] SMA spring's cooled length being measured after the spring reaches room temperature

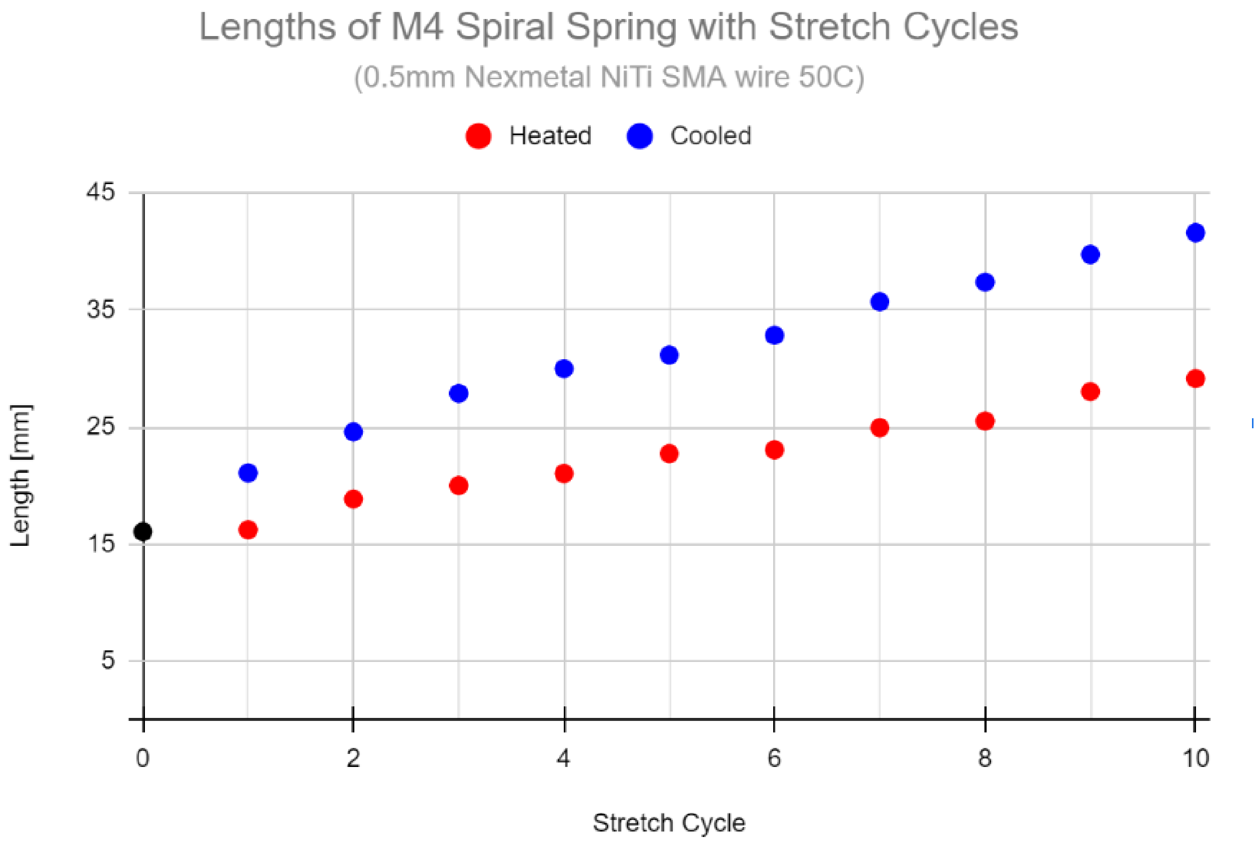


Figure E.2: M4 SMA spiral spring exhibiting elongating behavior after being stretched to approximately 10 cm for each stretch cycle. Black dot: the initial trained spring length.

Figure E.3: Hand formed zigzag spring (Figure 4.9- B) made using guidelines being measured with a digital caliper

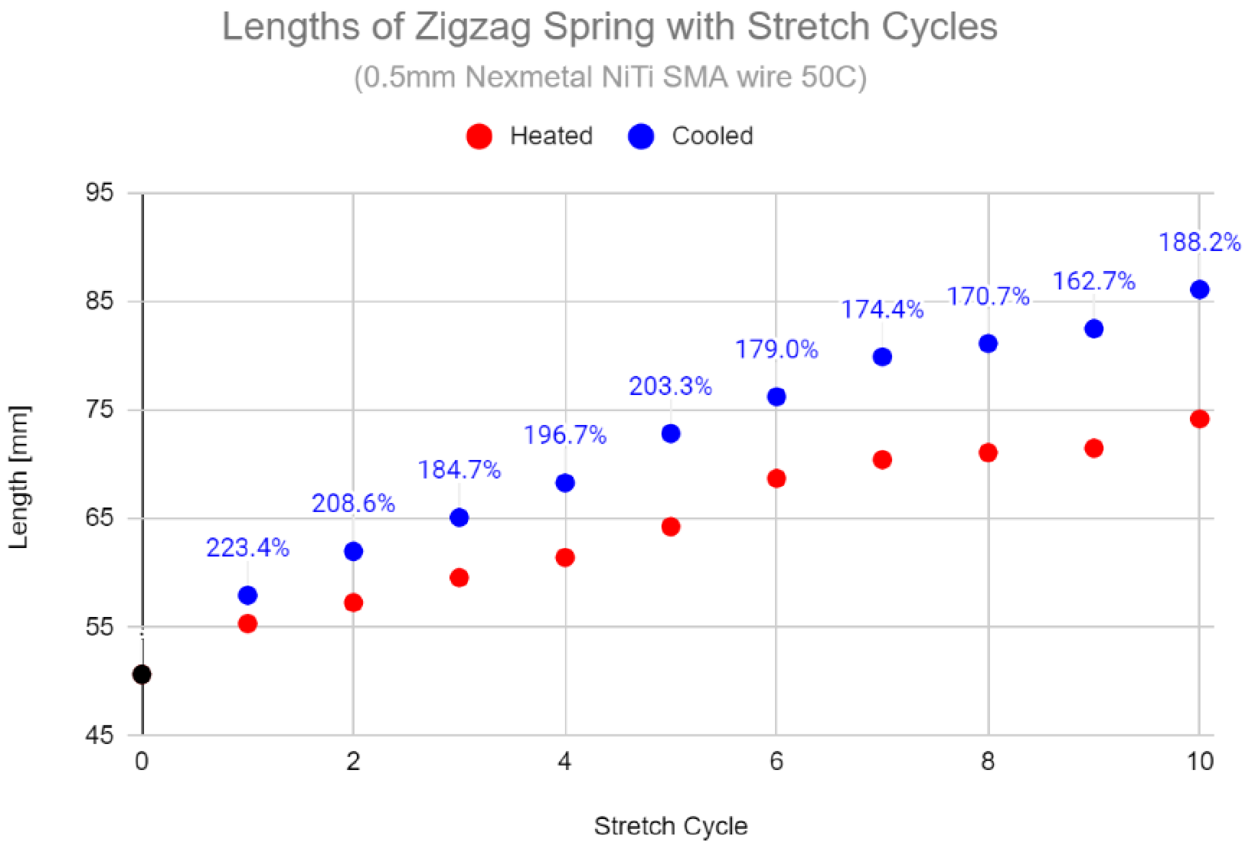


Figure E.4: Zigzag SMA spring exhibiting elongating behavior after being stretched to approximately 200% its previous cooled temperature length. The actual calculated stretch % displayed for each stretch cycle. Black dot: the initial trained spring length.

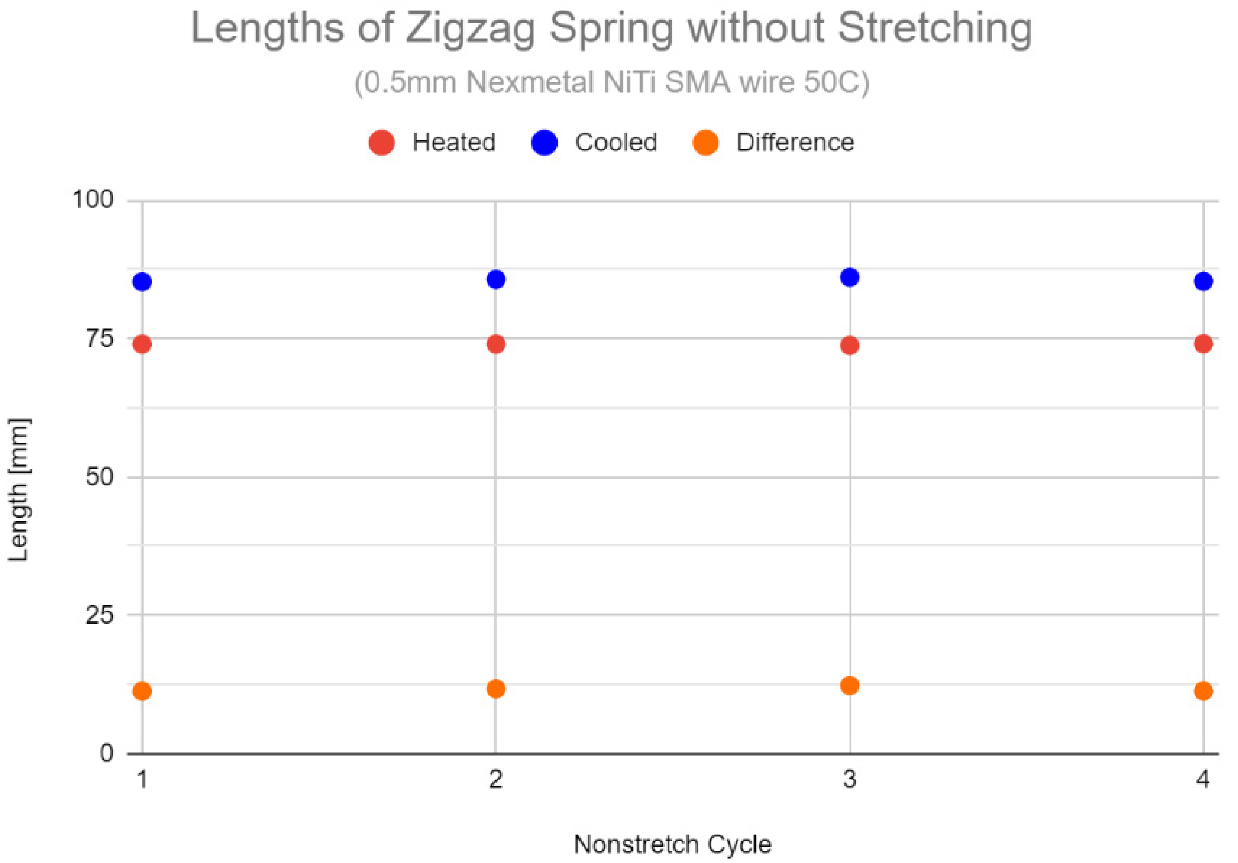
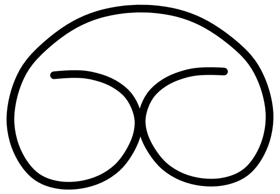


Figure E.5: Consistent heated and cooled length of the zigzag SMA spring with “pseudo two-way” behavior after going through four non-stretch cycles. Orange dots: difference between heated and cooled lengths

