Master Thesis

TU Delft
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Texture-changing Wearable Haptic Skin for Emotion and Perception Influence

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MSc Design for Interaction
28th August 2025

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Abstract

Abstract

This thesis addresses the lack of dynamic material embodiment in current wearable systems by investigating how texture-changing skins can act as expressive haptic interfaces. A literature review of current texture-changing material technologies revealed a research gap: most existing solutions are bulky, rigid, and restricted to coarse, large-scale deformations, limiting their suitability for wearable contexts.

To bridge this gap, several mechanisms—pneumatics, origami structures, knitted fabrics, and embedded fibers—were explored through iterative prototyping. The most promising direction, a hairy texture system driven by Shape Memory Alloys, demonstrated thinness, flexibility, and high tactile resolution. The resulting prototype achieved controlled, reversible texture transformations while remaining thin, lightweight and silent.

User evaluations indicate that these programmable textures elicit distinct affective responses, showing their potential as a medium for embodied emotional communication. The project contributes both a novel haptic interface mechanism and broader design knowledge on how dynamic textures may enrich future wearable systems by positioning material tactility as an active partner in interaction.

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Acknowledgement

I would like to give my heartfelt gratitude to my supervision team, Prof. dr. ir. Kaspar Jansen and Dr. Sepideh Ghodrat. Among all the teachers I have met, they have been the most supportive and encouraging. Whenever I encountered difficulties or doubts, they never failed to encourage me, guide me, and help me move forward.

I would like to thank Kaspar for his sharp eye for detail and technical insight. He consistently offered feedback that exceeded my expectations in both precision and depth, helping me see my project from perspectives I would not have reached on my own.

I would like to thank Sepideh for her encouragement and warmth, which gave me confidence at every step. Her hands-on guidance and patient mentorship have taught me so much, and her enthusiasm has been a continuous source of motivation.

I am also deeply thankful to Yi, who worked alongside me and supported this project as if it were her own.

My sincere thanks go to my friends Zhengyang and Ziyu, whose encouragement always reached me in my most difficult moments.

And lastly, I want to thank my cat Mila. She has been an unexpected source of inspiration for this project. And of course, I also owe her special thanks for not spilling coffee on my computer, and not deleting my files.

Chapter 1
Introduction

Tactile interaction with surface texture significantly influences users' emotional and perceptual engagement with products. However, most wearable devices employ static material finishes or simple vibrational haptic feedback, which do not replicate the complex qualities of natural textures. This research aims to develop an interactive surface that incorporates dynamic textures to communicate emotion through touch.

Current research on morphing materials primarily addresses large-scale shape changes or low-resolution surface effects. These solutions are often bulky, rigid, or unsuitable for wearable applications. This gap highlights the need to design thin, flexible, high-resolution haptic skins capable of dynamically modulating textures to influence emotional perception through tactile interaction.

Following an evaluation of multiple morphing texture concepts, the research focused on the development of a hairy texture-changing interface.

The design combines a slitted top layer with a metal bristle bottom layer. When the top layer is fully up, the surface feels smooth and flat. When the Shape Memory Alloy (SMA) actuator pulls the top layer downward, the needles are exposed through the slits. This action transforms the surface into a coarse, sandpaper-like texture.

