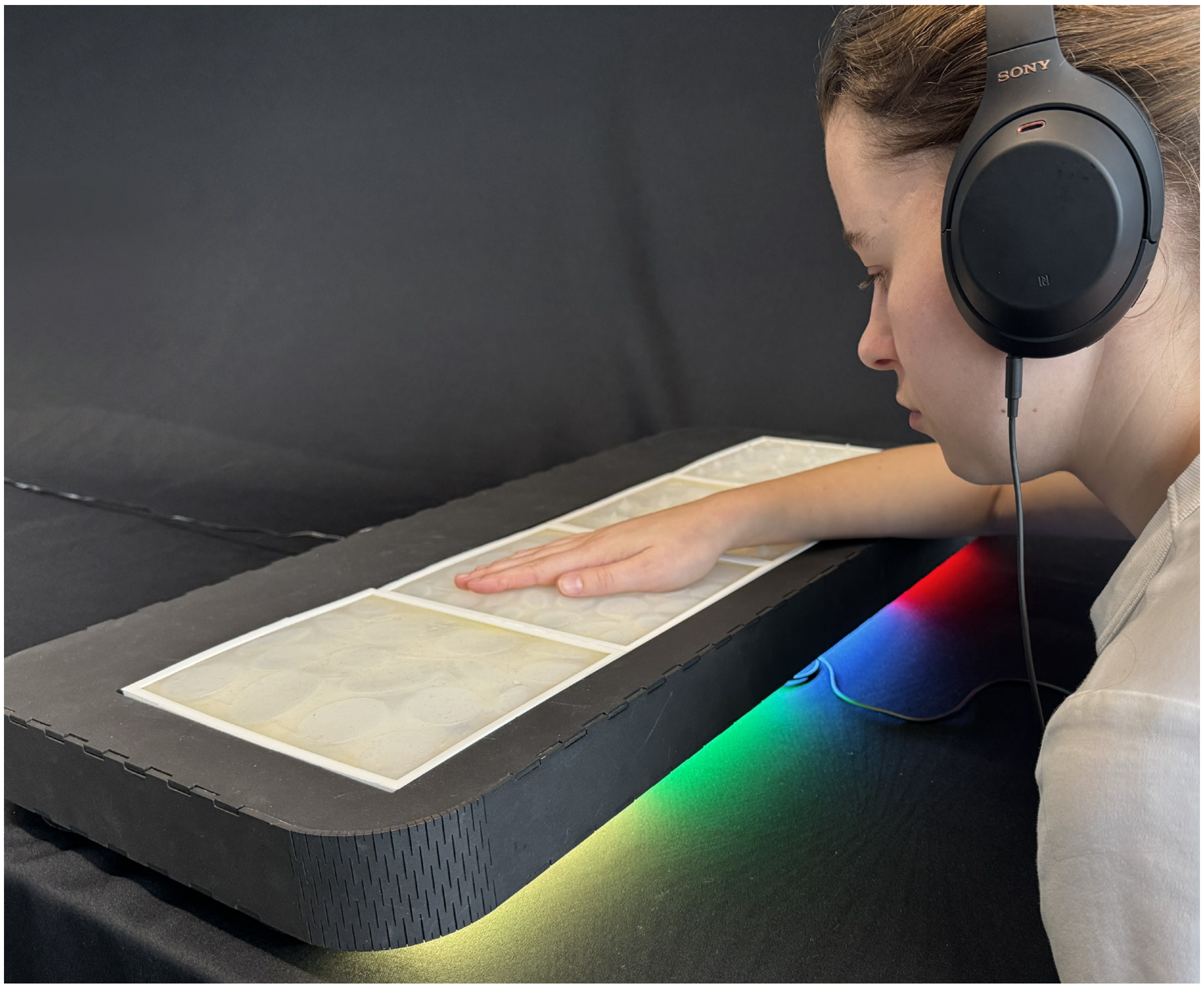
Tactone: A design tool for multimodal soft robotics

Joep van den Berg
Technical University of Eindhoven
Eindhoven, The Netherlands
j.c.v.d.berg2@student.tue.nl

Jesse Strijker
Technical University of Eindhoven
Eindhoven, The Netherlands
j.j.strijker@student.tue.nl

Zilu Tang
Technical University of Eindhoven
Eindhoven, The Netherlands
z.tang@student.tue.nl

Puck Verbeek
Technical University of Eindhoven
Eindhoven, The Netherlands
p.verbeek@student.tue.nl



ABSTRACT

Soft robotics design has traditionally prioritized functionality, often overlooking the critical role of aesthetics, particularly sound and haptics, in shaping user perception and experience. To address this gap, we developed Tactone, a modular, multisensorial design tool aimed at bridging the gap between sound and the tactile perception of shape-changing interfaces.

Designed for individuals with little to no experience in soft robotics, Tactone combines material-centered and multisensory approaches, enabling designers to experiment with haptic interactions, textures, and responsive audio feedback. User studies demonstrate its versatility, highlighting Tactone's (possible) implementation as an exploration tool for ideation and a refinement tool for fine-tuning interactions. These findings underscore the importance of a holistic, embodied approach to soft robotics design. Moving forward, improvements in modularity, response time, and interaction fluidity could further enhance.

Authors Keywords

soft robotics; shape changing interfaces; pneumatics; somaesthetic; design tool

CSS Concepts

- human robot interaction

Paste the appropriate copyright/license statement here. ACM now supports three different publication options:

- ACM copyright: ACM holds the copyright on the work. This is the historical approach.
- License: The author(s) retain copyright, but ACM receives an exclusive publication license.
- Open Access: The author(s) wish to pay for the work to be open access. The additional fee must be paid to ACM.

This text field is large enough to hold the appropriate release statement assuming it is single-spaced in Times New Roman 7-point font. Please do not change or modify the size of this text box.
Each submission will be assigned a DOI string to be included here.

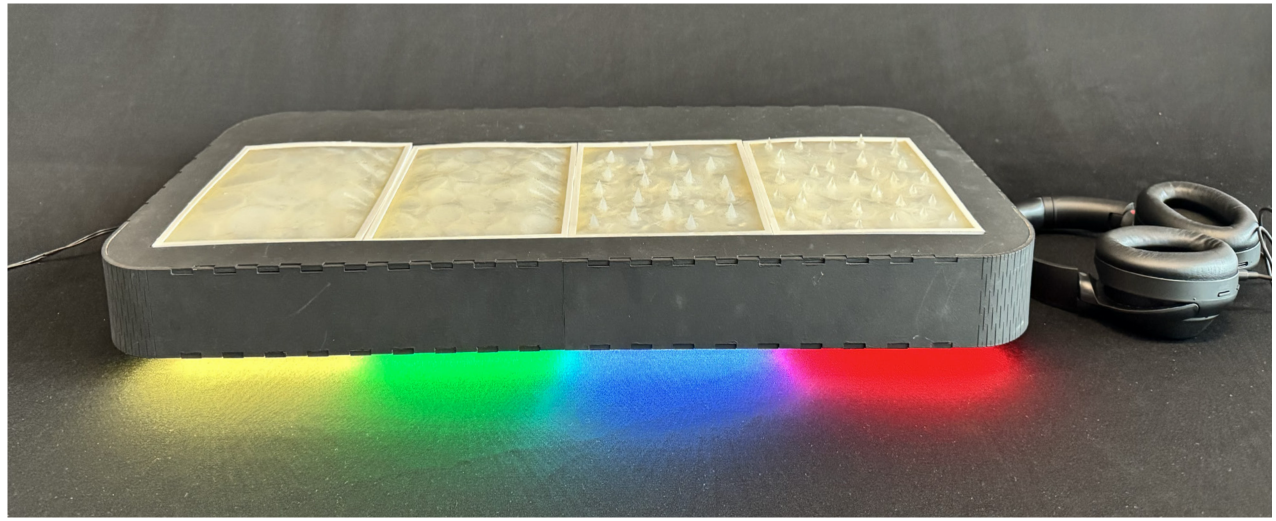
1. INTRODUCTION

The design of soft robots is mainly based on engineering practices, aimed at functionality. Udsen and Jørgensen [43] critique this by highlighting the growing importance of aesthetics in human-computer interaction (HCI). While HCI typically emphasizes usability over aesthetics, they advocate for an integrative approach that considers aesthetics as an essential component of user-centered design, to create more effective and meaningful interactions.

Jørgensen [23] explores this role of aesthetics within soft robotics. He critiques the focus on technical performance in soft robotics, arguing it limits potential for meaningful human-robot interactions (HRI). By integrating principles like somaesthetic [38; 41], robots can foster both functional effectiveness and emotional connections. Jørgensen [23] advocates balancing aesthetics with technical design to unlock new areas for innovation and creativity.