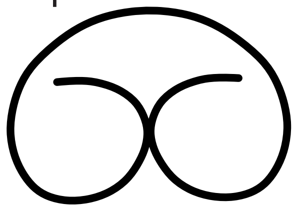
Appendix F: Forearm Cone Pieces

Refer to the attached scanned drawings

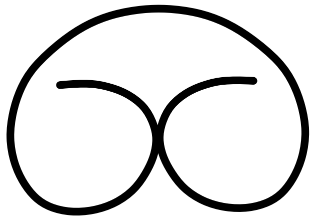
Appendix G: Heart Shape Guidelines



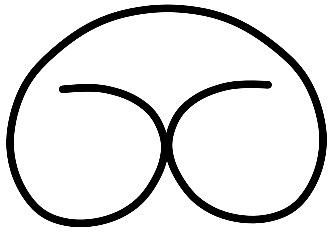
132mm



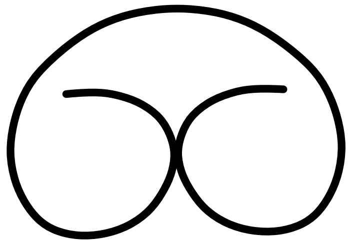
141mm



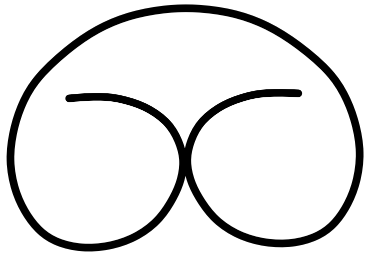
150mm



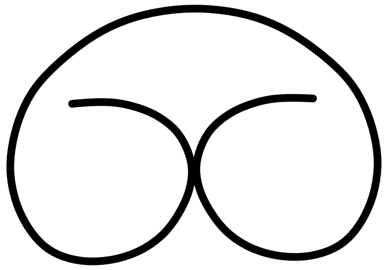
160mm



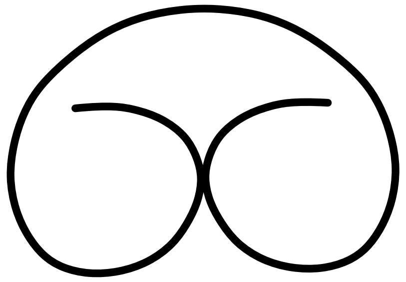
169mm



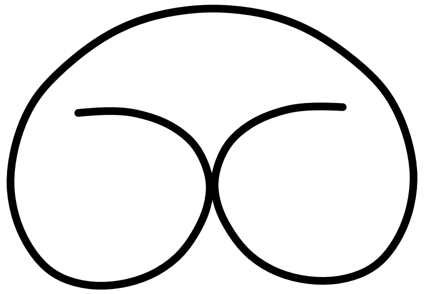
178mm



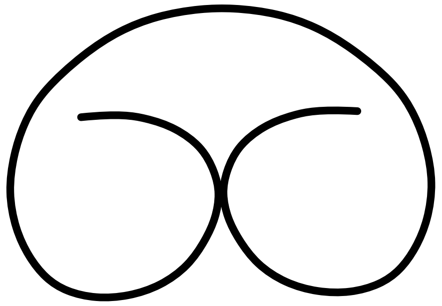
187mm



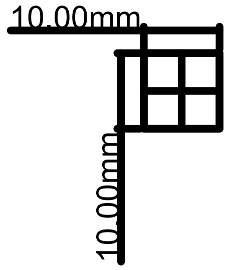
197mm

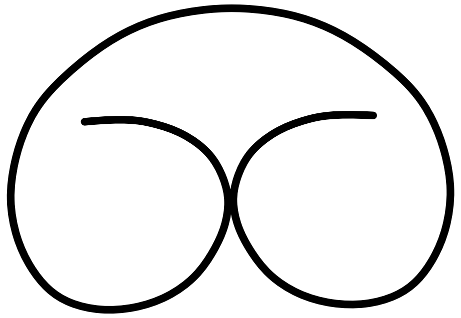


206mm

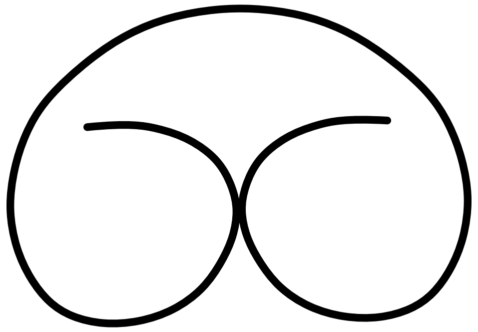


215mm





224mm



234mm

Appendix H: Sleeve Cover Pattern Pieces

Refer to the attached scanned drawings

Appendix I: Arduino Code

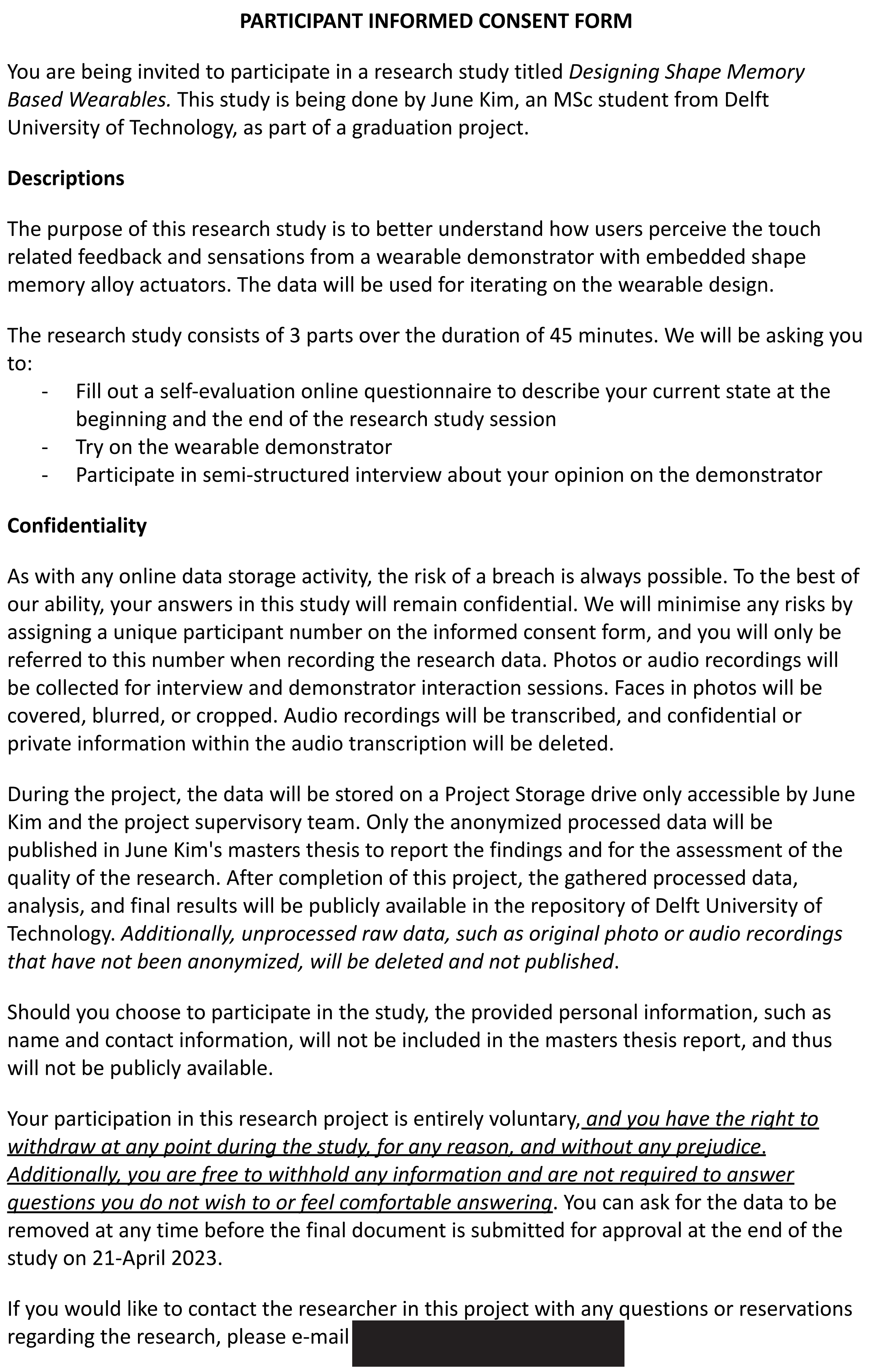
```
//assigning pin numbers
#define SMAPIN 5
#define FORCE_SENSOR_PIN_0 A0  // the FSR and 47K pulldown are connected to A0

////////////////////////////////////////////////////////////////////////////////////////////////////
//vvvvvvvvv ----- Change Variable inputs based on prototype ----- vvvvvvvvvvvvvvvvv

// Max limits the current through the wire (maximum analogWrite value is 255)
const int MAX = 255;

//duration to collect force sensor output in milliseconds (1000 millisec = 1 sec)
const unsigned long force_duration = 2000;

// defining array values for none, small, medium, high
const int pwmValue_arr[4] = { 0, MAX*0.6, MAX*0.8, MAX };
const unsigned long heat_mod_arr[4] = { 0, 5, 8, 10 };    // heat duration modifier in seconds
const unsigned long cool_mod_arr[4] = { 0, 20, 30, 40};  // cool duration modifier in seconds

// Define the number of samples to keep track of for sensor reading smoothing
const int numReadings = 10;

//^^^^^^^^^^ ----- Change Variable inputs based on prototype ----- ^^^^^^^^^^^^^^^^^
//////////////////////////////////////////////////////////////////////////////////////////////////

// variables for timer
unsigned long startMillis;
unsigned long currentMillis;
unsigned long Force_currentMillis;

// defining struct of group of variables
struct group {
  String force_type;
  bool SMA_started;
  int pwmValue;
  unsigned long heat_duration;
  unsigned long cool_duration;
};

group SMA_var; //creating a group
bool start; //to start heating+cooling cycle

// defining variables for smoothing
int readings[numReadings];  // the readings from the force sensor input
int total = 0;              // the running total
int avg_force = 0;          // the average force sensor reading


void setup() {
  // initialize the serial output and pins
  Serial.begin(115200);

  // SMAPIN is the pin to which the SMA wire is connected (via the MOSFET)
  pinMode(SMAPIN, OUTPUT);

  // initialize all the force readings to 0:
  for (int j = 0; j < numReadings; j++) {
```

```
    readings[j] = 0;
  }

  startMillis = millis();  //initial start time
}

void loop() {

// Detecting if force sensor has been pressed deliberately for force_duration amount of time
  if (analogRead(FORCE_SENSOR_PIN_0) > 100) {
    Force_currentMillis = millis();

    // smoothing force sensor reading collected over force_duration
    // filter out possible force sensor noise
    while (Force_currentMillis - startMillis <= force_duration) {
      avg_force = smoothing_read();
      Force_currentMillis = millis();
    }

    //Reset startMillis for timers
    startMillis = Force_currentMillis;

    //Define type of SMA behavior based on average force reading
    SMA_var = SMA_behavior(avg_force);

    Serial.print(SMA_var.force_type);
    Serial.print(“, “);
    Serial.print(avg_force);
    Serial.print(“, heat time: “);
    Serial.print(SMA_var.heat_duration / 1000);
    Serial.print(“ sec, cool time: “);
    Serial.print(SMA_var.cool_duration / 1000);
    Serial.println(“ sec”);

    start = SMA_var.SMA_started;

  } else {
    //force sensor hasn’t been pressed long enough to count as user input
    avg_force = 0;
    start = false;
  }

// initiating heating + cooling cycle for SMA
  while (start == true) {
    cycle(SMA_var);
  }
}



// smoothing function copied from Arduino Smoothing Example
int smoothing_read() {

  for (int i = 0; i < numReadings; i++) {
    // subtract the last reading:
    total = total - readings[i];
    // read from the sensor:
    readings[i] = analogRead(FORCE_SENSOR_PIN_0);
    // add the reading to the total:
```

```
    total = total + readings[i];
    delay(1);
  }

  //return the average of sensor reading
  return total / numReadings;
}



// take in avg_force (as x), determine the type of SMA behavior
group SMA_behavior(int x) {

  group var;

  if (x < 100) {
    // average force reading less than 100

    var = { “No Force”, false, pwmValue_arr[0], 1000 * heat_mod_arr[0], 1000 * cool_mod_arr[0] };

  } else if (x >= 100 && x < 500) {
    // average force reading from 100 to 499

    var = { “Small Force”, true, pwmValue_arr[1], 1000 * heat_mod_arr[1], 1000 * cool_mod_arr[1] };
    currentMillis = millis();  //start SMA heating timer

  } else if (x >= 500 && x < 700) {
    // average force reading from 500 to 699

    var = { “Medium Force”, true, pwmValue_arr[2], 1000 * heat_mod_arr[2], 1000 * cool_mod_arr[2]
           };
    currentMillis = millis();  //start SMA heating timer

  } else {
    // average force reading 700 and above

    var = { “High Force”, true, pwmValue_arr[3], 1000 * heat_mod_arr[3], 1000 * cool_mod_arr[3] };
    currentMillis = millis();  //start SMA heating timer
  }

  return var;
}


// heating + cooling cycle of SMA once heating is triggered
void cycle(group z) {

  if (currentMillis - startMillis <= z.heat_duration) {
    // Heating up SMA
    analogWrite(SMAPIN, z.pwmValue);

    Serial.print(“Heating. Timer “);
    Serial.print((currentMillis - startMillis) / 1000);
    Serial.print(“ out of “);
    Serial.print(z.heat_duration/1000);
    Serial.print(“ sec, “);
    Serial.println(z.force_type);

    currentMillis = millis();
```

```
  } else if ((currentMillis - startMillis > z.heat_duration) && (currentMillis - startMillis <= z.heat_dura-
          tion + z.cool_duration)) {
    //Cooling down SMA
    //Prevents users from activating the heating cycle until SMA cools down enough
    analogWrite(SMAPIN, 0);

    Serial.print(“Cooling. Timer “);
    Serial.print(((currentMillis - startMillis) / 1000) - z.heat_duration / 1000);
    Serial.print(“ out of “);
    Serial.print(z.cool_duration/1000);
    Serial.print(“ sec, “);
    Serial.println(z.force_type);

    currentMillis = millis();

  } else {
    //finish heating + cooling cycle
    analogWrite(SMAPIN, 0);
    start = false;

    Serial.println(“Reset”);
    currentMillis = millis();
    startMillis = currentMillis;
  }
}
```

Appendix J: User Test Informed Consent Form



PARTICIPANT INFORMED CONSENT FORM

You are being invited to participate in a research study titled *Designing Shape Memory Based Wearables.* This study is being done by June Kim, an MSc student from Delft University of Technology, as part of a graduation project.

Descriptions

The purpose of this research study is to better understand how users perceive the touch related feedback and sensations from a wearable demonstrator with embedded shape memory alloy actuators. The data will be used for iterating on the wearable design.