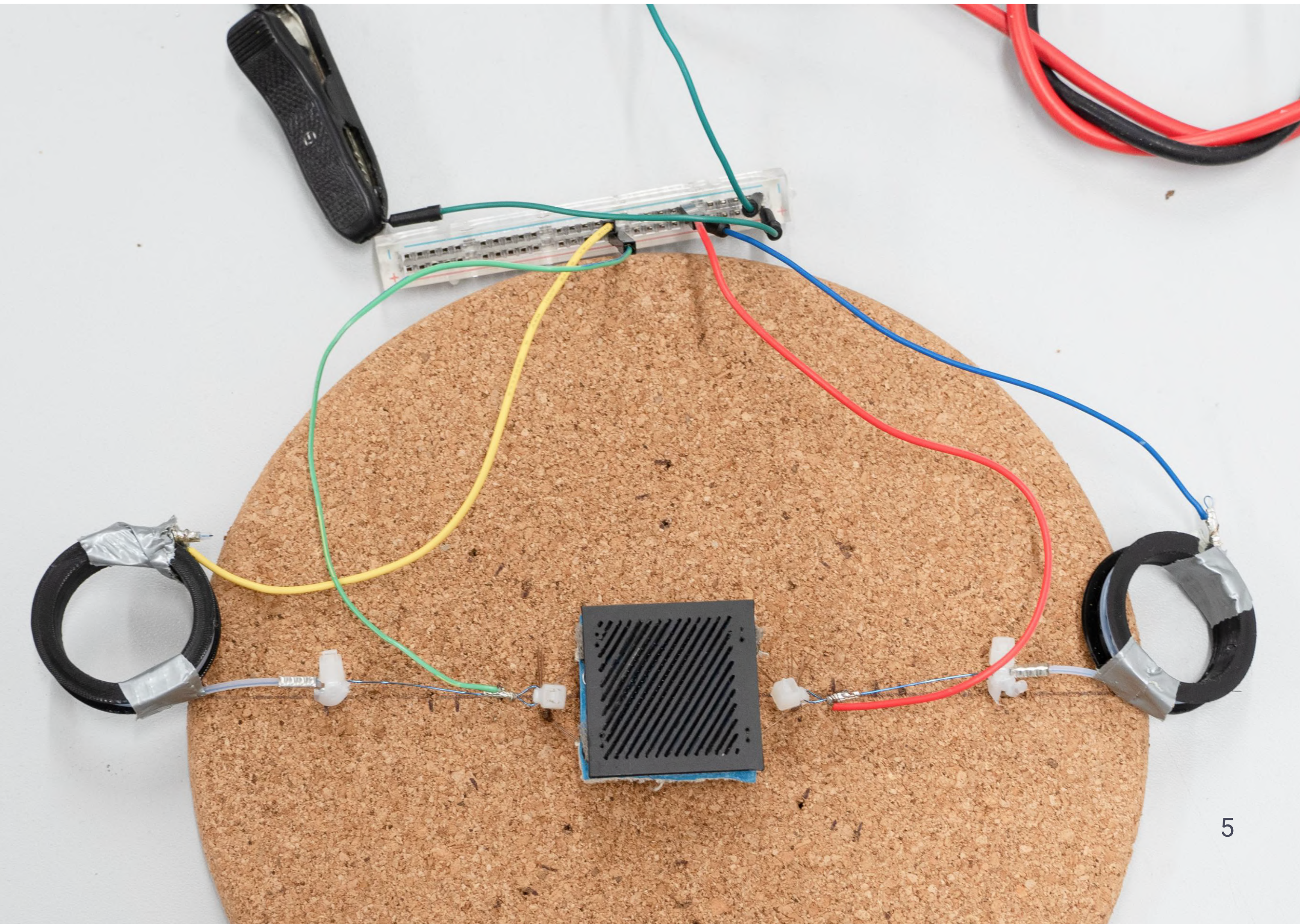
The resulting design is noiseless, lightweight, and flexible, which facilitates adaptation to various surfaces as a haptic interface for user interaction.

Figure 1. Photograph of the texture changing surface

Chapter 2
Design Process

This section outlined the methodological foundation of the project, which combined the Double Diamond framework, Research through Design, and Material-Driven Design. The Double Diamond structured the process into two iterative cycles of exploration and convergence, leading from broad ideation to the selection and realization of the Hairy Texture concept.

Figure 1. Photograph of the testing plate



2.1 Design Methodology

The design process combined three complementary approaches to guide the exploration and development of my texture-changing wearable interface.

Firstly, the Double Diamond framework structured the overall trajectory into two clear cycles of divergence and convergence. In the first cycle, I explored a broad range of texture-changing mechanisms through literature review, early experiments, and ideation before converging on the Hairy Texture concept as the most promising direction. In the second cycle, I expanded this concept by investigating how it could be practically realized — searching for suitable materials, testing different structural configurations, and finally developing a functional prototype that could be integrated into a wearable form.