Somaesthetic emphasizes bodily perception and experience, addressing how users physically and emotionally engage with products or spaces [41]. This leads to more intuitive, user-friendly designs that consider the body as an active participant. Somaesthetic design goes beyond visual aesthetics as it also includes tactile, auditory, and kinesthetic experiences. This multi-sensory approach makes designs more immersive and inclusive. For instance, integrating texture, sound, or motion into a product's design can deepen a user's connection and improve functionality [38].

We offer designers a tool which assists in selecting haptics and sounds to achieve their desired perception of a soft robotic. Contributing to the perception of soft robotics, by combining multiple modalities such as sound, movement and touch to invoke emotions. It is relevant to note that there are nuances in emotions and how they are invoked. Therefore, the design aims to remain ambiguous, leaving room for human interpretation. Instead of clear commands and responses, the prototype emits movements, sounds or haptic experiences that require the designer to infer its "intent". Therefore, we hope to showcase how tiny alterations in sensory experiences influence the perception of soft robotics. Offering designers an instrument that helps in selecting haptics and sounds to achieve their desired perception of a soft robotic.



2. RELATED WORKS

The related works consists of two main elements. Starting with an orientation on how multiple senses, such as sound and haptics, influence human emotions [24]. Followed with an orientation on design projects related to somaesthetics and where other sensory experiences with soft robotics will be discussed.

2.1 Sound in Soft Robotics

Soft robotic sound production

Explorations into combining soft robotics and sound have been done in a very limited sense. Jørgensen [24] mentions that a lot of current soft robotics are actuated at the means of electronic actuators which provide sound by themselves. In the future dielectric elastomers soft robotics might become devoid of sound, but thus far no reason has been presented for functionally exploring sound in soft robotics. The aesthetic interplay between movement and sound for soft robotics is one example of this [24]. Jørgensen [24] compares two different sound characteristics of artificial origins, described as "hard" and "soft", however, no major difference was found in the interactions. This could show that regardless of the type of sound, people did not interact differently with the soft robotic.

Sound translation to emotion

Sound strongly influences a human's emotional state, especially the often used major and minor chords [31]. There is a clear connection between the major chords for happiness, the minor chords for sadness [31] and specifically the major seventh chords bring up a sense of nostalgia [28]. Non-linear sounds and dissonance elicit fear as sound dangerous and/or unnatural to the human ear [31]. Musicians and non-musicians show similar responses between the association of music and emotion [31; 28].

2.2 Haptics in Soft Robotics

There are multiple elements to touch that contribute to the user experience. The main identified elements are materials and activation, as they elicit a user reaction based on their properties.

Materials

Material properties, like roughness, can influence user experience by providing tactile feedback, which traditional touch interfaces often lack. Gohlke et al. [27] explored tactile feedback with pneumatic systems, enabling interfaces to respond based on user movement, position, etc. transcending flat surfaces. A variety of different interactions when interacting with materials, such as stroking, scratching, or pressing can reflect users' emotions [22].

Highlighting the potential for rich, multisensory feedback in material design and enhancement of emotional interactions.

Actuation

Actuation in soft robotics opens new opportunities for exploring non-verbal communication through organic and expressive movements [53]. By designing actuation patterns, robots can convey emotions and attract attention, offering means of embodied interaction exceeding language[3; 46] Meerbeek et al.'s [35] work evaluates expressions and behaviors to create meaningful user connections. Evaluating these movements involves considering both their visual and tactile elements, as Tractinsky et al. [42] emphasizes.

Combined with actuation, silicone allows robots to express nuanced emotions [6; 51]. However, one should consider the users comfort, particularly when balancing tactile engagement and emotional responses in human-robot interaction [10].

2.3 Visual aesthetics in Soft Robotics

Visual Appearance

Human actions can be triggered by visual perception, making a robot's appearance a crucial factor in shaping human-robot interactions (HRI) [45]. Kanda et al. [25] analyze the visual appearance of humanoid robots emphasizing that a robot's physics influences user perception, emotional responses, and engagement. Increased human likeness can lead to discomfort (uncanny valley), so the morphology of a robot should therefore match its intended function [45]. Caricatured representation can therefore be more effective than more realistic representations [12]. Overall, aesthetics profoundly impacts HRI, emphasizing the importance of aligning a robot's appearance with its intended function.

Color Perception

Beyond visual stimuli, color triggers physiological changes, influencing us emotionally, mentally, and physically [13][15][9]. People relate to color through personal association based on personal events; cultural or symbolic meaning, through symbolic significance over generations; and unconscious psychological meaning [15; 49]. Regardless of personal or cultural meaning, every color has a psychological impact shaping human responses instinctively [15]. Specific details can be found in Appendix A.

2.4 Emotion

Shapes

There is a visual connection between shapes and emotions. Objects with rounded edges are related to positive emotions, while sharp edges are perceived with negative emotions. Meanwhile, edges and surfaces are associated with low arousal when they are smooth and associated with high arousal when they are with visual variations. For example, happiness and calmness can be represented by large, smooth and round shapes, expressing positivity and low arousal. Sadness and anger, on the other hand, can be shown by smaller, sharp shapes representing negativity and high arousal [16]. Hoffman and Yu demonstrate that subtle shape-changing actuations, mapped to emotional valence (e.g., spikes for anger or goosebumps for excitement), can evoke emotions, guide focus, and enhance human-robot communication, particularly when using lifelike materials like silicone.

Movement

Physical dynamics can serve as a medium for nonverbal communication. The Laban Movement Analysis (LMA) describes how 'strong' and 'sudden' movements can convey anger, while 'light' and 'free' movements express happiness [37]. Vertical oscillations, evoke emotions like joy or sadness. Where quicker upward motions signal excitement, and slower downward motions suggest melancholy.

These modulations help humans interpret robotic actions as emotional expressions without complex human-like features, suggesting that basic movement patterns can evoke emotional responses [29]. Vibration patterns can enrich emotional expression by dynamically adjusting the rhythm and intensity [39; 28]. Similarly, tactile interactions like stroking or squeezing influence perception. For example, faster movements increase arousal evoking anger and excitement, while slower gentle touches evoke calmness [54]. Showing how nuanced movement and haptic cues can increase emotional connections.

Material

Tactile experience of materials invokes emotions. Studies have shown that participants often associate smooth, warm, and soft materials with positive emotions, while rough and cold textures provoke discomfort or negative responses [5].

2.5 Orientation design projects

Drawing inspiration from somaesthetics and haptic interaction projects, helped with the project direction. For example, the heated walking carpet of Dublin et al. [41] , where the temperature of the carpet changed based on foot pressure, and the somaesthetic meditation wearable by Ezer et al. [40] , that heated specific parts of the body draws attention inward, show how sensory stimuli, like temperature changes, can enhance bodily and emotional awareness. Similarly, projects like Azalea [38] and TactorBots [33] demonstrate how tactile feedback enhances interaction and evokes emotion. Leading to experiments with haptic and motion cues in this project.

Borg et al. [2] hybrid approach combines somaesthetic design and design thinking. Underlining the value of functional and sensory-rich designs. As they enable open-ended interpretations and embodied experiences rather than predefined emotional responses.

3. METHODOLOGY

Throughout the design process, both a material-centered and multisensorial approach were taken, to explore the aesthetics of shape-changing interfaces in soft robotics. A brief exploration of actuation and movement in soft robotics using accessible materials was conducted. These explorations created interest into shape-changing interfaces.

With the interest in mind it was decided to continue with a material-centered approach allowing examination of properties and behavior of soft flexible materials, like silicone and TPU [49]. Iterative prototyping enabled exploration of the durability and adaptability of soft materials essential for soft robotics. This approach allowed for a better understanding of how different materials could serve as adaptable interfaces [26].

Exploring materials first allowed for a better understanding of the material possibilities. It is important to move beyond visual-centric methodologies to include other sensory dimensions [18]. Classen [7] emphasizes that senses form a fundamental framework for understanding human experiences and social interactions. Therefore, the focus shifted from a material-centered approach to a multisensorial approach. The approach by Schifferstein [34] encourages designers to combine senses to form experiences. This approach defined expressions, explored sensory properties, and synthesized insights into data maps to retain data richness.

Ferrise [11] highlights how mixed reality enhances prototyping. This explored interaction with the robots through tactile, visual, and auditory feedback. This approach focused on analyzing how sensory elements influenced user engagement and perception and creating immersive experience. Sound was explored through material manipulation to enhance auditory feedback [49]. Haptics examined tactile engagement through texture and resistance [17]. Finally, visual transformations such as changes in form or color examined the user interaction and perception [1].

These approaches combined material properties with multisensorial experiences. Iterative evaluations of sound, haptics, and visuals created a holistic design process for soft robotics aesthetics.