The research study consists of 3 parts over the duration of 45 minutes. We will be asking you to:

- Fill out a self-evaluation online questionnaire to describe your current state at the beginning and the end of the research study session
- Try on the wearable demonstrator
- Participate in semi-structured interview about your opinion on the demonstrator

Confidentiality

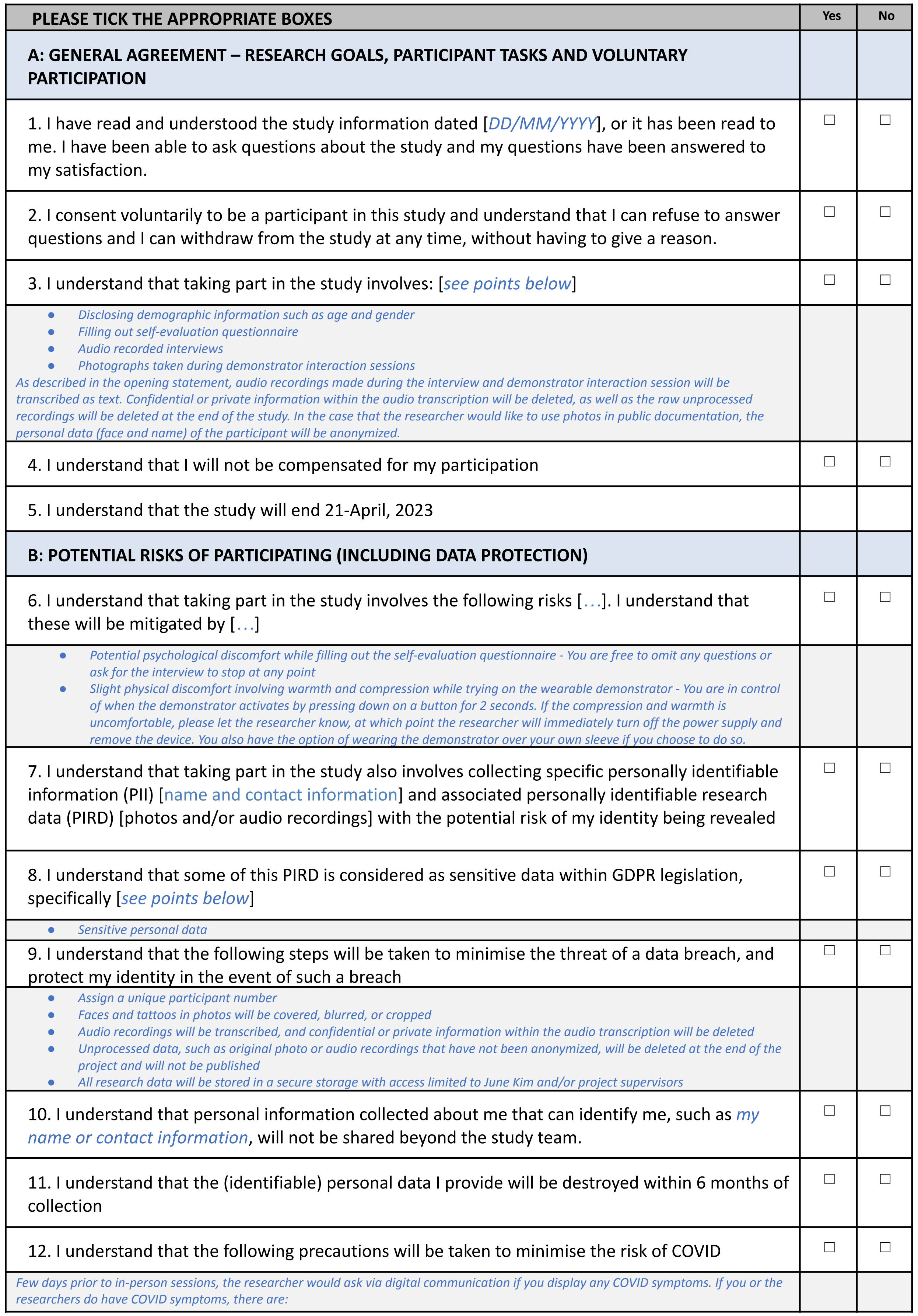
As with any online data storage activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimise any risks by assigning a unique participant number on the informed consent form, and you will only be referred to this number when recording the research data. Photos or audio recordings will be collected for interview and demonstrator interaction sessions. Faces in photos will be covered, blurred, or cropped. Audio recordings will be transcribed, and confidential or private information within the audio transcription will be deleted.

During the project, the data will be stored on a Project Storage drive only accessible by June Kim and the project supervisory team. Only the anonymized processed data will be published in June Kim's masters thesis to report the findings and for the assessment of the quality of the research. After completion of this project, the gathered processed data, analysis, and final results will be publicly available in the repository of Delft University of Technology. *Additionally, unprocessed raw data, such as original photo or audio recordings that have not been anonymized, will be deleted and not published*.

Should you choose to participate in the study, the provided personal information, such as name and contact information, will not be included in the masters thesis report, and thus will not be publicly available.

Your participation in this research project is entirely voluntary, *and you have the right to withdraw at any point during the study, for any reason, and without any prejudice. Additionally, you are free to withhold any information and are not required to answer questions you do not wish to or feel comfortable answering*. You can ask for the data to be removed at any time before the final document is submitted for approval at the end of the study on 21-April 2023.

If you would like to contact the researcher in this project with any questions or reservations regarding the research, please e-mail [redacted]



PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated [*DD/MM/YYYY*], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
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: [*see points below*]	☐	☐
● *Disclosing demographic information such as age and gender* ● *Filling out self-evaluation questionnaire* ● *Audio recorded interviews* ● *Photographs taken during demonstrator interaction sessions* *As described in the opening statement, audio recordings made during the interview and demonstrator interaction session will be transcribed as text. Confidential or private information within the audio transcription will be deleted, as well as the raw unprocessed recordings will be deleted at the end of the study. In the case that the researcher would like to use photos in public documentation, the personal data (face and name) of the participant will be anonymized.*		
4. I understand that I will not be compensated for my participation	☐	☐
5. I understand that the study will end 21-April, 2023		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks [...]. I understand that these will be mitigated by [...]	☐	☐
● *Potential psychological discomfort while filling out the self-evaluation questionnaire - You are free to omit any questions or ask for the interview to stop at any point* ● *Slight physical discomfort involving warmth and compression while trying on the wearable demonstrator - You are in control of when the demonstrator activates by pressing down on a button for 2 seconds. If the compression and warmth is uncomfortable, please let the researcher know, at which point the researcher will immediately turn off the power supply and remove the device. You also have the option of wearing the demonstrator over your own sleeve if you choose to do so.*		
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [name and contact information] and associated personally identifiable research data (PIRD) [photos and/or audio recordings] 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 [*see points below*]	☐	☐
● *Sensitive personal data*		
9. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach	☐	☐
● *Assign a unique participant number* ● *Faces and tattoos in photos will be covered, blurred, or cropped* ● *Audio recordings will be transcribed, and confidential or private information within the audio transcription will be deleted* ● *Unprocessed data, such as original photo or audio recordings that have not been anonymized, will be deleted at the end of the project and will not be published* ● *All research data will be stored in a secure storage with access limited to June Kim and/or project supervisors*		
10. I understand that personal information collected about me that can identify me, such as *my name or contact information*, will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed within 6 months of collection	☐	☐
12. I understand that the following precautions will be taken to minimise the risk of COVID	☐	☐
Few days prior to in-person sessions, the researcher would ask via digital communication if you display any COVID symptoms. If you or the researchers do have COVID symptoms, there are:		

PLEASE TICK THE APPROPRIATE BOXES	**Yes**	**No**
- *Option to reschedule individual interviews or demonstrator interaction sessions in case of COVID infection* *Even if you or the researchers do not have COVID symptoms, you are free to ask the researchers to wear face masks during in-person sessions*		
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
13. I understand that after the research study, the de-identified information I provide will be used for reports and publications.	☐	☐
14. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
15. *Copyright of the works I provide such as images and written works belong to me, and I give permission for them to be used for the purposes of this research.*	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
16. I give permission for the de-identified *images and quotes* that I provide to be archived in the TU Delft Graduation Project repository so it can be used for future research and learning.	☐	☐
17. I understand that access to this repository is open to the public.	☐	☐

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.

Researcher name [printed] Signature Date

Appendix K: Project Brief

DESIGN FOR our future

TUDelft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

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

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

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

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

family name Kim
initials given name June
student number 5254914
street & no.
zipcode & city
country
phone
email

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

SUPERVISORY TEAM **

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

** chair Dr. Sepideh Ghodrat dept. / section: SDE/EM
** mentor Dr. Haian Xue dept. / section: HCD/DA
2nd mentor
organisation:
city: country:

comments (optional)

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

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

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

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 1 of 7

TUDelft

Procedural Checks - IDE Master Graduation

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

chair Dr. Sepideh Ghodrat date 19 - 09 - 2022 signature Sepideh Ghodrat - IO Digitally signed by Sepideh Ghodrat - IO Date: 2022.09.19 10:01:40 +02'00'

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

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

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

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

○ YES all 1st year master courses passed

○ NO missing 1st year master courses are:

name ______ date - - signature ______

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

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

Content: ○ APPROVED ○ NOT APPROVED

Procedure: ○ APPROVED ○ NOT APPROVED

comments

name ______ date - - signature ______

TUDelft

Personal Project Brief - IDE Master Graduation

Designing Shape Memory Based Wearables for Anxiety Modulation project title

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

start date 05 - 09 - 2022 31 - 01 - 2023 end date

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

According to an online survey conducted by the Dutch National Institute for Public Health and the Environment in April and May of 2020, approximately 30% of the 89,945 respondents 16 years and older have indicated that they experienced increased anxiety during the COVID-19 pandemic (Figure 1). Although the pandemic may have exacerbated anxiety among the Dutch population, it is undeniable that mental health has been a point of concern long before COVID. Especially with the attached negative social stigma, many individuals often do not want to be identified as struggling with mental health, but debilitating anxiety attacks can happen anytime and anywhere.

To help reduce anxiety and overstimulation, some individuals with Autism Spectrum Disorder (ASD) or Attention Deficit Hyperactivity Disorder (ADHD) utilize deep touch pressure (DTP) in the form of weighted blankets or compression "hugging" vests (Duvall et al., 2016). DTP is a form of tactile sensory input that can be provided by holding, stroking, hugging and squeezing, which has been increasingly utilized in "acute mental healthcare settings for crisis intervention, preparatory purposes… as it gives subjects the feelings of safety, relaxation, and comfort" (Chen et al., 2013). Additionally, DTP can be used to help increase breathing awareness for the user (Jung et al., 2021), which is helpful for managing anxiety attacks even for individuals without ASD or ADHD.

Many of the current commercially available wearable DTP products are in the form of weighted vests or inflatable compression vests as seen in Figure 2a and 2b respectively. One of the main downsides with existing wearable DTP products is that they are not discreet. Weighted vests or non-adjustable vests must be periodically removed from the user to alleviate pressure as the user can acclimate to the pressure, making DTP ineffective (Duvall et al., 2016). Additionally, because of the bulkiness or the need for manual operation, wearable DTP products are difficult to conceal which can attract unwanted attention from nearby strangers. Since the main target user group is people who struggle with anxiety, getting unwanted attention can further aggravate the severity of anxiety attacks due to potential negative evaluation or scrutiny by others (Schneier & Goldmark, 2015).

Conversely, as shown in Figure 2c, there is research done to utilize shape memory alloys (SMA) or electronic textiles to address the aforementioned downside of existing wearable DTP products. These past research in SMA actuators or e-textiles can be beneficial for developing discreet wearable DTP products. However, these research tend to stop at the technological exploration level rather than being fully integrated into an actual product for users. As there is a clear disjunction between technological research and commercially available wearable DTP products, a new type of wearable product needs to be developed. Additionally, further research in user interaction with wearable DTP products is necessary to develop a functioning wearable product that is comfortable for the users to wear daily.

For the context of this graduation project, I would like to create a wearable product that uses SMA actuators developed at the TU Delft Emerging Materials Lab to help users with day-to-day anxiety. The target user group would be TU Delft students who voluntarily identify as struggling with varying degrees of anxiety. With this project, I hope to support people who are silently struggling with their mental health by developing a daily wearable product that can help them stay grounded in a non-clinical setting and not let anxiety dictate their life.

space available for images / figures on next page

Personal Project Brief - IDE Master Graduation

introduction (continued): space for images

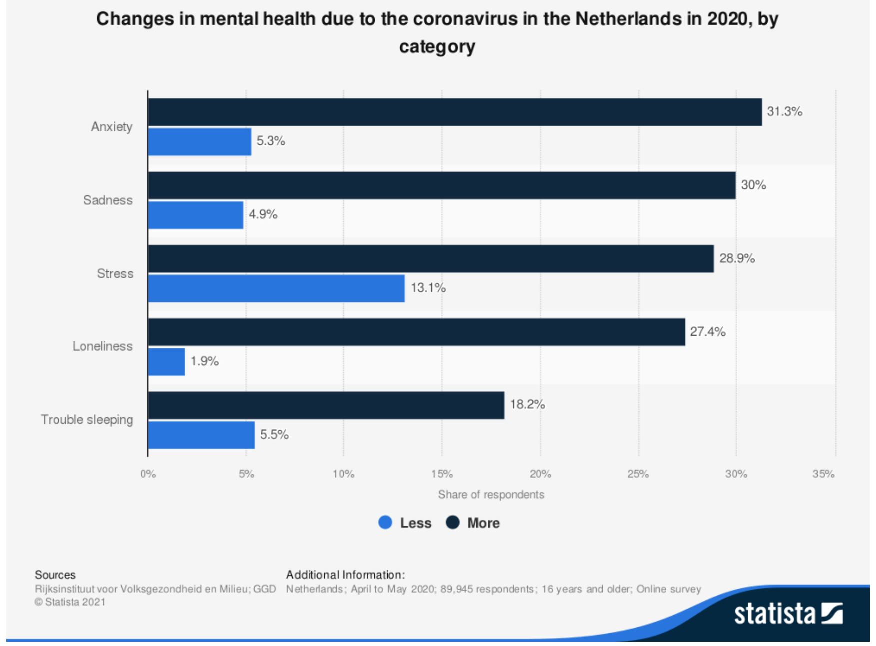


image / figure 1: Changes in mental health due to the COVID-19 pandemic in the Netherlands 2020

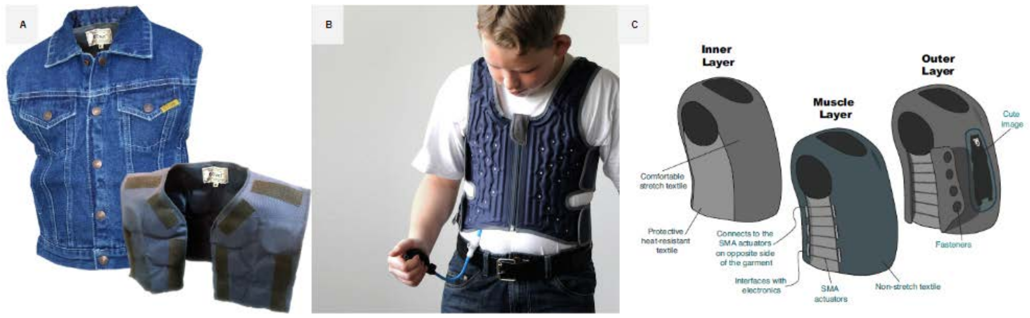


image / figure 2: (A) Weighted vest; OTvest, (B) inflatable vest; Squeasewear, (C) SMA hugging vest (Duvall, 2016)

Personal Project Brief - IDE Master Graduation

PROBLEM DEFINITION **

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

The main themes of this project are twofold: technology and user interaction.

Theme 1: Technology involved in creating a shape memory based wearable product for anxiety modulation

RQ 1.1 - What leads to the technological disjunction between research and commercially available wearable DTP products?
RQ 1.2 - Which SMA configurations can create the haptic feedback necessary for anxiety modulation and best suited for wearables?