Secondly, a Research through Design (RtD) approach was applied throughout the project. Each stage was grounded in iterative making and hands-on material experimentation. For example, I developed multiple physical prototypes to test different hair-like materials, slit layer designs, and actuation setups. The insights gained from these tests did not only validate technical feasibility but also generated new understanding about the tactile qualities and emotional expressiveness of the texture changes.

Finally, elements of Material-Driven Design informed parts of the process. Especially during the evaluation phase, the Material Experience framework guided how I assessed the material sample.

By combining these three methodological lenses, the project balanced structured exploration, iterative prototyping, and sensory-driven reflection to arrive at a feasible, emotionally expressive texture-changing mechanism suitable for wearable applications.

2.1 Process Diagram

The design process for this project is structured using the Double Diamond framework, which clearly separates divergent and convergent activities to help navigate an open-ended research challenge.

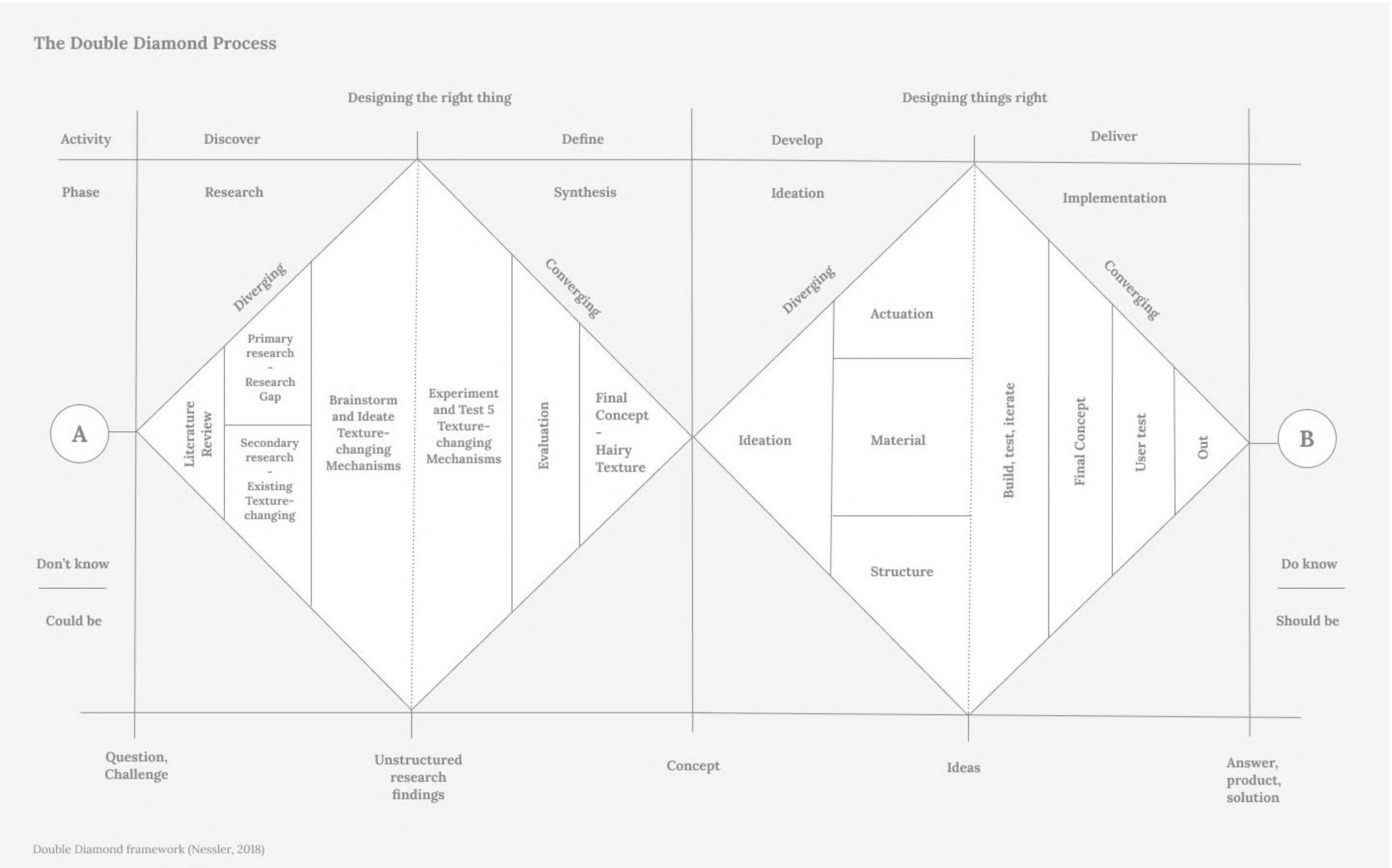
The initial research question addressed how a texture-changing wearable haptic skin can be designed to influence users' emotion and perception. To address this, the topic was explored from multiple perspectives through an extensive literature review, incorporating both primary and secondary research. This process identified a specific research gap: existing texture-changing interfaces frequently lack the combination of softness, thinness, high-resolution texture modulation, and emotional expressiveness necessary for wearable applications. Consequently, the research goal was defined as developing a feasible mechanism that fulfills these requirements and can be integrated into a wearable haptic interface.