4. EXPLORATION OF CONTEXT

a. exploring actuation with flexible materials

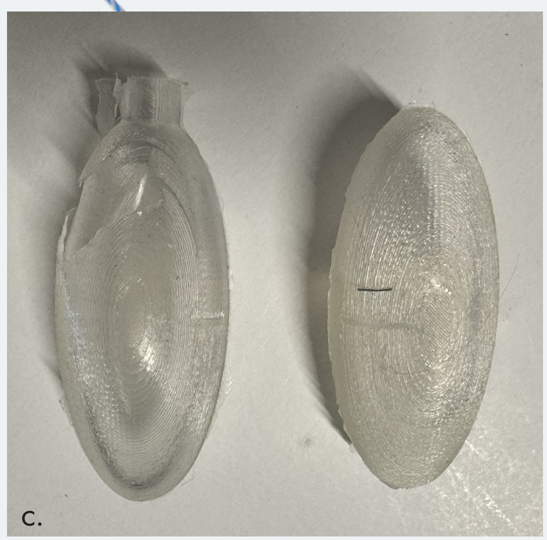
b. rubber exploration showed limited bendability

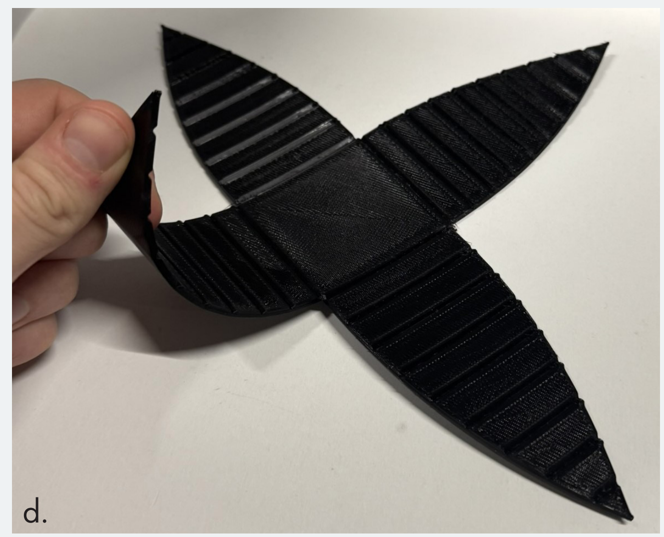
c. solid and hollow shapes were created from silicone to build confidence in using silicone and explore pneumatic applications

d. TPU and Nylon were explored, however they are less flexible and stiffer than silicone


a.

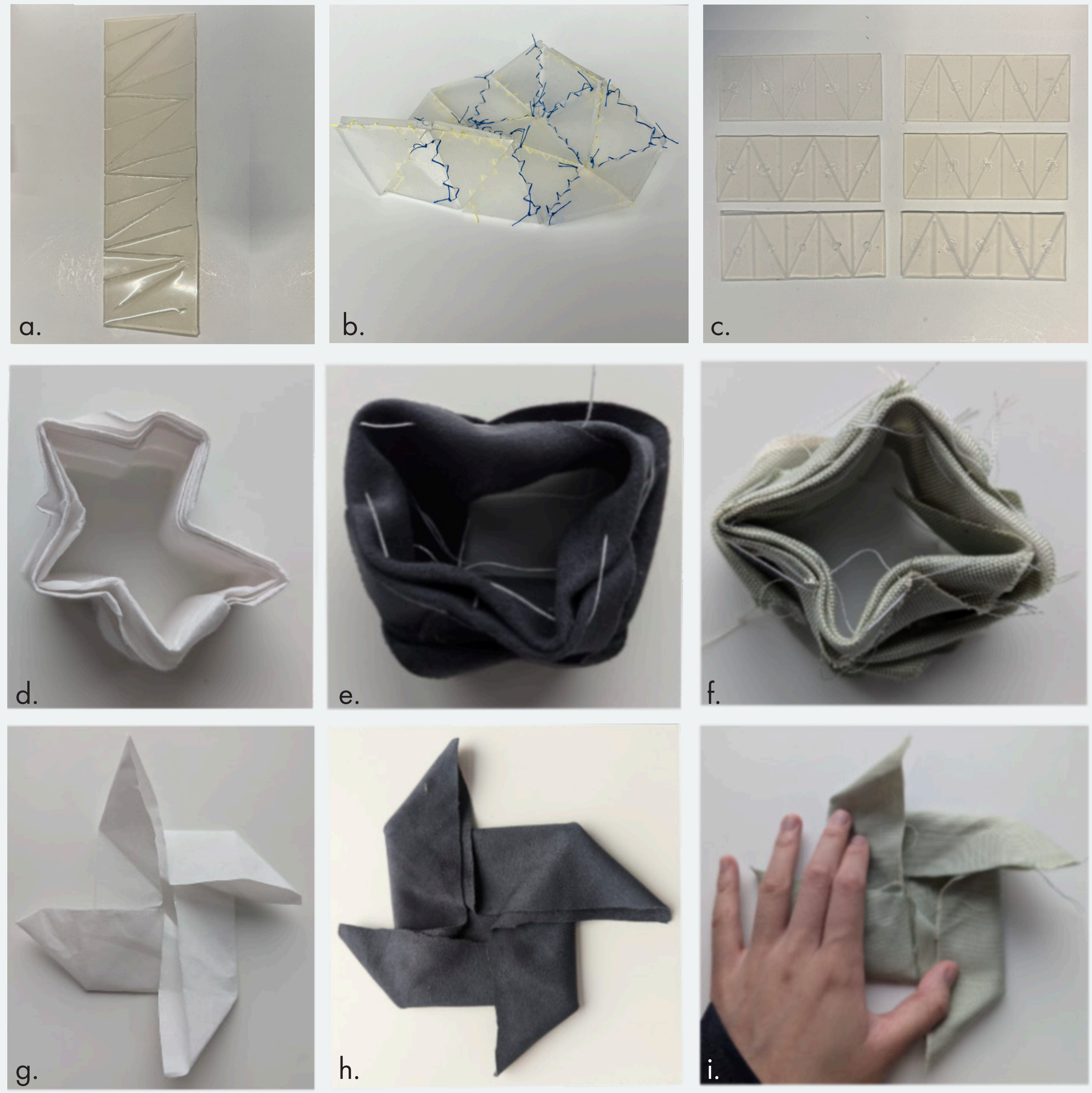

b.


c.


d.

5. DESIGN PROCESS TO MIDTERM CONCEPT

An important element of soft robotics is its actuation. To explore actuation of the different materials shown in the *"4.0 Exploration of context"*, the material properties were further examined. We explored silicone and fabric to see how its shape could potentially be manipulated or controlled through the use of mechanical or electronic actuation. Soft robotics' ability to manipulate its own shape aligns well with the origami principles, where paper is folded into specific patterns for structural efficiency or storage [20; 21]. Leading to exploring the potential for origami in silicone and fabric.



Origami material exploration

a. creating creases in **SILICONE** with tooth picks lacked foldability because of one sided creases

b. creating creases in **SILICONE** by stiching needs very precise stiching and is too labour intensive

c. **SILICONE** exploration of different thickness and crease depth showed that thinner material and deeper creases fold better