Theme 2: User interaction with wearable products

RQ 2.1 - What kinds of haptic feedback do users find useful for decreasing anxiety? How does the intensity, frequency, and location of the haptic feedback affect user experience?
RQ 2.2 - Are other forms of wearables (ex: belt/strap, bracelet etc.) better suited for comfortable and discreet DTP wearable that can encourage daily use?

ASSIGNMENT **

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

Design and create a functional prototype of a shape memory based wearable product that can help reduce the user's anxiety levels in a day-to-day context through the use of DTP and haptic feedback in a non-clinical setting.

The focus of this graduation project is to improve on wearable DTP products by bridging the gap between commercially available solutions and existing research in SMA actuators. Ideally, the end result would be a wearable product that:

1. Is discreet and comfortable for the user to wear daily
2. Creates haptic feedback through SMA actuators for anxiety modulation

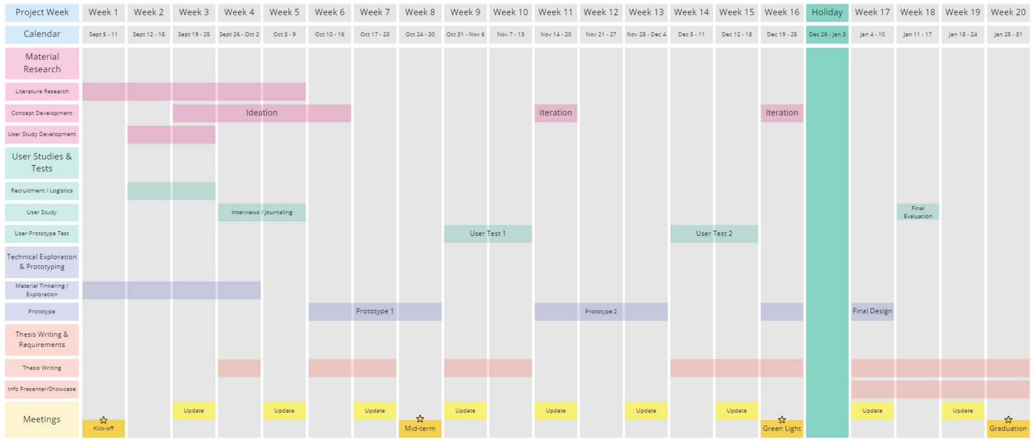
However, it is important to note that these criteria may change overtime as more insights are gathered through in-depth literature review, material tinkering, and user studies/interviews. For example, even though the currently commercially available wearable DTP products are mainly in the form of full size vests, it may be possible to identify the areas at which the user feels the most amount of pressure from SMA actuators through user studies and use smaller wearables, such as belts or straps.

PLANNING AND APPROACH **

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

start date 5 - 9 - 2022

31 - 1 - 2023 end date



This schedule is subject to change as the project progresses.

I will start my graduation project by first focusing on literature review and tinkering with SMA actuators to have a better understanding of technological possibilities and limitations. Meanwhile, I'll also be setting up user studies that involve journaling and interviews. Ideally, since mental health can be a sensitive topic that some participants may have trouble communicating, I would like to have a small group of dedicated participants who are willing to participate in all the user studies and tests to better understand their anxiety related needs.

Because I would like to conduct several user tests with iterative prototypes, tinkering with SMA actuators early on in the project is imperative. Each prototype would undergo user tests to evaluate the design, usability or effectiveness of the wearable on reducing anxiety, and the results from the evaluation will be used to improve upon the next prototype.

The last 2 weeks will be focused on rounding off the project including finishing the thesis report and other mandatory deliverables.

MOTIVATION AND PERSONAL AMBITIONS

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

This project stemmed from my personal struggle with mental health and anxiety. Especially as someone who had to move from a young age to various countries with different languages and cultures, I've been in situations when I just needed nonverbal comfort free of judgment, like a hug, to help ground myself and break out of anxiety attacks. Additionally, I've been wanting to work with SMAs, e-textiles and wearables but haven't come across the right project opportunity or electives. So when I learned about DTP vests, I thought it would be the perfect graduation project topic that can combine my interest in wearable technology and the need for a physical product that can help with anxiety.

Although I am not looking to take this project beyond the graduation context, I am hoping to apply the knowledge I've learned as well as learn new skill sets that can help me in my future endeavors as a designer. Through this graduation project, I would like to prove my competence in technological research and prototyping/fabrication techniques. On the other hand, I would like to learn how to work with SMA systems and gain further experience in user centered design and project management.

Reference:

Chen, H. Y., Yang, H., Chi, H. J., & Chen, H. M. (2013). Physiological Effects of Deep Touch Pressure on Anxiety Alleviation: The Weighted Blanket Approach. Journal of Medical and Biological Engineering, 33(5), 463–470. https://doi.org/10.5405/jmbe.1043

Duvall, J. C., Dunne, L. E., Schleif, N., & Holschuh, B. (2016). Active "hugging" vest for deep touch pressure therapy. Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct. https://doi.org/10.1145/2968219.2971344

Jung, A., Alfaras, M., Karpashevich, P., Primett, W., & Höök, K. (2021). Exploring Awareness of Breathing through Deep Touch Pressure. Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3411764.3445533

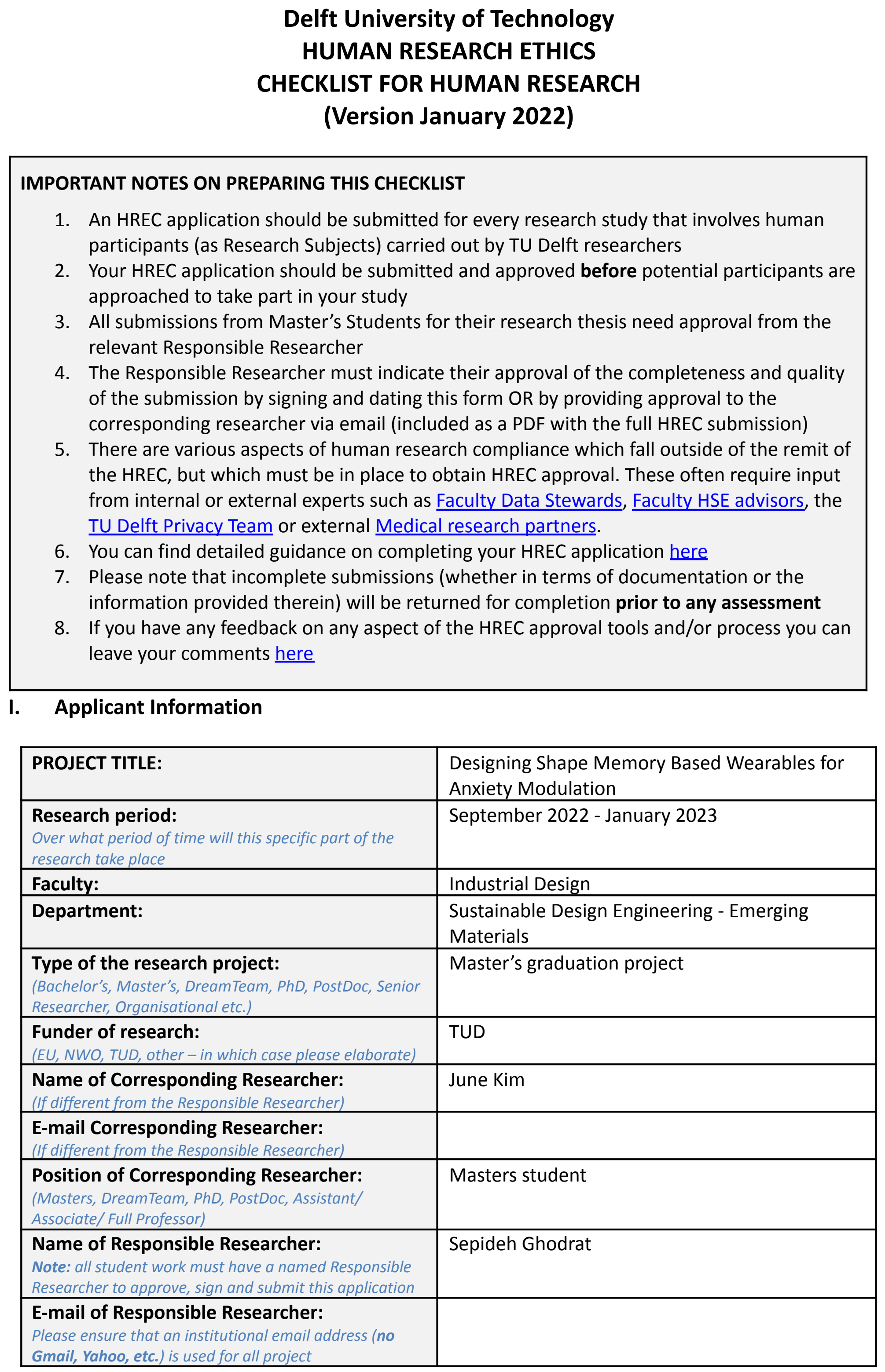
Schneier, F., & Goldmark, J. (2015). Social Anxiety Disorder. Anxiety Disorders and Gender, 49–67. https://doi.org/10.1007/978-3-319-13060-6_3

Stewart, C. (2021, September 29). Changes in mental health due to the coronavirus in the Netherlands in 2020, by category [Graph]. Statista. https://www.statista.com/statistics/1115803/dutch-mental-health-coronavirus/

FINAL COMMENTS

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

Appendix L: HREC Application - User Study



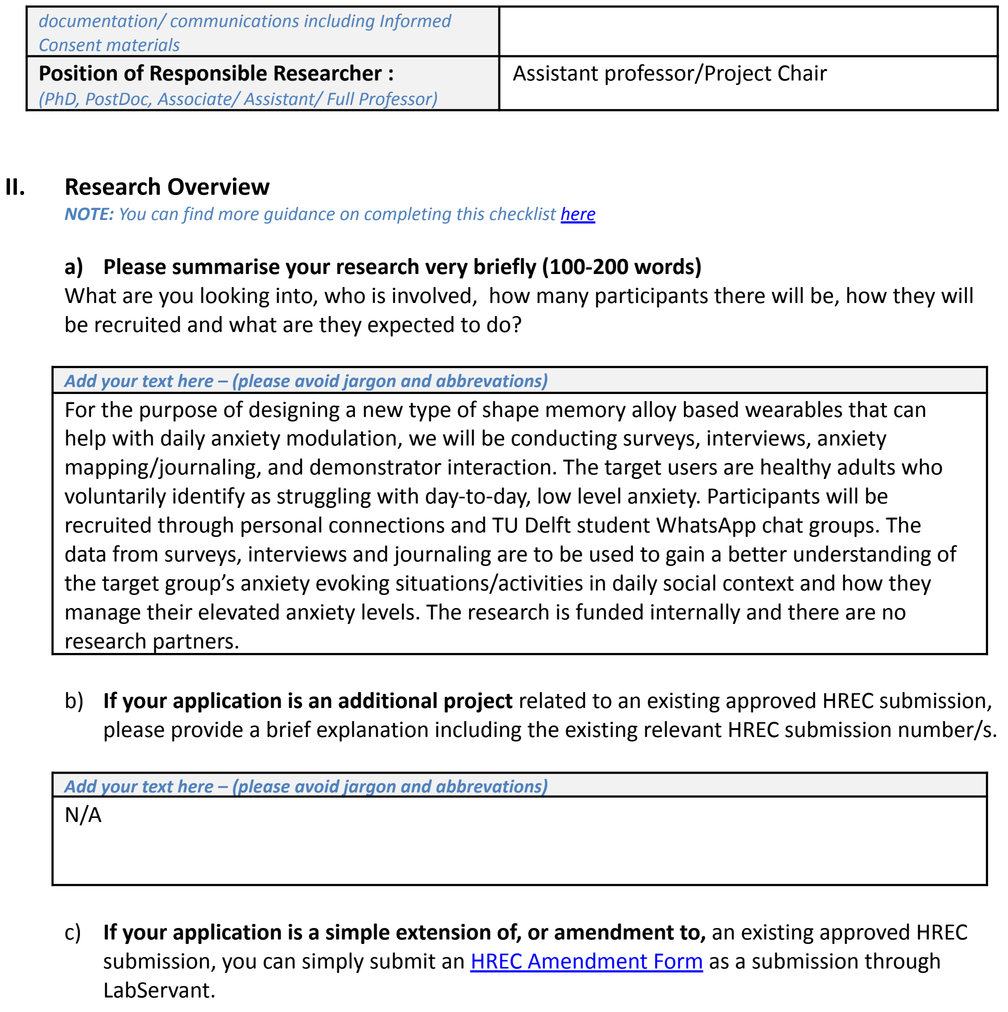
Delft University of Technology
HUMAN RESEARCH ETHICS
CHECKLIST FOR HUMAN RESEARCH
(Version January 2022)

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:	Designing Shape Memory Based Wearables for Anxiety Modulation
Research period: *Over what period of time will this specific part of the research take place*	September 2022 - January 2023
Faculty:	Industrial Design
Department:	Sustainable Design Engineering - 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)*	June Kim
E-mail Corresponding Researcher: *(If different from the Responsible Researcher)*	
Position of Corresponding Researcher: *(Masters, DreamTeam, PhD, PostDoc, Assistant/ Associate/ Full Professor)*	Masters student
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	
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 abbrevations)

For the purpose of designing a new type of shape memory alloy based wearables that can help with daily anxiety modulation, we will be conducting surveys, interviews, anxiety mapping/journaling, and demonstrator interaction. The target users are healthy adults who voluntarily identify as struggling with day-to-day, low level anxiety. Participants will be recruited through personal connections and TU Delft student WhatsApp chat groups. The data from surveys, interviews and journaling are to be used to gain a better understanding of the target group's anxiety evoking situations/activities in daily social context and how they manage their elevated anxiety levels. The research is funded internally and there are no research partners.