Guided by this goal, the first divergent phase involved brainstorming and ideating various approaches to achieve texture change. Five initial concepts were generated and evaluated through experiments, material samples, and comparative analysis. A performance matrix with quantifiable criteria, including emotional difference, texture resolution, wearability, and fabrication ease, was applied to systematically compare the options. The Hairy Texture mechanism emerged as the most promising concept.

The second phase focused on further developing the selected direction. Additional divergent exploration addressed practical realization of the Hairy Texture mechanism, including identification of suitable actuation principles, selection of materials such as metal bristle fabric and slit layers, and prototyping of various structural configurations. Iterative fabrication, testing, and refinement led to convergence on a final design. The resulting functional prototype integrates a string-based pulling mechanism with a tube-guided shape memory alloy (SMA) system to enable programmable, repeatable texture change.

The working prototype was tested with users to evaluate its tactile performance and to identify potential applications. This process generated concrete design knowledge regarding the realization of a thin, flexible, and emotionally expressive texture-changing surface, thereby progressing from an initial open research question to a defined design solution.

Figure 3. Roadmap of Design Process (based on Double-Diamond)



Chapter 3

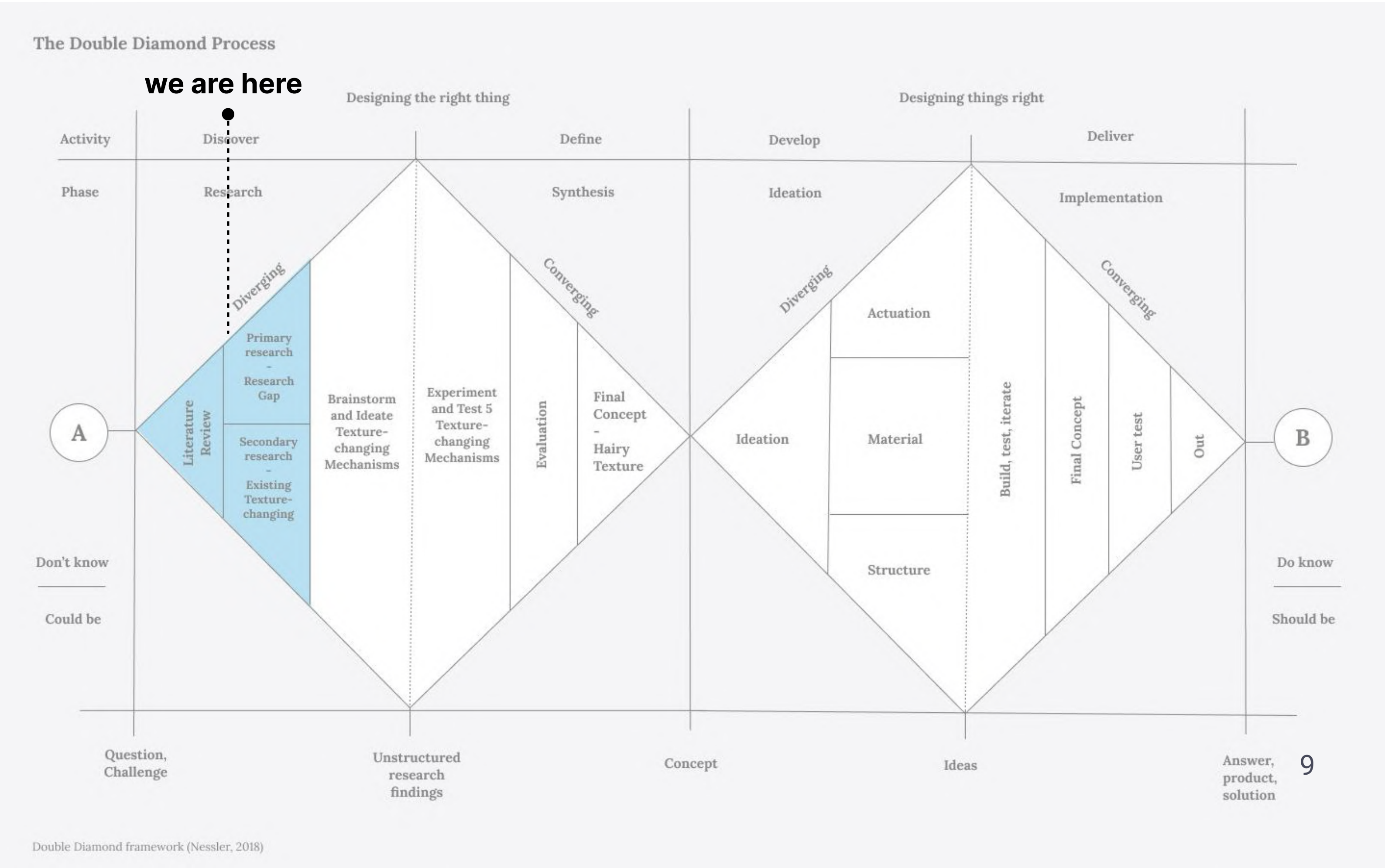
Literature Review

The interaction between users and surface textures has a significant influence on emotional and perceptual experiences. As wearable technologies evolve toward more sensory and affective forms of engagement, touch offers new potential for emotionally expressive, embodied interaction.

However, current approaches to haptic design remain limited in their ability to replicate the richness, subtlety, and responsiveness of natural textures. Many wearable systems rely on static materials or simple vibration feedback, which constrain the depth of tactile communication and overlook the expressive capacity of morphing surfaces.