d. **TABLE CLOTH** keeps shape due to paper like properties

e. **SUEDE** cannot keep shape even when sewn

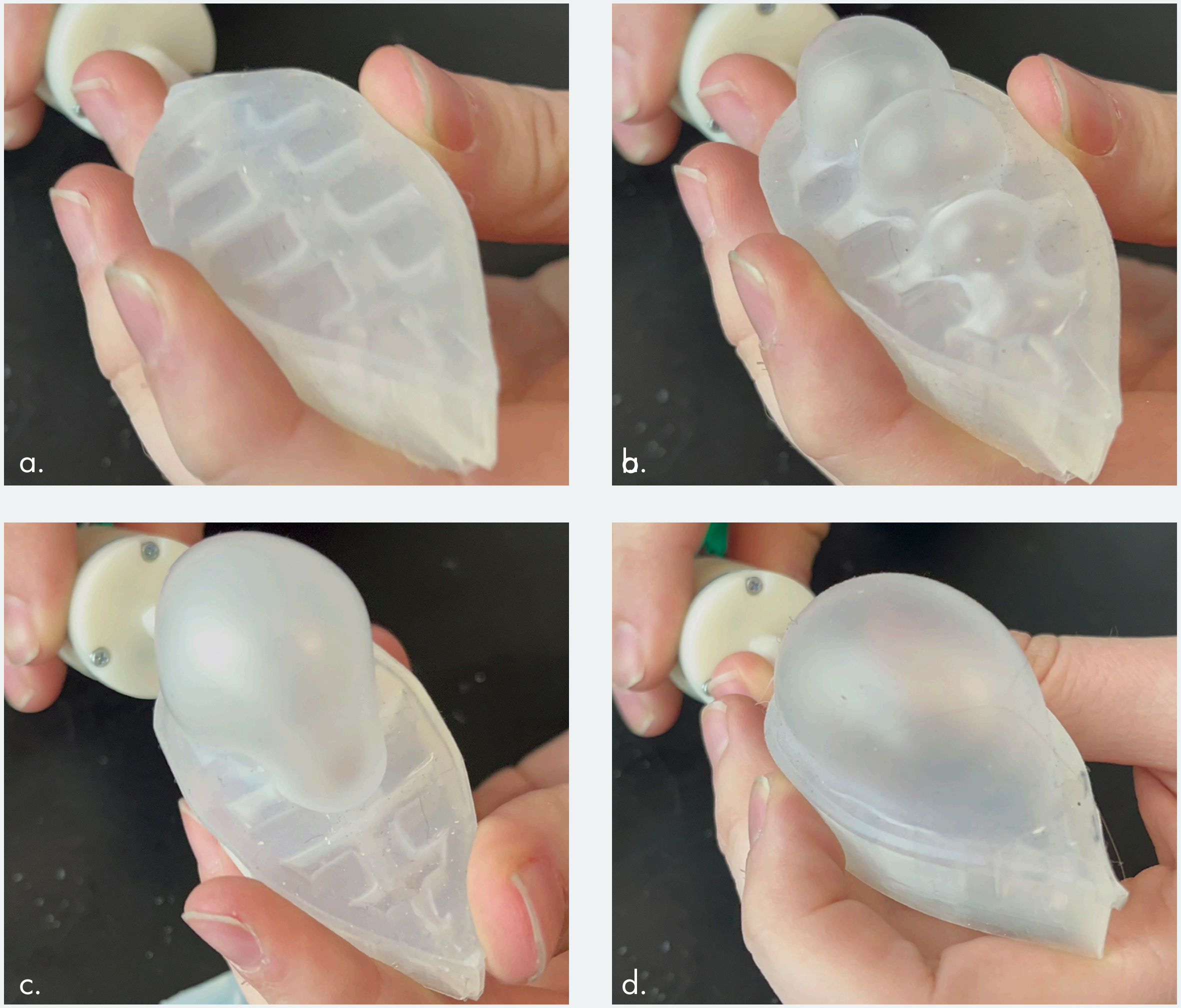
f. **WOVEN FABRIC** needs to be sewed to keep shape

g. **TABLE CLOTH** keeps shape due to paper like properties

h. **SUEDE** keeps shape due to gravity

i. **WOVEN FABRIC** tends to go out

REFLECTION: these explorations showed that origami manipulation of non-foldable materials is rather complicated and not easily achievable when it comes to actuation for this project.



a. Eurosil 33 seal does not allow for actuation, therefore the other leaves were sealed with Ecoflex 30

b. The leave was supposed to bend upon actuation but because of the thickness of the inner walls we perceived inflation

c. Ecoflex 30 closed of the air flow when casted on the walls

d. Removal of the inner walls showed larger inflation as opposed to the intended bending

5.1 Pneumatics

The origami explorations were followed by exploring pneumatics in silicone. Multiple explorations were performed, by casting an open leave shape, and sealing the leaves with a more flexible silicone (Ecoflex 30). The thickness of silicone was not taken into account initially resulting in leaves too rigid to bend or inflate with air.

To become more familiar with pneumatic actuation a simple electronic circuit was built operating an air pump. This allowed controlled airflow into the silicone casts causing them to expand, bend, and change shape. A microphone was integrated into the circuit, allowing different volume levels to influence the strength of the activation. Activating the pump only when it detects external sound enabled the pneumatic leaves to change shape in response to sound signals.

5.2 Conclusion and midterm concept

In conclusion, the iterative exploration of materials and actuation methods laid a strong foundation for advancing to a midterm concept. Each material study highlighted unique affordances and limitations for creating responsive, shape changing forms. Pneumatic experiments revealed how actuation can transform static materials into sensory rich interactions. An initial exploration of sound activated elements underscored the value of incorporating less visual-centric sensory experiences.

These actuation explorations showed that soft robotics hold potential to engage senses beyond sight, pointing toward interaction that emphasizes touch, sound, and movement. Leading to a focus shift from a material-centered approach to a multisensorial approach. The midterm concept was built on these insights with the goal of designing a multisensorial emotion physicalization. This concept envisions a soft robotic interface that addresses undervalued sensory senses in soft robotics, touch and sound, to convey emotional nuances. Aiming to create an interactive experience where users can feel and hear emotional states expressed through material shifts and responsive sound cues. This design vision seeks to address somaesthetics and thereby deepen user engagement through a holistic sensory experience.

6. DESIGN PROCESS TO FINAL DESIGN

After the midterm, different application areas were explored, such as (head) phones and art installations, to come to the final design. Since a driving force behind this project is to contribute to the aesthetics of soft robotics, a target group was concluded, where designers were targeted to make them more aware of these aesthetics.

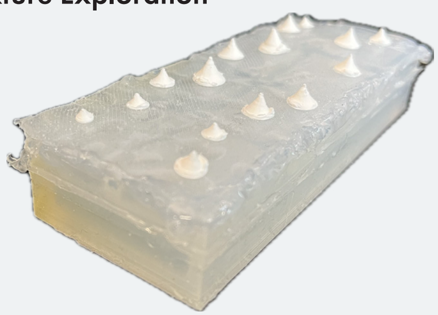
Lo-fi prototypes were made to explore tactile interactions. Through experiencing the tactile interactions ourselves the direction of the project became clear. A design gap was identified emphasizing the underexplored role of sound in soft robotics. Therefore, an interactive multisensorial pad will be made. It is designed for designers to explore the combination of haptics and sound within soft robotics. The designer can interact with the pad while listening to the corresponding sounds. This encourages designers to think about the perception of their soft robotic.

After this direction was chosen the interactive pads were explored. Different silicone pads were created to evoke different emotions, such as a bubbly and a spike one. Different molds were made and casted separately to then assemble everything together using silicone glue. It was found that silicone glue worked good enough for assembling the smaller silicone pads. However, when the silicone pads were increased in size the silicone glue was not strong enough, leading to different assembly methods for the big pads. The big silicone pads needed more support walls to keep the pad from ballooning. This iterative process led to the final design of Tactone.

Silicone Pneumatic Texture Exploration

uninflated soft feeling spikes

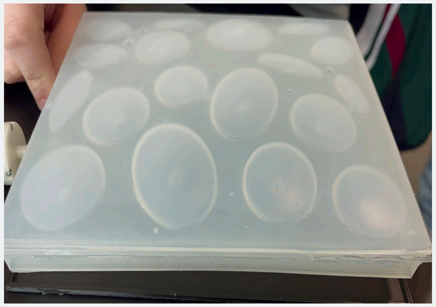
inflated soft feeling spikes



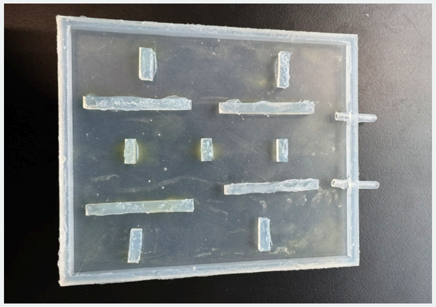
uninflated sharp spike

inflated sharp spike

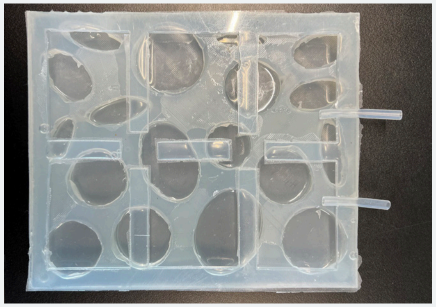
Scaling Up



initial scale up showed a ballooning effect of the entire pad



creation of compartments allowed for better air distribution



casting the sections on top of each other improved their bonding

compartementilization allowed for the intended inflation

7. TACTONE - FINAL DESIGN

Tactone comprises of physical and digital components working together to provide control of exploring haptics and sound in soft robotics. Tactone consists of a physical tool, which can be modified and played around with at the hand of digital Guide (Appendix B) that is delivered alongside it.

With these components, designers can use tactone as a perception tool in their design process, encouraging them to explore haptics and sound of soft robotics, helping them design the perception of their soft robot. Created for designers with little experience in designing soft robots, shape changing interfaces or sound design. By moving around the pre-built pads, by creating their own pads, by uploading different audio files or even by altering the type of actuation of Tactone, we provide designers with an easier way of exploring what kind of multisensory aspects suit their soft robotic.
The Tactone guide and open-source materials such as .stl's of the molds, audio files and code can be found in Appendix C.