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				
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 biassed due to personal ties with researcher** **2. Test results could be biassed due to recruitment being done in similar demographic (mainly TUD students in 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		X				

			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**
community leader or family member who has this customary role – within or outside the EU; the data producer of a long-term cohort study)						
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				
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?		X				

			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**
If yes please confirm that your fieldwork has been discussed with the appropriate safety/security advisors and approved by your Department/Faculty.						
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.**		

			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**
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		**Name and contact information of participants will be collected for administrative purposes only via online questionnaire and informed consent form**	**1. Use a questionnaire platform that allows anonymity. ONLY collect contact information through the questionnaire if the respondent is interested in further participating in the research study** **2. Personal information only to be kept in project storage drive accessible by June Kim, and the information will be deleted once the project is done** **3. Assign a unique 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 video and/or audio recorded for observation and transcription purposes. Information regarding daily anxiety and emotions will be collected through participant self-reported journaling.	1. Participants will be informed that the gathered data will be anonymised. Data will be deleted if consent is withdrawn later 2. Only anonymized photos or video clips (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, raw data of video recordings and photos of participants would be stored in the project drive only accessible by June Kim. . 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, video, 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				

			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**
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 June Kim'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)
June Kim
Signature of Corresponding Researcher:
Date: 10/10/2022

Name of Responsible Researcher (print)
Signature (or upload consent by mail) Responsible Researcher:
Date: 11.10.2022 Sepideh Ghodrat

V. Completing your HREC application

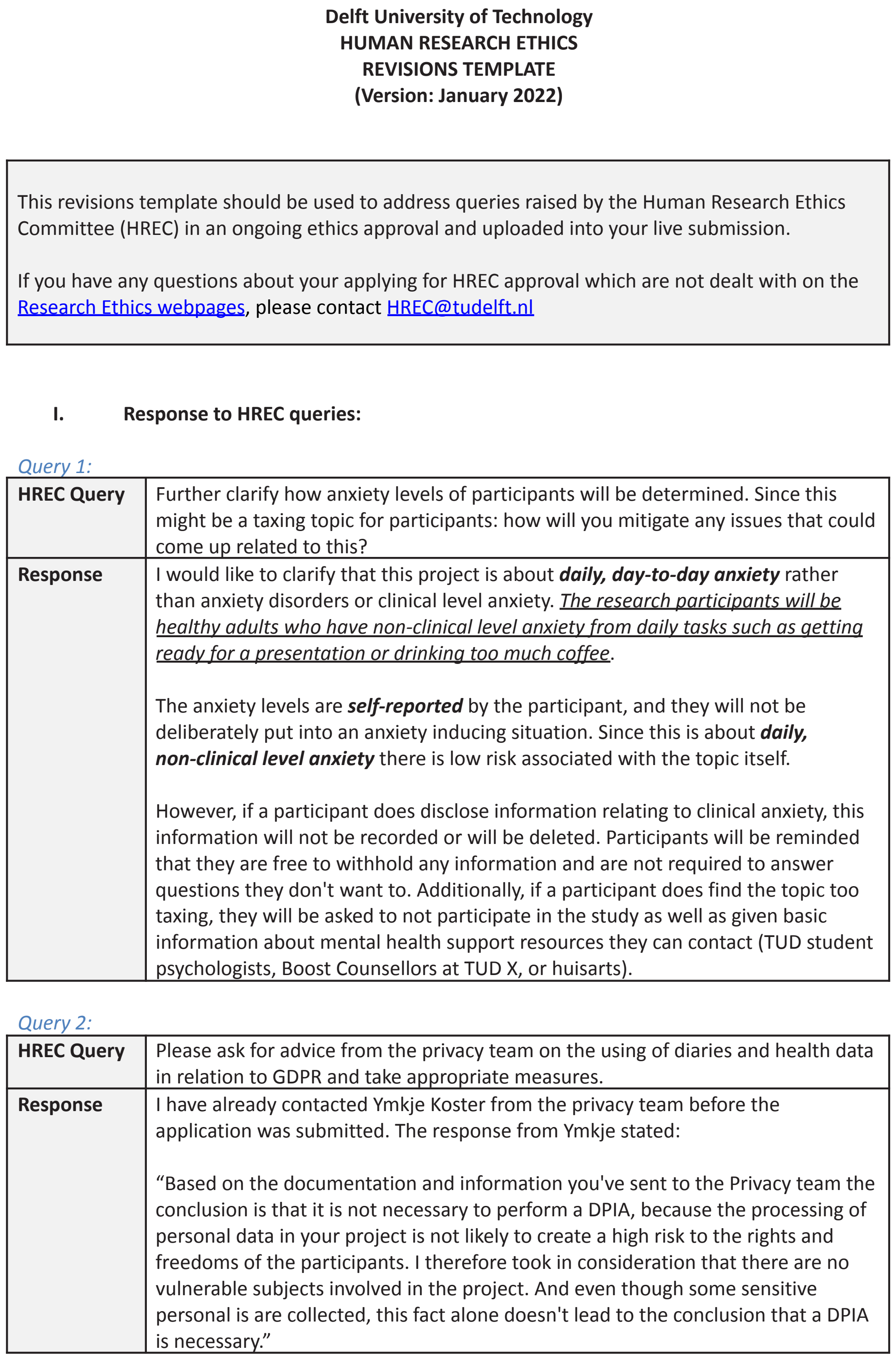
Please use the following list to check that you have provided all relevant documentation

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



Delft University of Technology
HUMAN RESEARCH ETHICS
REVISIONS TEMPLATE
(Version: January 2022)

This revisions template should be used to address queries raised by the Human Research Ethics Committee (HREC) in an ongoing ethics approval and uploaded into your live submission.

If you have any questions about your applying for HREC approval which are not dealt with on the Research Ethics webpages, please contact HREC@tudelft.nl

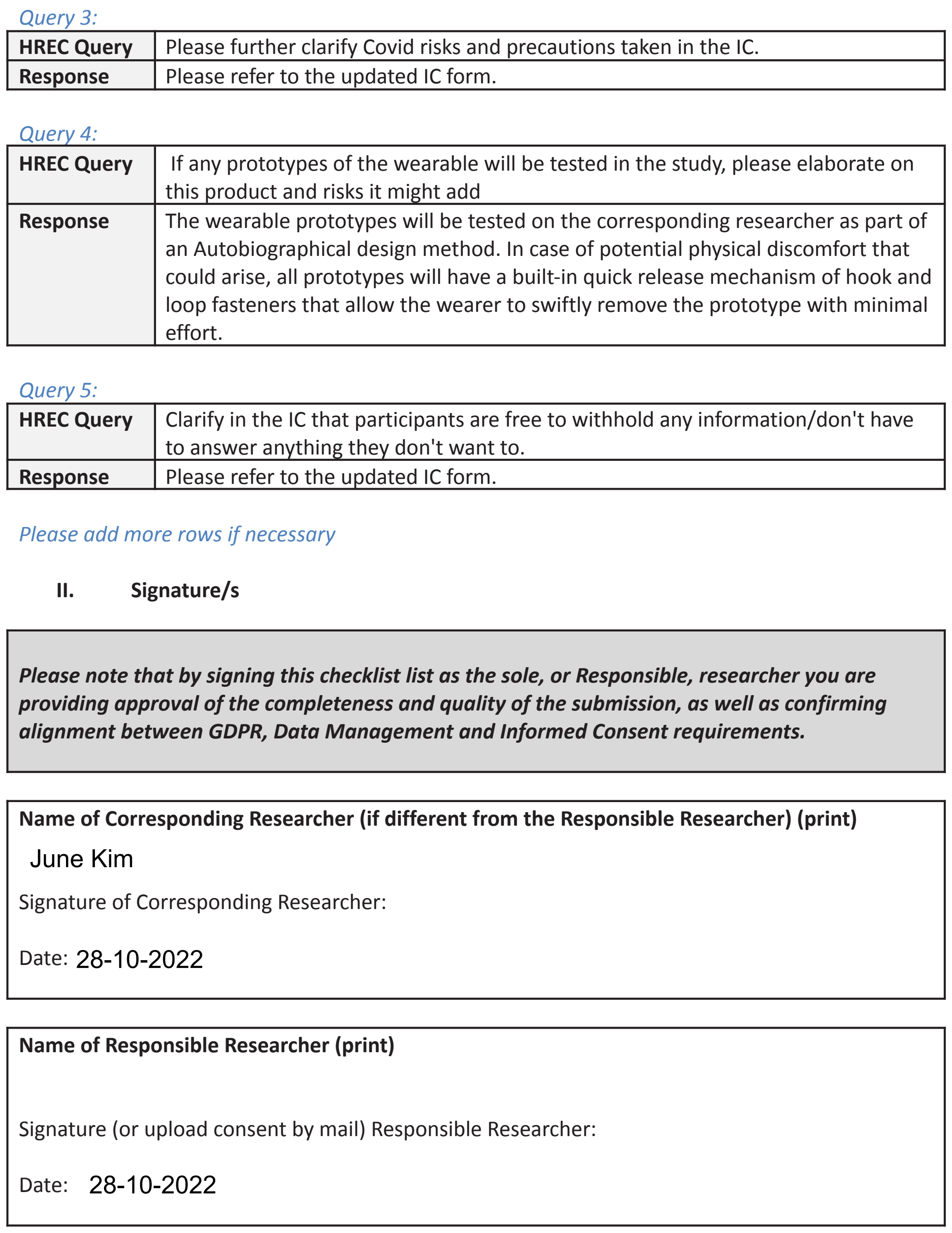
I. Response to HREC queries:

Query 1:

HREC Query	Further clarify how anxiety levels of participants will be determined. Since this might be a taxing topic for participants: how will you mitigate any issues that could come up related to this?
Response	I would like to clarify that this project is about ***daily, day-to-day anxiety*** rather than anxiety disorders or clinical level anxiety. *The research participants will be healthy adults who have non-clinical level anxiety from daily tasks such as getting ready for a presentation or drinking too much coffee*. The anxiety levels are ***self-reported*** by the participant, and they will not be deliberately put into an anxiety inducing situation. Since this is about ***daily, non-clinical level anxiety*** there is low risk associated with the topic itself. However, if a participant does disclose information relating to clinical anxiety, this information will not be recorded or will be deleted. Participants will be reminded that they are free to withhold any information and are not required to answer questions they don't want to. Additionally, if a participant does find the topic too taxing, they will be asked to not participate in the study as well as given basic information about mental health support resources they can contact (TUD student psychologists, Boost Counsellors at TUD X, or huisarts).

Query 2:

HREC Query	Please ask for advice from the privacy team on the using of diaries and health data in relation to GDPR and take appropriate measures.
Response	I have already contacted Ymkje Koster from the privacy team before the application was submitted. The response from Ymkje stated: "Based on the documentation and information you've sent to the Privacy team the conclusion is that it is not necessary to perform a DPIA, because the processing of personal data in your project is not likely to create a high risk to the rights and freedoms of the participants. I therefore took in consideration that there are no vulnerable subjects involved in the project. And even though some sensitive personal is are collected, this fact alone doesn't lead to the conclusion that a DPIA is necessary."



Query 3:

HREC Query	Please further clarify Covid risks and precautions taken in the IC.
Response	Please refer to the updated IC form.

Query 4:

HREC Query	If any prototypes of the wearable will be tested in the study, please elaborate on this product and risks it might add
Response	The wearable prototypes will be tested on the corresponding researcher as part of an Autobiographical design method. In case of potential physical discomfort that could arise, all prototypes will have a built-in quick release mechanism of hook and loop fasteners that allow the wearer to swiftly remove the prototype with minimal effort.

Query 5:

HREC Query	Clarify in the IC that participants are free to withhold any information/don't have to answer anything they don't want to.
Response	Please refer to the updated IC form.

Please add more rows if necessary

II. 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)
June Kim
Signature of Corresponding Researcher:

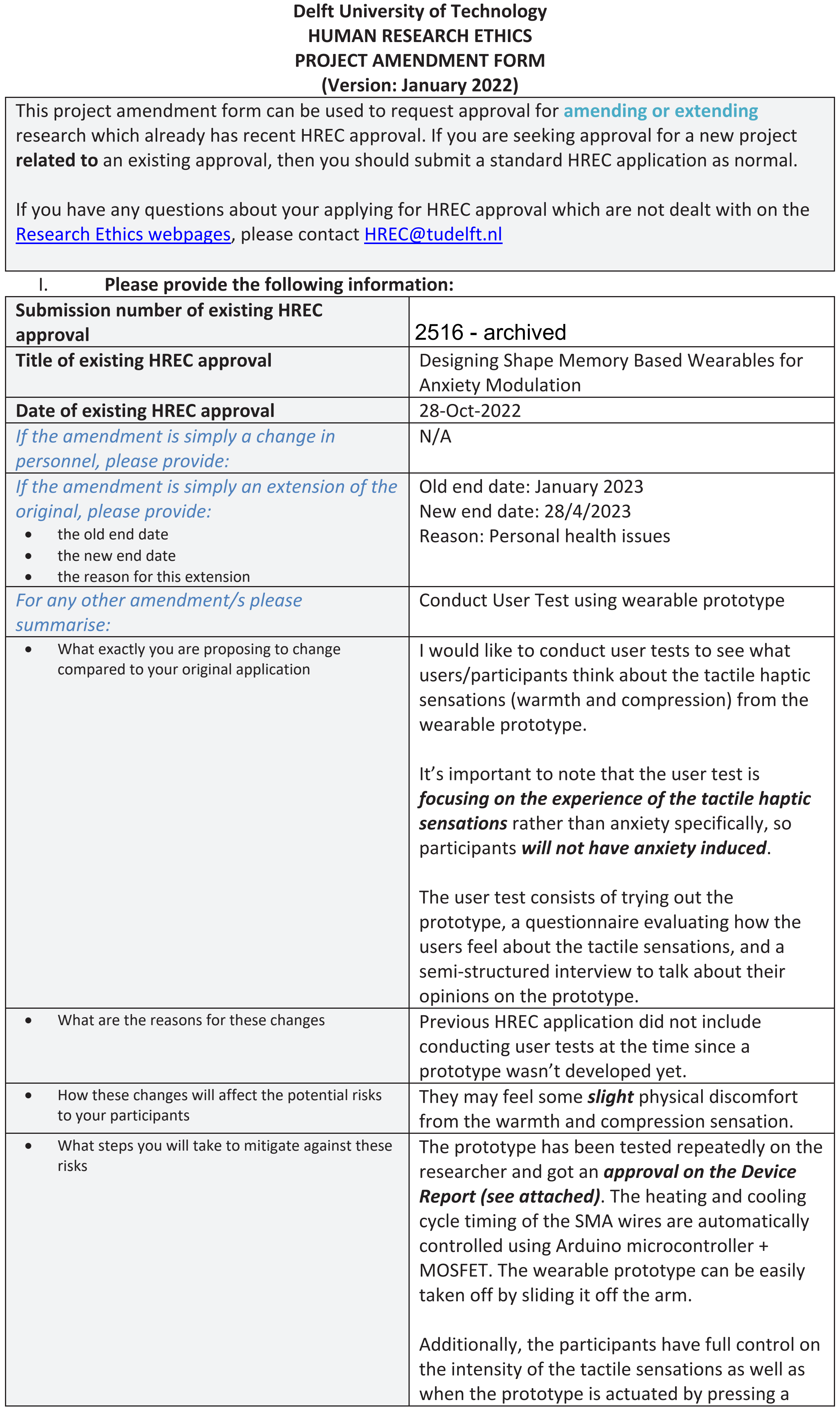
Date: 28-10-2022

Name of Responsible Researcher (print)