The literature reviewed here lays the conceptual and technical foundation for the design and development phase of this project.

Figure 4. Roadmap of Design Process (based on Double-Diamond)



3.1 Tactile Interaction in Wearables

The Trend Toward Sensory and Emotional Wearables

Wearable technology is increasingly moving beyond functional toward more multisensory and emotionally responsive experiences. Among the senses, touch opens up new design opportunities to mediate emotions Obrist et al. (2015). As tactile engagement deepens, emotional and psychological states are becoming core elements of what wearables are designed to recognize and support (Picard, 2009). Together, these developments reframe wearables as intimate interfaces for sensing, feeling, and expressing emotions.

3.2 Embodiment through Tactile Interaction

3.2.1 Intimacy of Wearable Contact

Wearable devices maintain continuous contact with the body, in contrast to handheld devices that require active manipulation. Gemperle et al. (2001) note that tactile interfaces are particularly significant for wearables due to their proximity to the skin, which contains approximately 1.86 square meters of touch receptors. This physical closeness positions tactile interactions as a central aspect of the wearable experience. Consequently, tactile displays provide an effective means for wearables to facilitate interaction during routine bodily movement.

3.2.2 From Sensing to Meaning-Making

Tactile interaction in wearables is a sustained bodily dialogue, grounded in embodied engagement with the material environment. It shapes meaning, behavior, and emotional resonance as the body continuously coordinates with material feedback. As Fernandino et al. (2016) observe, the human haptic system enables us to sense not just the presence of surfaces or materials, but also to act through them. This coupling of sensation and movement forms one of the primary ways in which bodily engagement occurs.