7.1 Silicone interaction

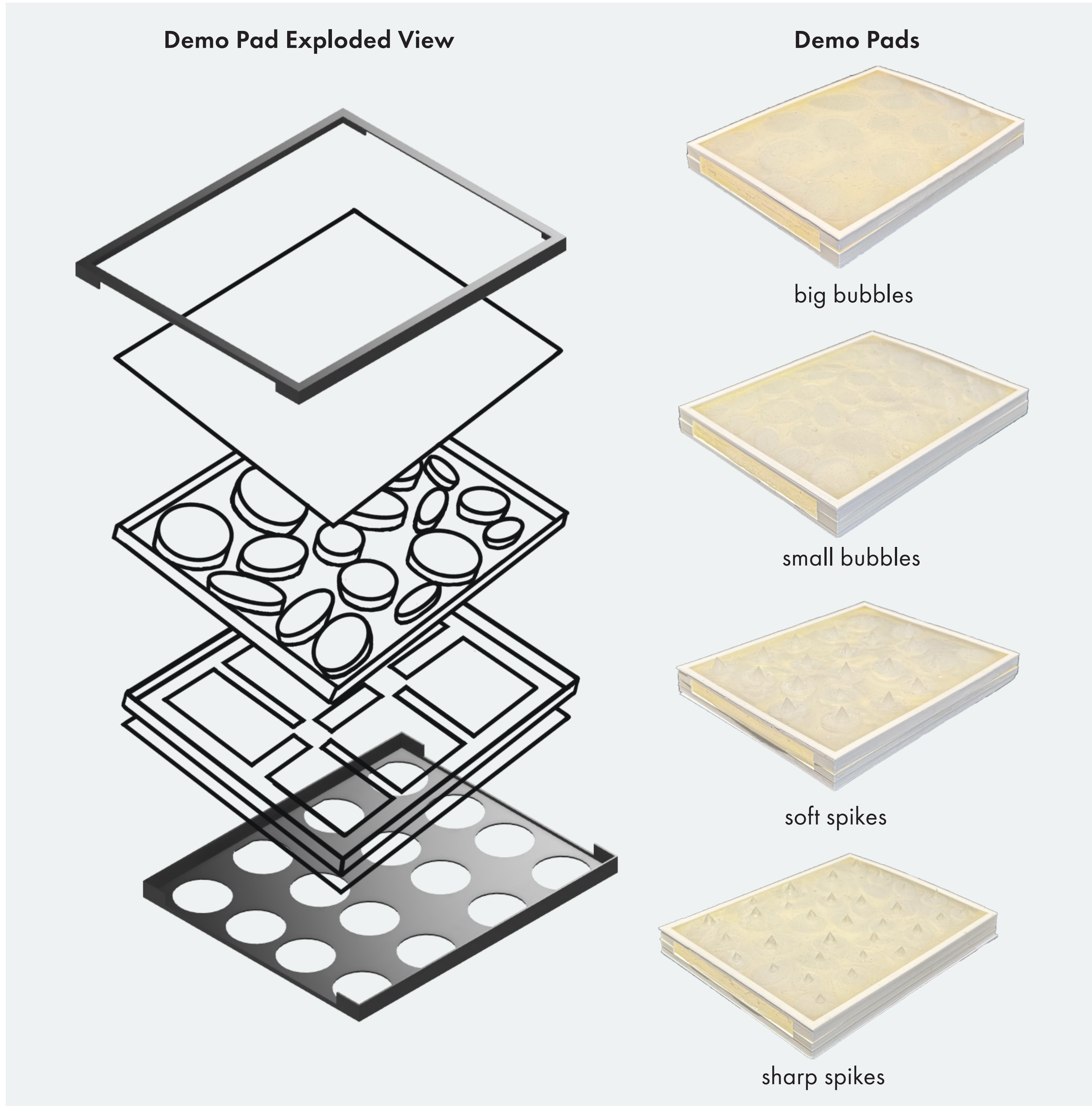
Tactone comes with four demo pads, which are based on emotion physicalization in relation to shapes, movement, and texture. The four demo pads serve as a versatile list of options allowing the designer to start their exploration. These versatile emotions of happy – calm – sad – stress, were also applied to the other modalities, such as sound.

Through iterative explorations, as seen in chapter six, the final pad construction was found. The pads have a four-part casting process, but essentially consist of three parts, a top layer, middle layer, and bottom layer. The casting process is explained in the modularity guide, this guides the user to create their own silicone pads, see Appendix B.

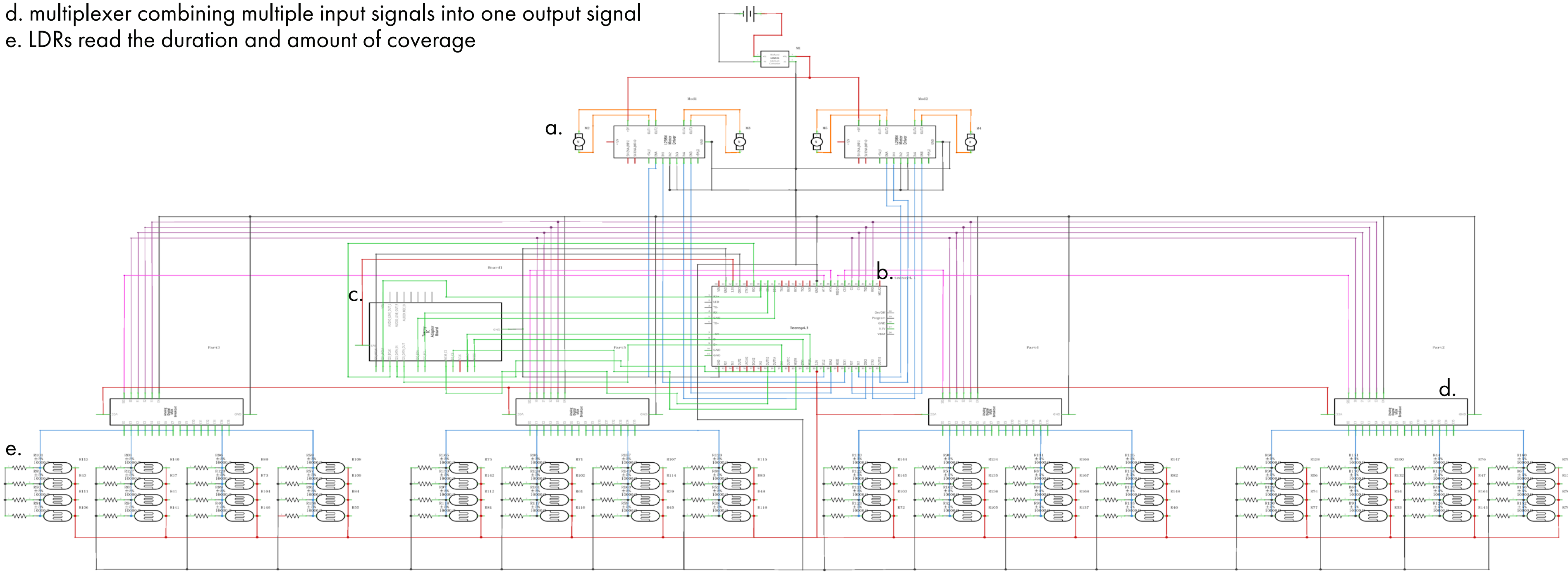
Ultimately the designer will interact with the top layer. The top layer has two different designs. One design is a smooth layer, which will form a smooth bubble when inflated. This design is used for three out of the four pads, where one of them will be coated with transparent PLA spikes to create a sharp spike design. The other design is also a spike layer, in which the spikes are made from silicone. Making them softer than the PLA for contrast.

The middle layer, divides the air into different compartments, creating large or small bubbles in the top layer. The size of the bubbles is dependent on the size of the holes in the middle layer. The middle layer design can therefore be changed by the designer to create new types of tactile interactions (Appendix B).

The bottom layer is cast in two separate parts. Compartmentalizing the bottom was necessary to prevent the air from inflating the bottom rather than the top layer. This compartmentalization is achieved by casting the inner and outer walls onto the middle layer first and then casting the bottom of the pad afterwards. This allowed for creating nice holes in the outer wall to hook the pneumatic pumps into. The layers are cast one after another, in order to cast the silicone on to each other. Ultimately, silicone glue was not needed anymore, making the pad stronger and more airtight.



a. when the pump is triggered by the LDRs the silicone pad will inflate
b. Teensy 4.1 is used as micro controller
c. audio shield stores aurio on the Teensy 4.1
d. multiplexer combining multiple input signals into one output signal
e. LDRs read the duration and amount of coverage



7.2 Electronics

Tactone combines pneumatics, sound and user input. Light Dependent Resistors (LDRs) are used for detecting coverage. The duration and proportion of the LDRs being covered are recorded, the pad with more LDRs being covered will be recognized as being in the “user interaction” state. Consequently, Tactone will play the corresponding sound (see 7.3 Sound), and the associated pump will be activated. This allows the user to experience tactile feedback on the pad when interacting with it. The airpumps can be changed out for other kinds of actuation, using the guide (Appendix B).