Signature (or upload consent by mail) Responsible Researcher:

Date: 28-10-2022

Appendix M: HREC Application - User Test



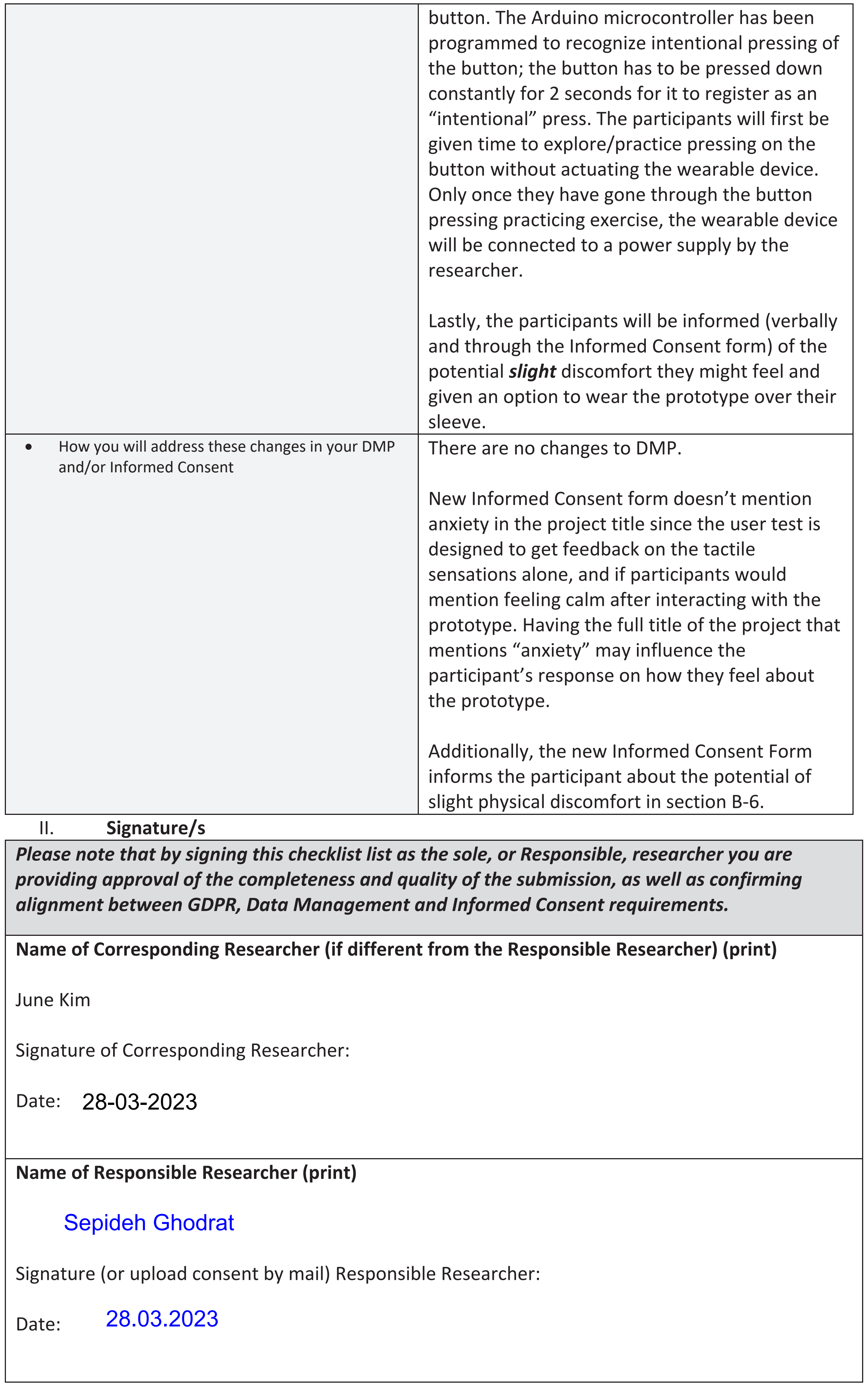
Delft University of Technology
HUMAN RESEARCH ETHICS
PROJECT AMENDMENT FORM
(Version: January 2022)

This project amendment form can be used to request approval for amending or extending research which already has recent HREC approval. If you are seeking approval for a new project **related to** an existing approval, then you should submit a standard HREC application as normal.

If you have any questions about your applying for HREC approval which are not dealt with on the Research Ethics webpages, please contact HREC@tudelft.nl

I. **Please provide the following information:**

Submission number of existing HREC approval	2516 - archived
Title of existing HREC approval	Designing Shape Memory Based Wearables for Anxiety Modulation
Date of existing HREC approval	28-Oct-2022
If the amendment is simply a change in personnel, please provide:	N/A
If the amendment is simply an extension of the original, please provide: • the old end date • the new end date • the reason for this extension	Old end date: January 2023 New end date: 28/4/2023 Reason: Personal health issues
For any other amendment/s please summarise:	Conduct User Test using wearable prototype
• What exactly you are proposing to change compared to your original application	I would like to conduct user tests to see what users/participants think about the tactile haptic sensations (warmth and compression) from the wearable prototype. It's important to note that the user test is ***focusing on the experience of the tactile haptic sensations*** rather than anxiety specifically, so participants ***will not have anxiety induced***. The user test consists of trying out the prototype, a questionnaire evaluating how the users feel about the tactile sensations, and a semi-structured interview to talk about their opinions on the prototype.
• What are the reasons for these changes	Previous HREC application did not include conducting user tests at the time since a prototype wasn't developed yet.
• How these changes will affect the potential risks to your participants	They may feel some ***slight*** physical discomfort from the warmth and compression sensation.
• What steps you will take to mitigate against these risks	The prototype has been tested repeatedly on the researcher and got an ***approval on the Device Report (see attached)***. The heating and cooling cycle timing of the SMA wires are automatically controlled using Arduino microcontroller + MOSFET. The wearable prototype can be easily taken off by sliding it off the arm. Additionally, the participants have full control on the intensity of the tactile sensations as well as when the prototype is actuated by pressing a button. The Arduino microcontroller has been programmed to recognize intentional pressing of the button; the button has to be pressed down constantly for 2 seconds for it to register as an "intentional" press. The participants will first be given time to explore/practice pressing on the button without actuating the wearable device. Only once they have gone through the button pressing practicing exercise, the wearable device will be connected to a power supply by the researcher. Lastly, the participants will be informed (verbally and through the Informed Consent form) of the potential ***slight*** discomfort they might feel and given an option to wear the prototype over their sleeve.
• How you will address these changes in your DMP and/or Informed Consent	There are no changes to DMP. New Informed Consent form doesn't mention anxiety in the project title since the user test is designed to get feedback on the tactile sensations alone, and if participants would mention feeling calm after interacting with the prototype. Having the full title of the project that mentions "anxiety" may influence the participant's response on how they feel about the prototype. Additionally, the new Informed Consent Form informs the participant about the potential of slight physical discomfort in section B-6.



II. **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)

June Kim

Signature of Corresponding Researcher:

Date: 28-03-2023

Name of Responsible Researcher (print)

Sepideh Ghodrat

Signature (or upload consent by mail) Responsible Researcher:

Date: 28.03.2023

Appendix N: Device Report

Delft University of Technology
INSPECTION REPORT FOR DEVICES TO BE USED IN CONNECTION WITH HUMAN SUBJECT RESEARCH

This report should be completed for every experimental device that is to be used in interaction with humans and that is not CE certified or used in a setting where the CE certification no longer applies[1].

The first part of the report has to be completed by the researcher and/or a responsible technician.

Then, the safety officer (Heath, Security and Environment advisor) of the faculty responsible for the device has to inspect the device and fill in the second part of this form. An actual list of safety-officers is provided on this webpage.

Note that in addition to this, all experiments that involve human subjects have to be approved by the Human Research Ethics Committee of TU Delft. Information on ethics topics, including the application process, is provided on the HREC website.

Device identification (name, location): Shape Memory Alloy wire actuated compression sleeve

Configurations inspected[2]: NA

Type of experiment to be carried out on the device:[3] User controlled compression and warmth to the forearm while seated at a desk. Testing the haptic feedback effect on providing calming sensation

Name(s) of applicants(s): June Kim

Job title(s) of applicants(s): Master Student

(Please note that the inspection report should be filled in by a TU Delft employee. In case of a BSc/MSc thesis project, the responsible supervisor has to fill in and sign the inspection report.)

Name of Supervisor: Prof. Dr. Ghodrat, S.

Date: 23.03.2023

Signature(s): Sepideh Ghodrat - IO

Digitally signed by Sepideh Ghodrat - IO
Date: 2023.03.23 16:09:08 +01'00'

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[1] Modified, altered, used for a purpose not reasonably foreseen in the CE certification

[2] If the devices can be used in multiple configurations, otherwise insert NA

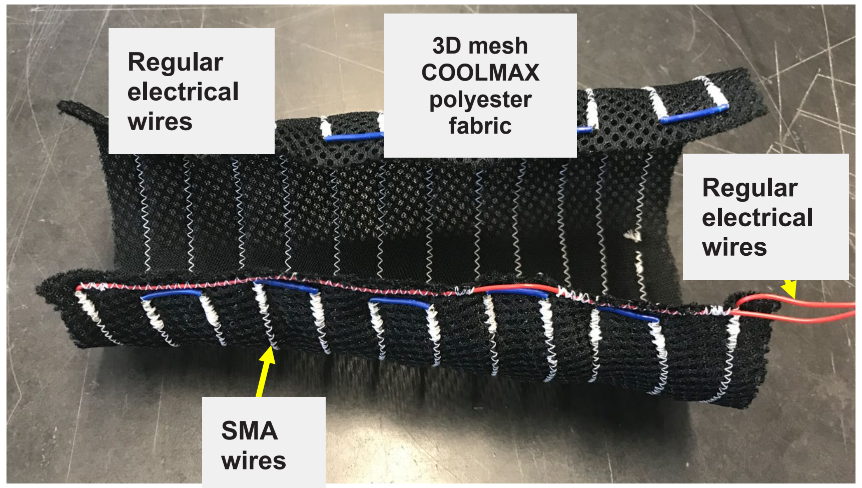
[3] e.g. driving, flying, VR navigation, physical exercise, ...

Setup summary

Please provide a brief description of the experimental device (functions and components) and the setup in which context it supposed to be used. Please document with pictures where necessary.

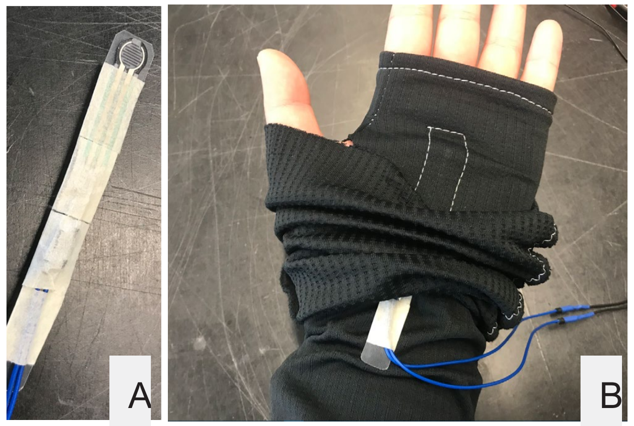
More elaborate descriptions should be added as an appendix (see below).

The Shape Memory Alloy (SMA) based wearable sleeve device provides compression and warmth to the user's forearm using a SMA actuator (Picture 1). The 1mm diameter NiTi SMA wire used for the actuator has an activation temperature of 45-50 degree C and sewn on top of a single layer of COOLMAX 3D mesh polyester fabric. The SMA wires are connected via regular solid core electrical wires.



Picture 1: SMA actuator embedded in COOLMAX 3D mesh polyester fabric (https://www.extremtextil.de/en/3d-mesh-3mm-coolmax-elastic-330g-sqm-black.html)

The sleeve has 3 different compression settings that are user controlled by pressing on a force-sensing resistor (Picture 2a) that goes into a pocket positioned on the user's palm (Picture 2b) in a fabric sleeve cover.