3.2.3 Bodily Dialogues with Materials

Tactile interaction in wearables comprises a dynamic sequence of motion, including bodily movement, adjustment, and response (Biswas & Visell, 2021). When users interact with materials by pressing, releasing, or tracing along surfaces, they engage in an ongoing exchange rather than merely sensing static properties. This dynamic interaction is fundamental to the wearable experience, although it frequently remains unrecognized.

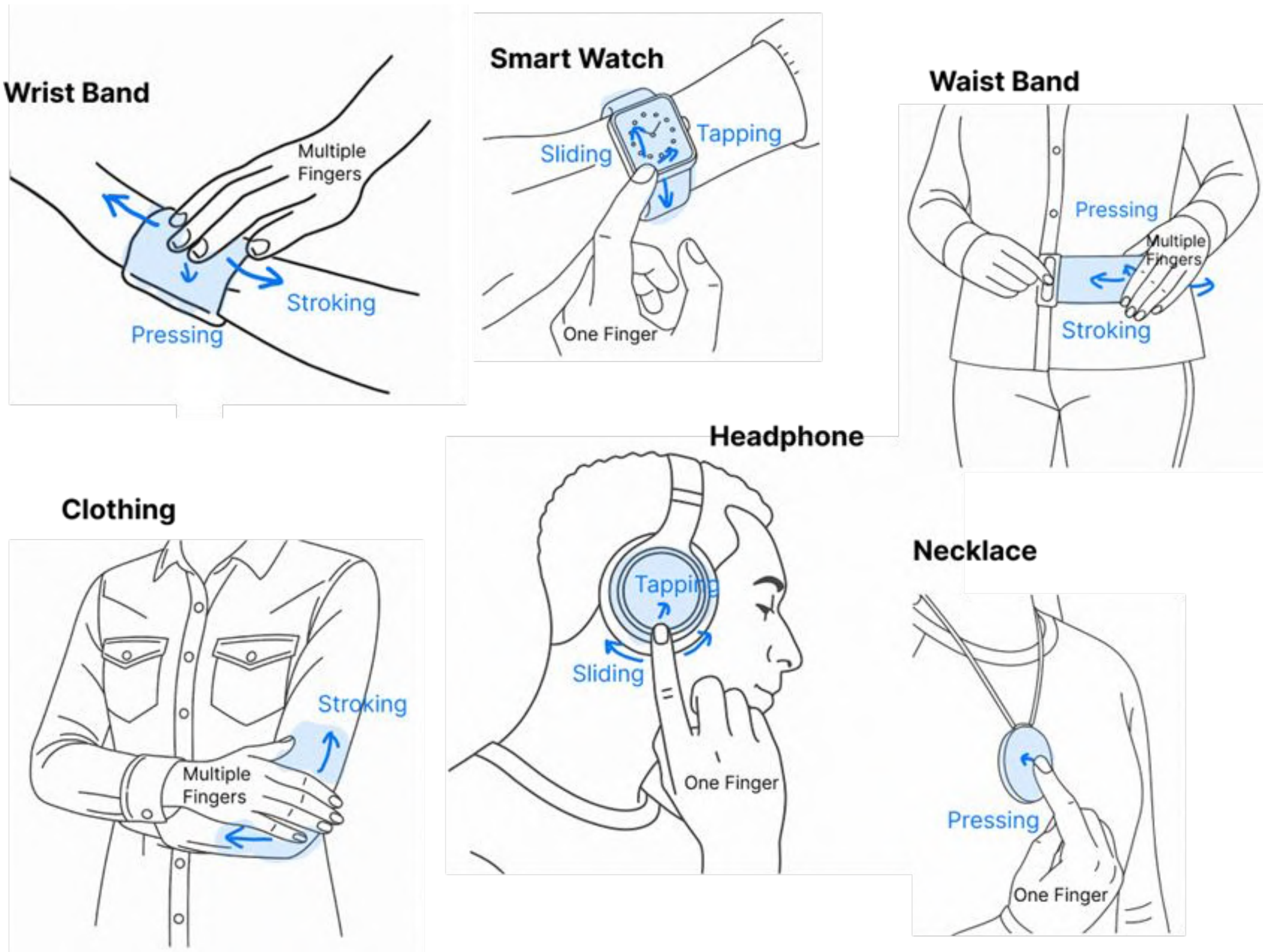


Figure 5. Analysis of interaction movements in the wearable context

For instance, Winters et al. (2022) explored this mutual exchange process through shape-shifting textiles that modulate their structure in response to touch. Participants interacted by stretching, pulling, and releasing fabric elements, prompting rhythmic changes in