7.3 Sound

Tactone consists of four demo pads, which each have a corresponding sound file. The tactile interaction is complemented by the sound, for example, a stressful uncomfortable sound is combined with rising sharp spikes. The sound changes based on coverage and duration. The coverage refers to the amount of LDR’s that are blocked, and the duration refers to how long the pad is covered.

The audio files consist of two parts, a rhythm and a lead. Duration affects both parts equally, with sound gradually ramping up over a couple seconds. Coverage modulates the lead sound via a high-pass filter, revealing more sound as the coverage increases. An octave and reverb effect enhance the filter sweeps, creating dynamic auditory feedback as the sound evolves with user interaction. The rhythm remains unaffected for clarity and exploration.

The four pads have the emotion guidelines of happy, calm, sad and distress. Happiness features bright, chime-like tones in major chords. Calm uses animal noises for a soothing effect. Sadness incorporates slow piano melodies and minor chords with haunting choir notes. Lastly distress employs non-linear soundscapes with rumbling bass, wailing tones, and dissonant notes, evoking urgency and discomfort.

8. VALIDATION

8.1 Explorative user study

An explorative user study was done, to refine our target group and to finetune our audio design. The participants were first asked simple questions to gather insights on the demographic, such as what kind of designer they are. The participants were then asked to hover over one pad with LDRs. Correspondingly they would listen to the sound changes based on how much the participants covered. The sound. They were listening to was intended to be a sad sound and would change from a muffled sound to a clear sound based on how much they covered the surface. The duration of the interaction also influenced the volume of the audio, making it more intense over time.

The reactions of the participants differed, some found the sound stressful and creepy while others found it calming. When the participants were asked to relate the sound to a silicone pad the responses were also different. Some said it fitted with the big bubbles while others found the spikes more fitting. This explorative user study showed that sound is subjective, therefore designers should be given the freedom to play around with different sound and haptics. This underlines the potential value of modularity of the haptics in our design.

8.2 Final user study

We conducted a user test session with eight design graduates to gain a better understanding of how these designers would include Tactone in their design process, and to receive general feedback on the design for future improvements.

Setup

The participants were asked to interact with Tactone, which was presented to them on an empty table with a black surface to limit distraction. Only afterwards they were explained the goal of Tactone. In this way the designers could freely experiment without prior bias or knowledge. The participants were then asked about their expertise area as a designer.

Participants

Eight design graduates with little experience in designing soft robotics or shape changing interfaces participated in the user test. Most participants only worked on one soft robotic project, with only one participant having done multiple projects within this area.

Procedure

During the study, participants are asked to imagine a scenario designing a soft robotic game controller and how, and if, they would use Tactone in their design process to design the perception of this game controller.

Results

In this scenario, most participants mentioned that they would use Tactone for the design of haptics, pressure and touch of the game controller. When participants were asked in which stage of the design process they would use the tool, the answers showed a distinction between two stages. Half of the participants preferred to use Tactone in the beginning of the process to get inspired, while others preferred to use Tactone halfway through the design process to finetune the haptics of their soft robot.

In conclusion, all participants would use Tactone in the design process of their soft robot. With two main scenarios on the application. With one Tactone being used as an exploration tool at the start of the design process, and the other one Tactone being used as a refinement tool after the first explorations are done.

9. DISCUSSION

Tactone has presented a value for designers in their design process and provides a tool that gives designers good first insights into elements of designing a soft robotic.

Influence of order and texture choice on user perception

A key factor to consider in the use of Tactone as a perception tool is the influence of the initial arrangement of the pads and the associated textures and audio. While the tool is designed for open-ended exploration, our design choices, such as the initial placement of pads, their textures, and the audio associations, may unintentionally impose a perceptual framework on designers. For example, smooth textures with calming sounds may suggest tranquility, while rough textures with sharp sounds might imply tension. These associations are not neutral; they stem from our interpretations of how specific sensations relate to emotions or behaviors. Designers might adopt these pre-existing emotional frameworks rather than fully exploring alternative interpretations of textures, inflations, and sounds. This raises an important question: *To what extent are designers influenced by our assumptions?*

To address this, Tactone could incorporate more modularity, such as randomized starting conditions, reducing the likelihood of implicit bias. Additionally, user studies comparing pre-set versus randomized arrangements could reveal how initial conditions shape exploration and emotional associations. Acknowledging this influence and designing for greater neutrality would help ensure Tactone remains an open-ended tool that empowers designers to freely explore and refine their soft robot's perceived aesthetics.

Intuitiveness of Tactone as a design tool

The intuitiveness of Tactone is critical to its effectiveness, especially for designers with little to no experience in soft robotics. This intuitiveness can be considered in two forms: the intuitiveness of interacting with the tool and the intuitiveness of integrating Tactone into the design process. The basic interaction, where tactile inflations trigger audio feedback, offers a clear and engaging entry point for exploration. However, the tool's modularity and flexibility, can present a learning curve when designers begin to customize aspects such as actuation, audio, or code.

To address this, Tactone includes a digital guide explaining how to modify each part of the system. While this provides support, the extent to which designers use and rely on the guide may vary. Some designers may prefer self-guided, intuitive experimentation, while others might benefit from more hands-on onboarding, such as practical examples or interactive tutorials. Observing how effectively designers integrate Tactone with or without the guide could highlight opportunities to streamline the learning process further.

One technical limitation of Tactone is its intuitiveness in use. In the exploratory user study, participants suggested connecting the inflation rhythm of the pads to the audio rhythm to make the interaction feel more natural. This connection was initially avoided to prevent Tactone from feeling like a musical instrument. However, the feedback shows that better synchronization between the pads and the audio could improve the user experience in ways we hadn't anticipated.

Another issue was the response speed of the system. Some participants noticed that the audio takes up to two seconds to start, which made the tool feel unresponsive during rapid interactions. This delay disrupted the flow of exploration and made it harder for users to interact. Reducing this delay and improving the system's overall responsiveness would make Tactone feel smoother and more engaging to use.

In summary, Tactone combines material-centered and multisensorial design methodologies to create a tool that explores the aesthetics of shape-changing interfaces in soft robotics. Key outcomes, such as the influence of the initial order and system intuitiveness, reveal opportunities for improvement. Future work could focus on enhancing Tactone's modularity and thus accessibility, such as through randomized arrangements, more easily interchangeable actuators, and customizable sensory mapping. Additionally, addressing technical limitations, such as response latency and sensory synchrony, will ensure a smoother and more engaging user experience. By iterating on these insights, Tactone can better serve as an open-ended, exploratory tool that empowers designers to refine the perceived aesthetics of soft robotics.

10. CONCLUSION

This project introduced Tactone, a modular, multisensorial design tool aimed at addressing the underexplored roles of sound and haptics in soft robotics. Tactone empowers designers with little experience in soft robotics, to explore the emotional and perceptual potential of shape-changing interfaces.

Through iterative explorations of materials like silicone, pneumatic actuation systems, and the integration of responsive audio feedback, Tactone demonstrates how multimodal interaction can enhance the user experience. The modular design encourages flexibility, enabling designers to experiment with sound, texture, and motion to evoke nuanced emotional responses. Results from user studies highlight two primary applications: Tactone serves as both an exploration tool for initial ideation and a refinement tool to fine-tune interactions later in the design process.

The findings underscore the importance of fostering a holistic, embodied approach to soft robotics, where sound, touch, and movement collaboratively shape the perception of soft robotics. Moving forward, improvements to modularity, response time, and interaction fluidity could further elevate Tactone's potential as an applicable design resource.

11. AKNOWLEDGEMENT

We want to thank our coach, Amy Winters for her guidance and expertise throughout this project. Along we want to thank the peers and coaches from the Sensory Matters squad for their feedback along the project. Next to that we want to thank d.search for helping us with the assembly of Tactone. Especially Wietze, who taught us a lot in the regards of troubleshooting electronics and handling multiplexers. And finally, we want to thank all the participants participating in our user study for their feedback.