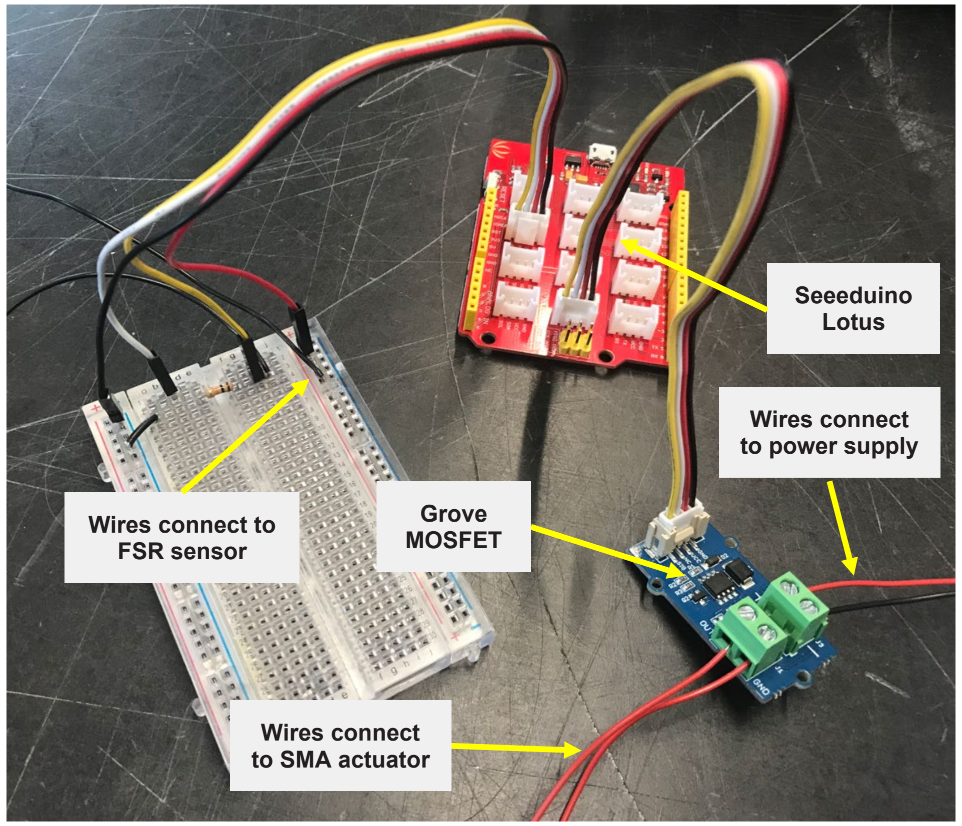


Picture 2: (A) Force-sensing resistor (FSR) taped to a flexible plastic strip, (B) FSR pocket

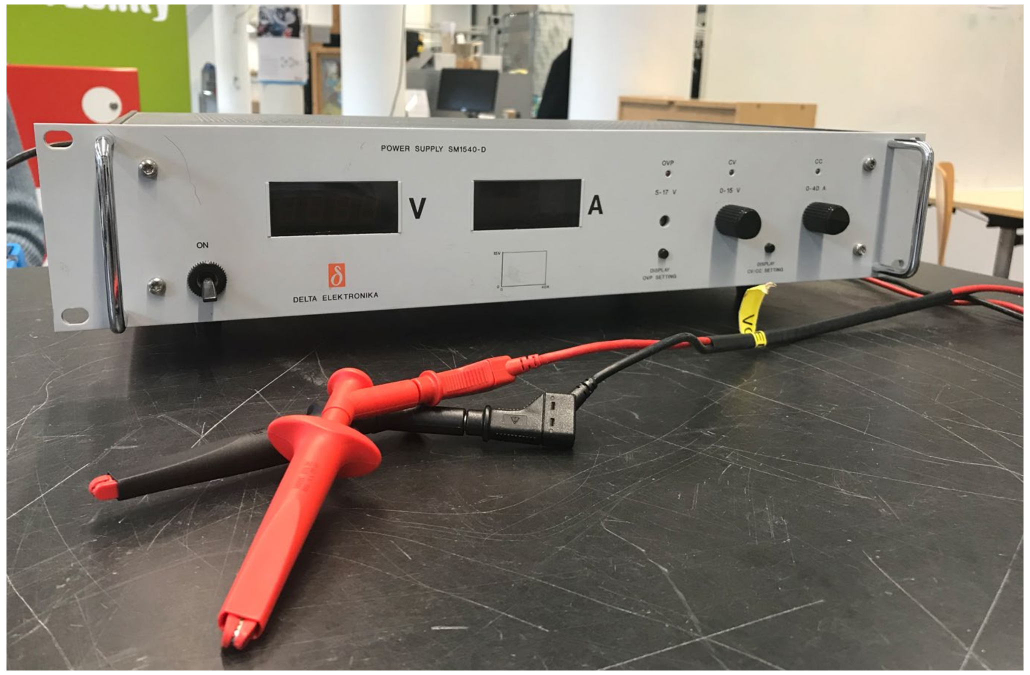
The fabric sleeve cover is made of elastic 2-ply eyelet lining fabric, and it consists of an inner sleeve and an outer sleeve. The SMA actuator is affixed to the inner sleeve with hook-and-loop/velcro fasteners (Picture 3A) and the outer sleeve can slide over the SMA actuator (Picture 3B) to completely cover the SMA actuator (Picture 3C). The sleeve assembly would be put on the participant by the researcher so that the participant would only come in direct contact with the elastic 2-ply eyelet lining fabric.

Picture 3: (A) Inner assembly of sleeve, (B) outer sleeve slide over SMA actuator, (C) Fully assembled wearable sleeve device

The microcontroller assembly (Picture 4) consists of a Seeeduino Lotus board, Grove MOSFET, and a breadboard. The SMA actuator connects to Grove MOSFET with an electrical power supply set to 11.1V (Picture 5). The FSR sensor connects to a Seeeduino Lotus board through a breadboard. In the coming weeks before the user tests, the microcontroller assembly, which will be inaccessible to the research participants, will be affixed to a plastic board to prevent wires from getting tangled or coming loose.



Picture 4: Microcontroller assembly for the wearable sleeve prototype



Picture 5: Electrical power supply set to 11.1V

Risk checklist

Please fill in the following checklist and consider these hazards that are typically present in many research setups. If a hazard is present, please describe how it is dealt with.

Also, mention any other hazards that are present.

Hazard type	Present	Hazard source	Mitigation measures
Mechanical (sharp edges, moving equipment, etc.)	No		
Electrical	Yes	The wearable sleeve device is still in a "prototype" stage, so there are electrical wires that connect from the device to the microcontroller assembly and power supply.	Flexible wires longer than 1 meter will be used to connect the sleeve device to the microcontroller assembly so that the research participants can move their arms freely without potentially disconnecting the wires. Also the SMA wires are sewn down and covered in several layers of fabric for electrical and heat insulation, so the participants will not come in direct contact with the SMA wires.
Structural failure	No		
Touch Temperature	Yes	The SMA wires are heated with electricity (Joule Heating) to their activation temperature of 45-50C.	Refer to the appendix section for detailed explanation.
Electromagnetic radiation	No		
Ionizing radiation	No		
(Near-)optical radiation (lasers, IR-, UV-, bright visible light sources)	No		
Noise exposure	No		
Materials (flammability, offgassing, etc.)	No		
Chemical processes	No		
Fall risk	No		
Other:			

Appendices

As mentioned previously, the SMA wires will not come in direct contact with the participants when they are wearing the sleeve device since the multiple layers of fabric provide electrical and heat insulation. Especially due to its geometric properties, the 3D mesh fabric allows air circulation for the SMA wires to cool down faster than any other types of fabric. The device has been tested on the researcher's arms numerous times without any heat induced discomfort.

Additionally, the SMA temperature is controlled by limiting the amount of current and the duration with a combination of microcontroller and MOSFET. The SMA wires are heated with electricity (Joule Heating) to their activation temperature of 45-50C. The microcontroller has been programmed to have three different predetermined settings:

1. Low compression: 0.6 of max current for 5 seconds
2. Medium compression: 0.8 of max current for 8 seconds
3. High compression: max current for 10 seconds

The research participants can choose one of the three predetermined settings by pressing on a force–sensing resistor (FSR); depending on how hard they press on the FSR, one of the three compression settings will activate. At the start of the user test, the researcher will explain the different compression settings to the participants and have them try pressing the FSR at different force levels without the power supply heating up the SMA wires.

For the high compression setting, the SMA wires would get a maximum of 4A at 11.1V for 10 seconds, which results in the SMA wires heating up to approximately 55C. However, it is important to note that the 55C temperature reading was measured by attaching a thermocouple wire directly to the surface of the SMA wire rather than over the fabric insulations.

When the thermocouple wire was placed between the researcher's skin and the innermost lining of the sleeve device, the maximum temperature reading ***did not exceed 38C*** even after multiple rapid heat cycles. According to Ong and Milne (2016), "[skin] burns will not occur if the temperature is below 44C'' and tissue injury will only occur at 44C after being exposed to the heat for several hours. Thus, the participants' skins will not be exposed to heat higher than 38C, and the participants will not be wearing the sleeve device for more than 20 minutes.

To add another layer of security, the microcontroller is programmed to prevent the participants from activating the SMA wires in rapid heating cycles. After the wires are heated for 5 - 10 seconds, the participants will not be able to heat the SMA wires again for 20 - 40 seconds depending on the 3 predetermined settings. This forced cooling duration prevents the rapid heating cycles and reduces heat build up. Since the sleeve device is still in a prototyping stage, the amount of current and heating duration may decrease, and cooling durations may increase to further reduce heat build up for the research participants.

Lastly, the sleeve device can be quickly removed by sliding it off like a glove if the research participant finds the heat build up uncomfortable. Also the participants will be given an option to wear the sleeve device over their own clothing sleeve for additional heat insulation.

Reference:

Ong, B., & Milne, N. (2016). Injury, Fatal and Nonfatal: Burns and Scalds. *Encyclopedia of Forensic and Legal Medicine*. https://doi.org/10.1016/b978-0-12-800034-2.00220-2

Device inspection

(to be filled in by the AMA advisor of the corresponding faculty)

Name: Peter Kohne

Faculty: Industrial Design Engineering

The device and its surroundings described above have been inspected. During this inspection I could not detect any extraordinary risks.

(Briefly describe what components have been inspected and to what extent (i.e. visually, mechanical testing, measurements for electrical safety etc.)

Date: 27-03-2023

Signature:

Inspection valid until[4]:

Note: changes to the device or set-up, or use of the device for an experiment type that it was not inspected for require a renewed inspection