tension and form. These cycles guided attention and bodily adaptation, illustrating how material responsiveness can anchor perception–action loops. In such loops, material resistance becomes an expressive force that shapes the user's bodily behavior and perceptual field. The body does not just feel—it thinks through touch. What if the material is not just sensed—it responds, participates, and contributes?

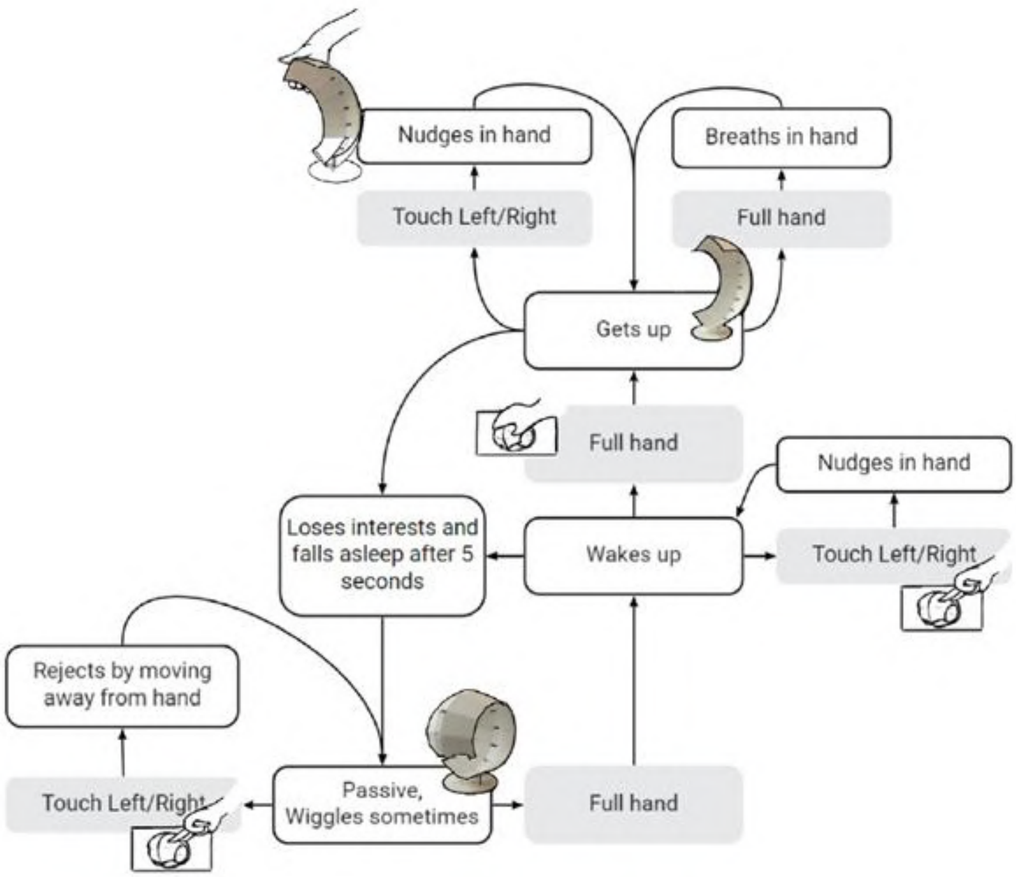


Figure 6. Perception action loop (Winters et al., 2022)

3.2.4 Emotion Through Embodied Interaction

This coordination between material and touch reflects what Dourish (2001) defines as embodied interaction: a process where meaning takes shape through situated, physical engagement. In this view, human touch and material feedback manifest meanings and interpretations through performing together.