12. REFERENCES

[1] Alexander, J., Roudaut, A., Steimle, J., Hornbæk, K., Bruns Alonso, M., Follmer, S., & Merritt, T. (2018). Grand Challenges in Shape-Changing Interface Research. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18), 1–14. https://doi.org/10.1145/3173574.3173873

[2] Alice Borg, Claudia Núñez Pacheco, Anna Karlsson, and Kristina Höök. 2024. Designerly Ways of Knowing- Soma Design Meets Industrial Design Thinking. In Proceedings of the Halfway to the Future Symposium (HttF '24). Association for Computing Machinery, New York, NY, USA, Article 7, 1–9. https://doi.org/10.1145/3686169.368617

[3] Alison Oldfield, Katherine Broomfield, Hemma Philamore, Richard Sewell, and Emma Powell. 2024. Softly Non-Spoken: Exploring the Potential of Soft Robotics to Support Non-Verbal Communication. In Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24). Association for Computing Machinery, New York, NY, USA, Article 296, 1–7. https://doi.org/10.1145/3613905.3650945

[4] Anne-Sofie Belling and Daniel Buzzo. 2021. The Rhythm of the Robot: A Prolegomenon to Posthuman Somaesthetics. In Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '21), February 14–17, 2021, Salzburg, Austria. ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3430524.3442470

[5] Bertheaux C, Toscano R, Fortunier R, Roux J-C, Charier D and Borg C (2020) Emotion Measurements Through the Touch of Materials Surfaces. Front. Hum. Neurosci. 13:455. doi: 10.3389/fnhum.2019.00455

[6] Cabibihan, John-John & Carrozza, M.C. & Dario, Paolo & Pattofatto, S. & Jomâa, Moez & Benallal, Ahmed. (2007). The Uncanny Valley and the Search for Human Skin-Like Materials for a Prosthetic Fingertip. Proceedings of the 2006 6th IEEE-RAS International Conference on Humanoid Robots, HUMANOIDS. 474 - 477. 10.1109/ICHR.2006.321315.

[7] C. Classen, "Foundations for an Anthropology of the Senses," International Social Science Journal, vol. 49, no. 153, pp. 401–412, Sept. 1997. DOI: 10.1111/j.1468-2451.1997.tb00032.x.

[8] Döring, Tanja. (2011). Material-centered design and evaluation of tangible user interfaces. Proceedings of the 5th International Conference on Tangible Embedded and Embodied Interaction, TEI'11. 437-438. 10.1145/1935701.1935819.

[9] Eckstut, A. and Eckstut, J. 2013. The Secret Language of Color: Science, Nature, History, Culture, Beauty of Red, Orange, Yellow, Green, Blue, & Violet. Black Dog & Leventhal Publishers, New York, NY.

[10] Elena B. Sabinson and Keith E. Green. 2021. How do we feel? User Perceptions of a Soft Robot Surface for Regulating Human Emotion in Confined Living Spaces. In 2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN). IEEE Press, 1153–1158. https://doi.org/10.1109/RO-MAN50785.2021.9515499

[11] Ferrise, F., Graziosi, S. & Bordegoni, M. Prototyping strategies for multisensory product experience engineering. J Intell Manuf 28, 1695–1707 (2017). https://doi.org/10.1007/s10845-015-1163-0

[12] Fong, T., Nourbakhsh, I., and Dautenhahn, K. 2003. A survey of socially interactive robots. Robotics and Autonomous Systems 42, 3-4 (March 2003), 143–166. https://doi.org/10.1016/S0921-8890(02)00372-X.

[13] Haller, K. 2019. The Little Book of Colour: How to Use the Psychology of Colour to Transform Your Life. Penguin Life, London, UK.

[14] Hammond, C. 2015. Do Colours Really Change Our Mood? BBC Future. https://www.bbc.com/future/article/20150402-do-colours-really-change-our-mood.

[15] Hardin, C. 2013. Berlin and Kay Theory. In Encyclopedia of Color Science and Technology, R. Luo, Ed. Springer, New York, NY. https://doi.org/10.1007/978-3-642-27851-8_62-2.

[16] H. Danilishyna, A. Popp, R. Koningsbruggen, and E. Hornecker. "Exploring Emotion Physicalization Through Soft Robotics." Mensch und Computer 2024 - Workshopband. Gesellschaft für Informatik e.V., Karlsruhe, Germany, 1-4 September 2024. DOI: 10.18420/muc2024-mci-demo-371.

[17] Hertenstein, M. J., & Weiss, S. J. (2011). The handbook of touch: Neuroscience, behavioral, and health perspectives. Springer.

[18] Howes, D. (Ed.). (2004). Empire of the Senses: The Sensual Culture Reader. English edition. Berg Publishers.

[19] I. F. Science. 2023. Non-Linear Sounds: There's a Science to Scary Noises. Retrieved November 24, 2024, from https://www.iflscience.com/non-linear-sounds-theres-a-science-to-scary-noises-71236

[20] Jackson, P. (2011). Folding techniques for designers: From sheet to form. London: Laurence King Publishing.

[21] Jackson, P. (2015). Complete pleats: Pleating techniques for fashion, architecture, and design. London: Laurence King Publishing.

[22] Jiong Sun, Sergey Redyuk, Erik Billing, Dan Högberg, and Paul Hemeren. 2017. Tactile Interaction and Social Touch: Classifying Human Touch Using a Soft Tactile Sensor. In Proceedings of the 5th International Conference on Human Agent Interaction (HAI '17). Association for Computing Machinery, New York, NY, USA, 523–526. https://doi.org/10.1145/3125739.3132614

[23] Jonas J. J. Jørgensen. 2023. Towards a Soft Science of Soft Robots. A Call for a Place for Aesthetics in Soft Robotics Research. ACM Trans. Hum.-Robot Interact. 12, 2, Article 15 (March 2023), 11 pages. https://doi.org/10.1145/3533681

[24] Jørgensen J and Christiansen MB (2021) The Sounds of Softness. Designing Sound for Human-Soft Robot Interaction. Front. Robot. AI 8:674121. doi: 10.3389/frobt.2021.674121

[25] Kanda, T., Miyashita, T., Osada, T., Haikawa, Y., and Ishiguro, H. 2009. Analysis of humanoid appearances in human-robot interaction. Proceedings of the 2009 IEEE International Conference on Robotics and Automation (ICRA), 2009, 1640–1645. https://doi.org/10.1109/ROBOT.2009.5152452.

[26] Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Material Driven Design (MDD): A method to design for material experiences. International Journal of Design, 9(2), 35–54.

[27] Kristian Gohlke, Wolfgang Sattler, and Eva Hornecker. 2022. AirPinch – An Inflatable Touch Fader with Pneumatic Tactile Feedback. In Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '22). Association for Computing Machinery, New York, NY, USA, Article 64, 1–6. https://doi.org/10.1145/3490149.3505568

[28] Lahdelma, Imre. (2017). At the interface between sensation and emotion: perceived qualities of single chords.

[29] Lakatos G, Gácsi M, Konok V, Brúder I, Bereczky B, et al. (2014) Emotion Attribution to a Non-Humanoid Robot in Different Social Situations. PLOS ONE 9(12): e114207. https://doi.org/10.1371/journal.pone.0114207

[30] Laurens Boer and Harvey Bewley. 2018. Reconfiguring the Appearance and Expression of Social Robots by Acknowledging their Otherness. In Proceedings of the 2018 Designing Interactive Systems Conference (DIS '18). Association for Computing Machinery, New York, NY, USA, 667–677. https://doi.org/10.1145/3196709.3196743

[31] PALLESEN, K.J., BRATTICO, E., BAILEY, C., KORVENOJA, A., KOIVISTO, J., GJEDDE, A. and CARLSON, S. (2005), Emotion Processing of Major, Minor, and Dissonant Chords. Annals of the New York Academy of Sciences, 1060: 450-453. https://doi.org/10.1196/annals.1360.047

[32] PJRC. "AudioSynthWaveformDc – Teensy Audio Library Documentation." https://www.pjrc.com/teensy/gui/?info=AudioSynthWaveformDc

[33]. Ran Zhou, Zachary Schwemler, Akshay Baweja, Harpreet Sareen, Casey Lee Hunt, and Daniel Leithinger. 2023. TactorBots: A Haptic Design Toolkit for Out-of-lab Exploration of Emotional Robotic Touch. In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23). Association for Computing Machinery, New York, NY, USA, Article 370, 1–19. https://doi.org/10.1145/3544548.3580799

[34] Schifferstein, H. N. J. (2010). Multi Sensory Design. ACM. https://doi.org/10.1145/2079216.2079270

[35] Sebastian van Ledden, Artur Lisetschko, Nadine Jansen, Dagmar Jendrusch, Julia Hermann, and Aysegül Dogangün. 2024. User-Centric Design of Social Robots in City Libraries: Exploration of the Interplay of Social Roles and User Expectations. In Proceedings of the 13th Nordic Conference on Human-Computer Interaction (NordiCHI '24). Association for Computing Machinery, New York, NY, USA, Article 13, 1–13. https://doi.org/10.1145/3679318.3685346

[36] S. Frühholz, W. Trost, and S. A. Kotz. 2021. The sound of emotions—Towards a unifying neural network perspective of affective sound processing. Neuroscience & Biobehavioral Reviews, 127, 1–15. https://doi.org/10.1016/j.neubiorev.2021.03.020