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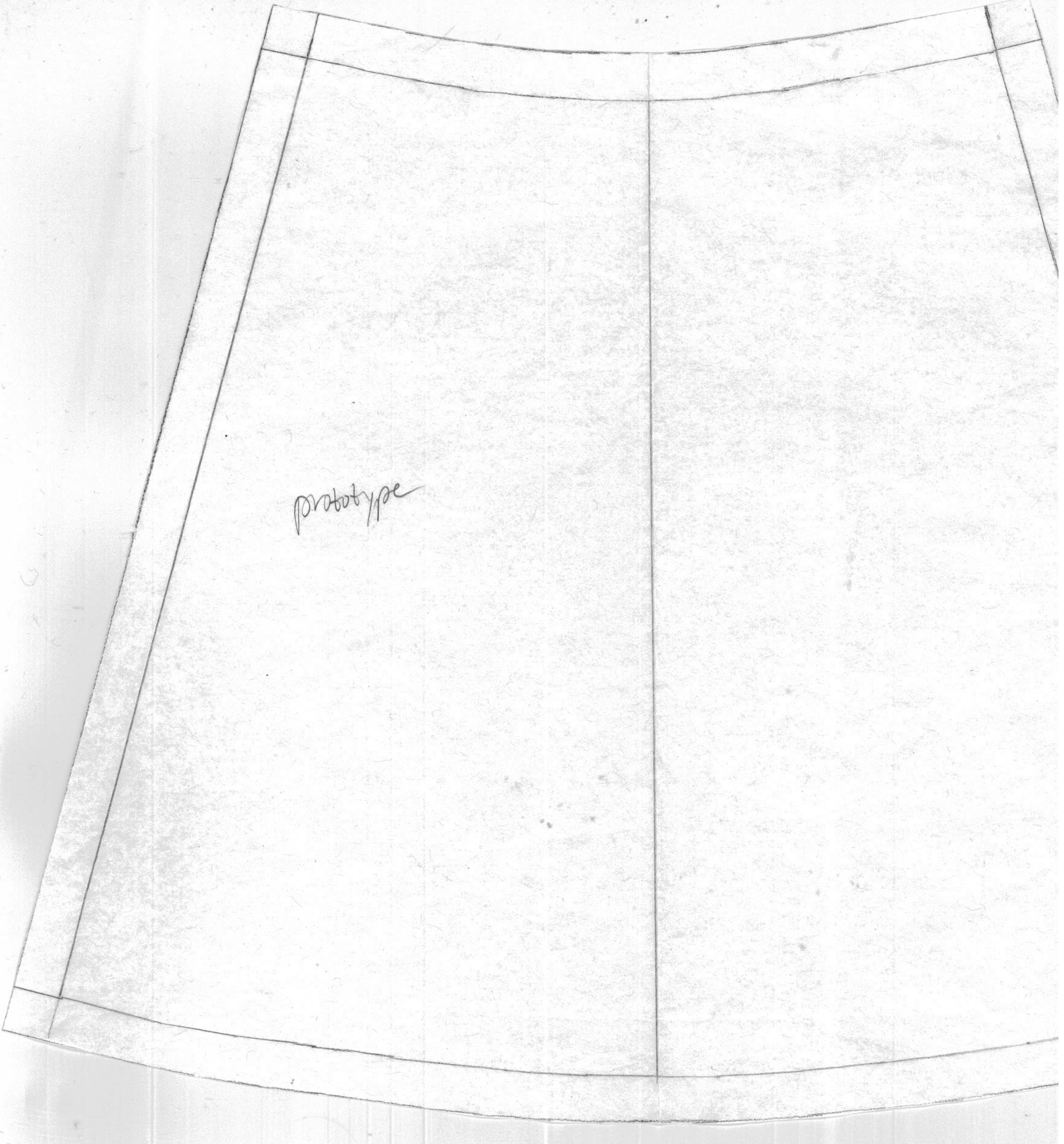
[4] Indicate validity of the inspection, with a maximum of 3 years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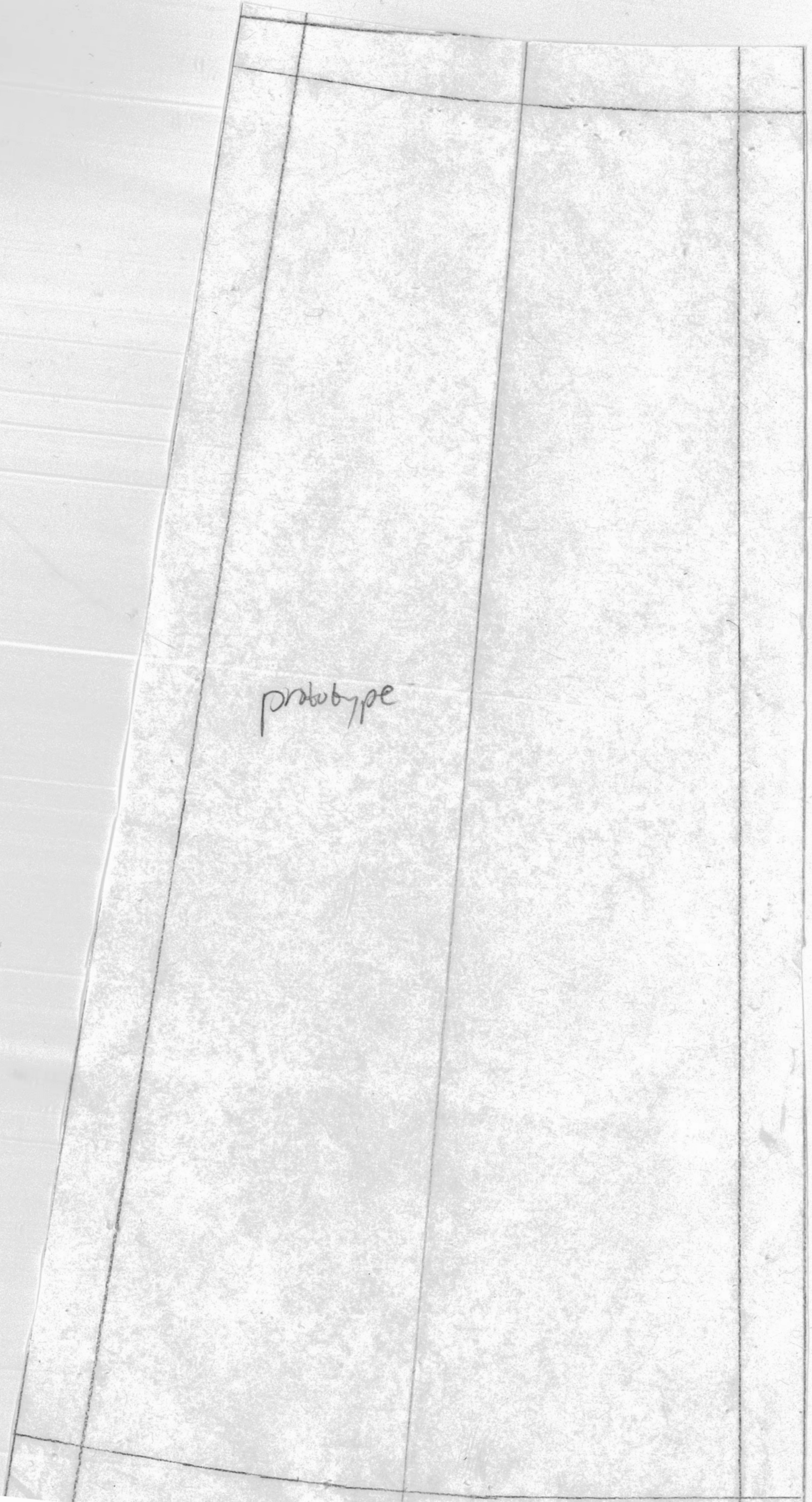
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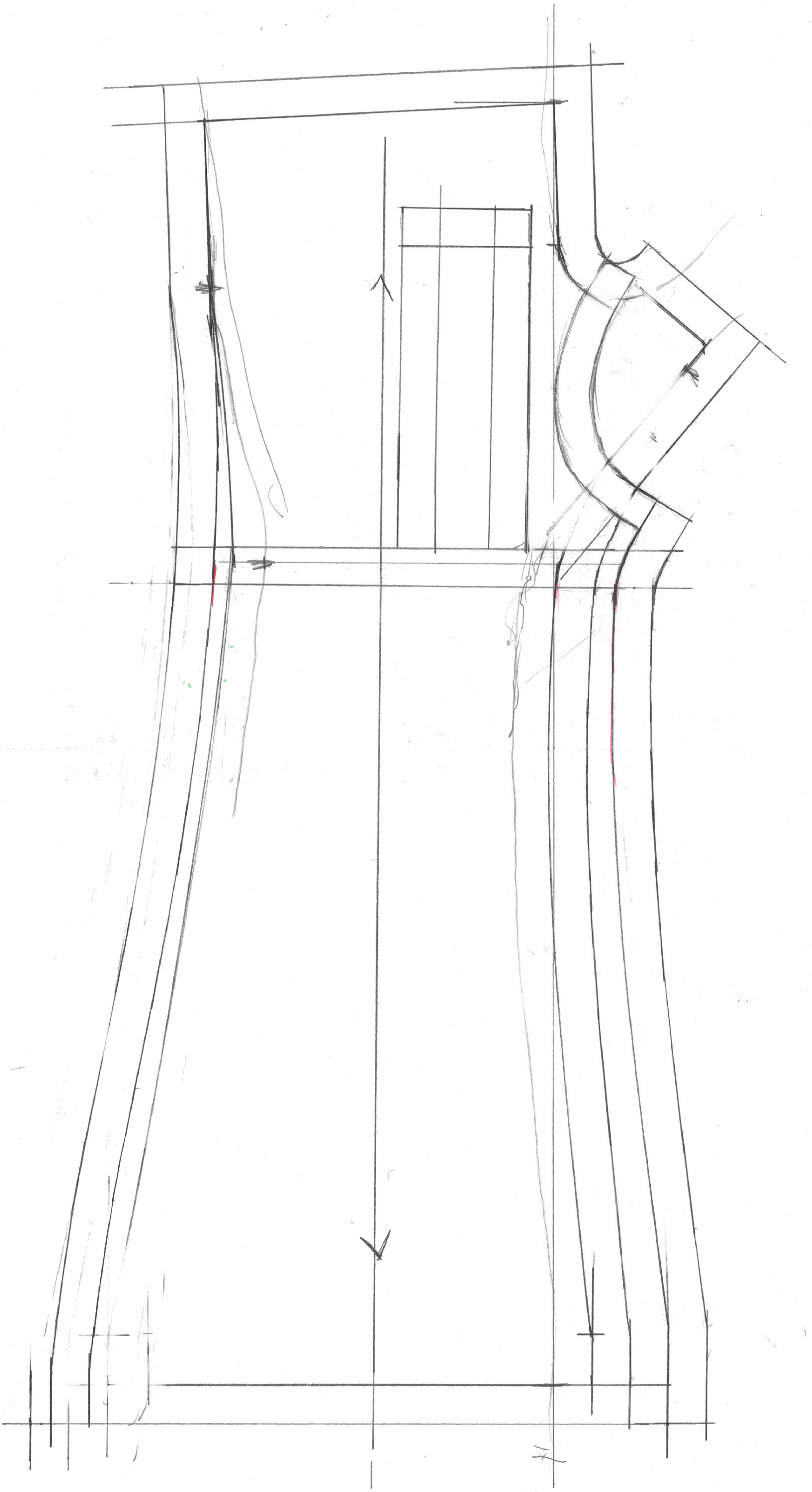

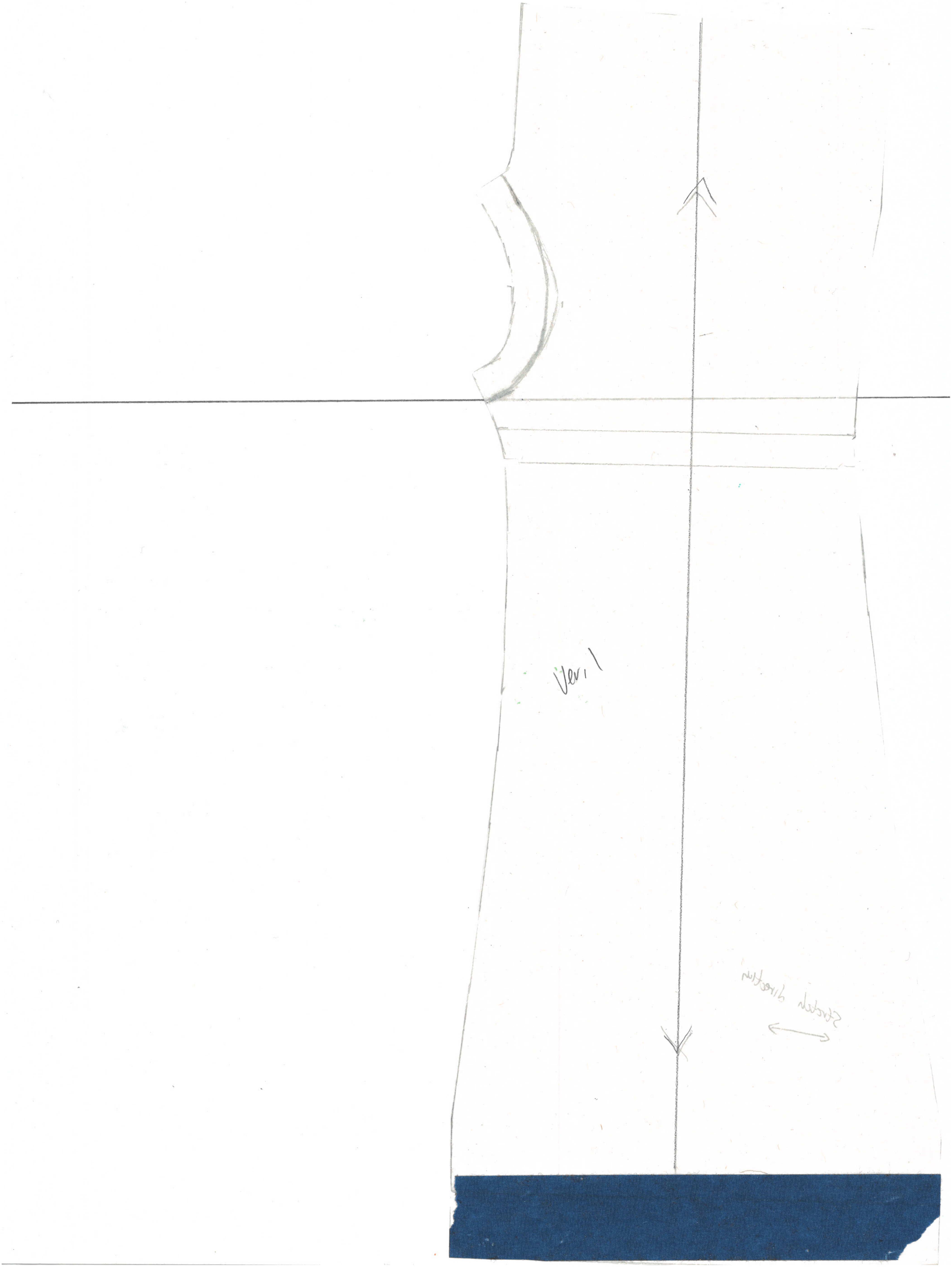
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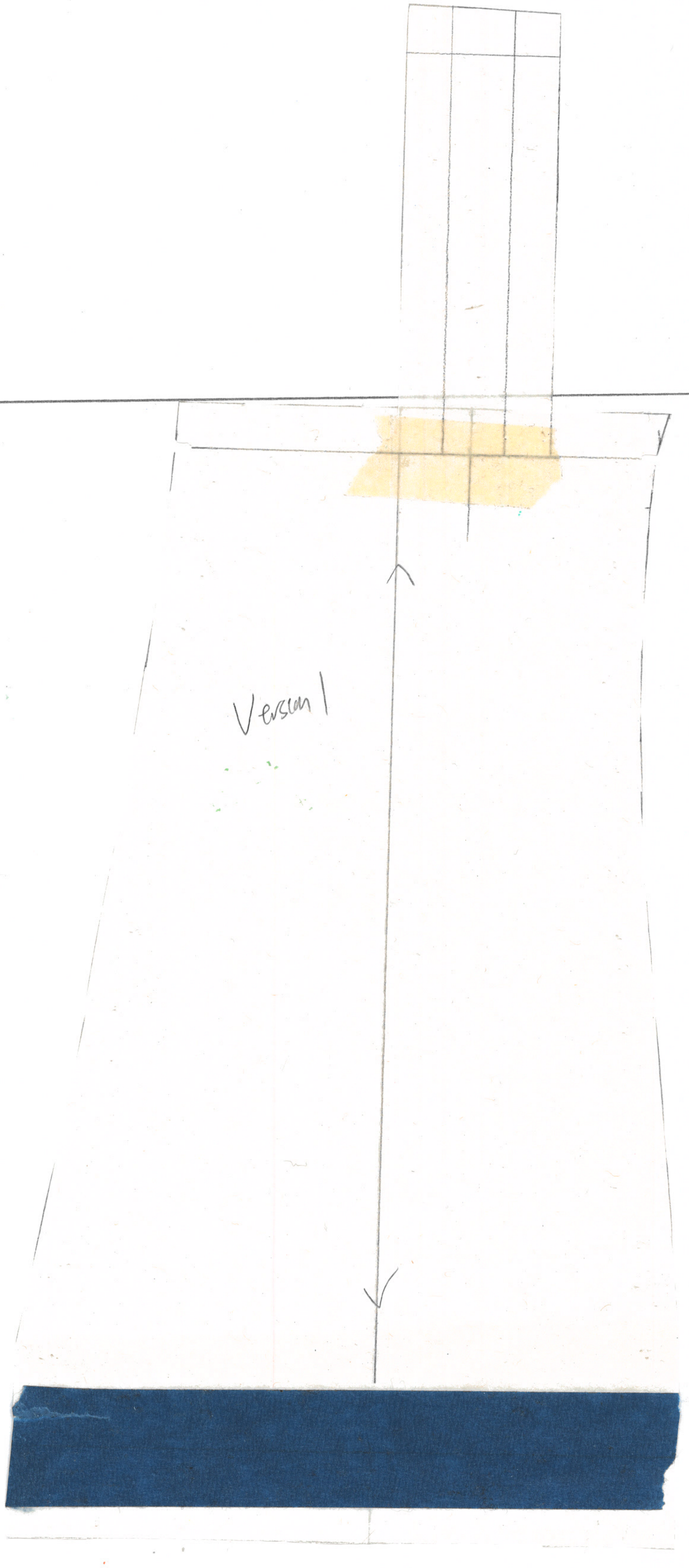
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