[37] Shafir T, Tsachor RP and Welch KB (2016) Emotion Regulation through Movement: Unique Sets of Movement Characteristics are Associated with and Enhance Basic Emotions. Front. Psychol. 6:2030. doi: 10.3389/fpsyg.2015.02030

[38] Sjoerd Hendriks, Simon Mare, Mafalda Gamboa, and Mehmet Aydın Baytaş. 2021. Azalea: Co-experience in Remote Dialog through Diminished Reality and Somaesthetic Interaction Design. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21). Association for Computing Machinery, New York, NY, USA, Article 261, 1–11. https://doi.org/10.1145/3411764.3445052

[39] S. ur Réhman, "Expressing Emotions through Vibration for Perception and Control," Master's Thesis, Luleå University of Technology, Department of Human Work Sciences, 2010. https://www.diva-portal.org/smash/get/diva2:308457/FULLTEXT01.pdf

[40] Talia Sofia Ezer, Jonathan Giron, Hadas Erel, and Oren Zuckerman. 2024. Somaesthetic Meditation Wearable: Exploring the Effect of Targeted Warmth Technology on Meditators' Experiences. In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems (CHI '24). Association for Computing Machinery, New York, NY, USA, Article 541, 1–14. https://doi.org/10.1145/3613904.3642557

[41] Tamar Dublin, Talia Sofia Ezer, and Oren Zuckerman. 2024. A Journey Inward: The Somaesthetic Experience of a Heated Walking Carpet. In Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '24). Association for Computing Machinery, New York, NY, USA, Article 18, 1–7. https://doi.org/10.1145/3613905.3650915

[42] Tractinsky, N & Katz, Adi & Ikar, D. (2000). What is beautiful is usable. Interacting with Computers. 13. 127-145. 10.1016/S0953-5438(00)00031-X.

[43] Udsen, L. E. and Jørgensen, A. H. 2005. The aesthetic turn: Unraveling recent aesthetic approaches to human-computer interaction. Digital Creativity 16, 4 (January 2005), 205–216. https://doi.org/10.1080/14626260500476564.

[44] Vallgårda, A., & Sokoler, T. (2010). A Material Strategy: Exploring Material Properties in Design. International Journal of Design, 4(3), 81–95.

[45] von Zitzewitz, J., Boesch, P.M., Wolf, P. et al. Quantifying the Human Likeness of a Humanoid Robot. Int J of Soc Robotics 5, 263–276 (2013). https://doi.org/10.1007/s12369-012-0177-4

[46] Wachsmuth, M. Lenzen, and G. Knoblich, Eds., *Embodied Communication in Humans and Machines*. Oxford University Press, 2008. ISBN: 9780199231751.

[47] Walker, M. 1991. The Power of Color. Avery Publishing Group, Garden City Park, NY.

[48] Wang X, Xu B, Zhang W, Wang J, Deng L, Ping J, Hu C and Li H (2023) Recognizing emotions induced by wearable haptic vibration using noninvasive electroencephalogram. Front. Neurosci. 17:1219553. doi: 10.3389/fnins.2023.1219553

[49] Winters, A., de Waart, S., & Bruns, M. (2022). Tension-and-Release: A design principle for dynamic materials. International Journal of Design, 16(2), 1–14. https://doi.org/10.57698/v16i2.01 Wright, A. 1998. The Beginner's Guide to Colour Psychology. Kyle Cathie, London, UK.

[50] Wright, A. 1998. The Beginner's Guide to Colour Psychology. Kyle Cathie, London, UK.

[51] Y. Hu, Z. Zhao, A. Vimal, and G. Hoffman, "Soft skin texture modulation for social robotics," in 2018 IEEE International Conference on Soft Robotics (RoboSoft), Livorno, Apr. 2018, pp. 182–187.

[52] Yuhan Hu and Guy Hoffman. 2023. What Can a Robot's Skin Be? Designing Texture-changing Skin for Human–Robot Social Interaction. J. Hum.-Robot Interact. 12, 2, Article 26 (June 2023), 19 pages. https://doi.org/10.1145/3532772

[53] Y. Wang, M. Liu, and L. Ren. 2017. Adaptive design of materials with 4D printing capabilities. Adv. Eng. Mater. 19, 1 (2017), Article 1700016. DOI: https://doi.org/10.1002/adem.201700016

[54] Zhu X, Feng T and Culbertson H (2022) Understanding the Effect of Speed on Human Emotion Perception in Mediated Social Touch Using Voice Coil Actuators. Front. Comput. Sci. 4:826637. doi: 10.3389/fcomp.2022.826637

13. APENDIX

Appendix A: Color Perception

In psychology there are four psychological primary colors, triggering different behaviours.
Red – Red affects us physically, triggering physical responses.
Yellow – Yellow affects our emotions, affecting the nervous system.
Blue – Blue affects our intellect, triggering mental responses.
Green – Green is the color of balance and harmony, balancing between mind, body, and emotions.

The eleven colors:
Red

- Affect physically & attract attention
- Positive: warmth, energy & excitement
- Negative: anger, annoyance, exhaustion

Pink

- Positive: the color of expression of a nurturing, caring and empathetic love
- Negative: needy, weak, helpless

Yellow

- Affecting emotions
- Positive: emotionally stimulating, make feel more confident, positive, optimistic
- Negative: irritation, anxiety, nervousness, depression (if wrong tone is used)

Orange

- Combines physical (red) & emotions (yellow)
- Positive: warm, friendly, energetic, fun, playfulness, stimulates social interaction & friendly conversation, expresses abundance
- Negative: childish, frivolous, unrefined & cheap (used too much or wrong tone)

Brown

- Positive: earth, wood, reassured, safe, solid, dependable, grounded
- Negative: dull, lifeless, boring, stubborn & unbending, lack humor

Blue

- Worlds favorite color
- Positive: logic & clarity of thought, mental calm, serenity & reflection
- Negative: cold, uncaring

Green

- Middle of the color system
- Positive: restful, balance, harmony
- Negative: stagnation, boredom

Purple

- Combination of power, energy & strength of red & integrity and truth of blue
- Positive: spiritual awareness, reflection, meditation
- Negative: lose touch with reality, cheap, nasty

Grey

- Positive: no positive association -> to be left alone
- Negative: draining, tiring

White

- Positive: perfection, pure, unblemished, peace, quite, simplicity, clarity, emotional safety
- Negative: cold, uncaring, sterile, isolating, remote

Black

- Positive: glamour, elegance, sophistication, authority, mystery
- Negative: menacing, scary, cold, unapproachable, overly serious

Appendix B: The Guide

Link: https://acrobat.adobe.com/id/urn:aaid:sc:eu:89082ad3-374a-4550-a4e0-aad73bee7e9a

Appendix C: GitHub

Link: https://github.com/ElmoNeedsArson/SensoryMatters_Tactone_Codebase/blob/main/README.md

Appendix D: Process Book

Link: https://acrobat.adobe.com/id/urn:aaid:sc:EU:b7276380-b166-4c86-a13c-dc6d229e0d6b

Appendix E: Interview Questions

What kind of designer are you?

Do you have a background in soft robotics, shape changing interfaces, tangible interaction, or sound design?

Scenario

If you were to design a soft robotic game controller, how would you use this tool to design the perception of this soft robot.

Which information would you need to use this in your daily practice?

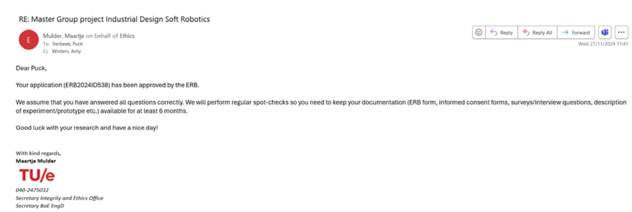
How would you use the tool in your design practice?

In which stage of the design process would you use the tool?

Would you change features of the pad, so it fits better in your design practice?

Appendix F: ERB Form

Link: https://acrobat.adobe.com/id/urn:aaid:sc:EU:1260afc5-771c-4e4c-845c-20535f22e7b1


RE: Master Group project Industrial Design Soft Robotics
Mulder, Maartje on behalf of Ethics
To Verbeek, Puck
Cc Winters, Amy
Wed 27/11/2024 11:41

Dear Puck,

Your application (ERB2024ID538) has been approved by the ERB.

We assume that you have answered all questions correctly. We will perform regular spot-checks so you need to keep your documentation (ERB form, informed consent forms, surveys/interview questions, description of experiment/prototype etc.) available for at least 6 months.

Good luck with your research and have a nice day!

With kind regards,
Maartje Mulder
TU/e
040-2475032
Secretary Integrity and Ethics Office
Secretary BoE EngD