Tactile interaction, in this light, becomes a participatory medium for interpretation. Meaning unfolds through movement, resistance, and material response. A texture that tightens, a surface that yields can each carry affective tone.

In the context of wearables, tactile interaction offers a uniquely intimate setting for embodied sense-making. The skin-level proximity and dynamic responsiveness of materials position wearables as expressive partners in bodily communication. Through texture, pressure, and movement, they carry not only information, but lived emotional experience.

3.2.5 Lack of Material Embodiment in Current Wearables

However, traditional wearable interactions are predominantly shaped by graphical user interfaces (GUIs) or vibration-based feedback, which tend to prioritize information clarity over mutual embodied engagement. These systems are effective in delivering information, but often overlook how materials contribute to shaping interaction through tactile engagement and bodily coordination. As Kwon et al. (2014) point out, "flat and rigid computer screens display highly vivid superficial objects; however, they lack the haptic sense of texture, temperature, and weight—materiality".

Materiality is not an optional aesthetic layer but a fundamental component through which bodily meaning is enacted. It gives physical presence to perception, allowing thoughts, emotions, and interactions to become tangible through touch. (Schroepfer, 2011). In the context of wearables, it is part of how emotion is felt and co-constructed

However, most existing wearable material properties remain static, predefined, and limited in their ability to modulate this tactile exchange. This absence of dynamic material properties in current wearable interfaces limits the user's opportunity to establish a sensory dialogue between body and touch.

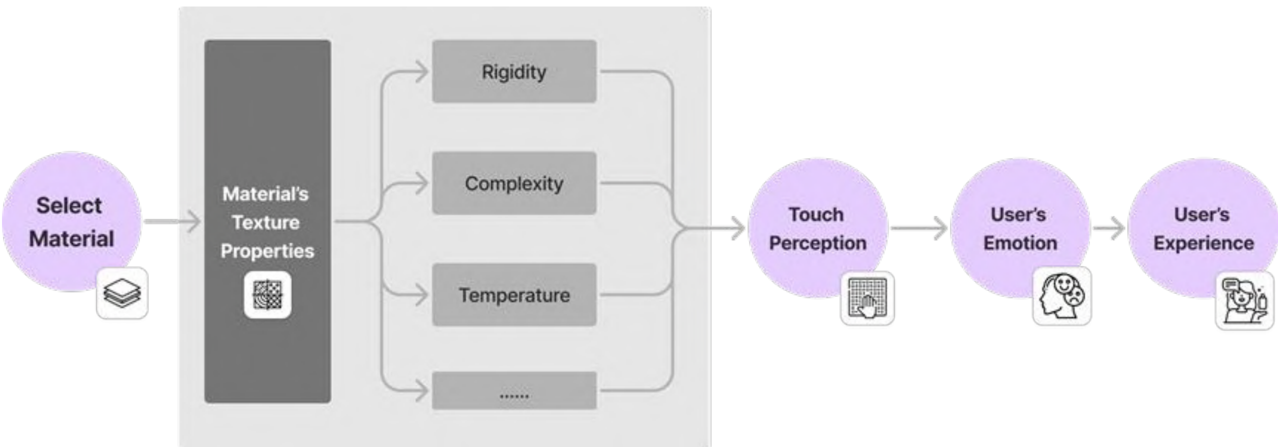


Figure 7. Current one-way process of texture's influence on perception and emotion

To realize the potential of wearables as embodied, emotional interfaces, materials with adaptable tactile qualities are required. Responsive materials enable wearables to engage users through dynamic and expressive tactile interactions, rather than functioning solely as data terminals attached to the body.

This highlights the need to move beyond GUI paradigms toward an approach that treats tactility of material as a communicative, affective element of design.

3.3 Haptic Interaction in Wearables

Haptic perception enables people to sense and interpret information through touch, and it can generally be categorized into cutaneous (surface-level) and kinesthetic (force and movement) modalities. These can each be explored through either active or passive modes, depending on whether the user initiates the movement or the device provides the motion.(Rodríguez et al., 2019)

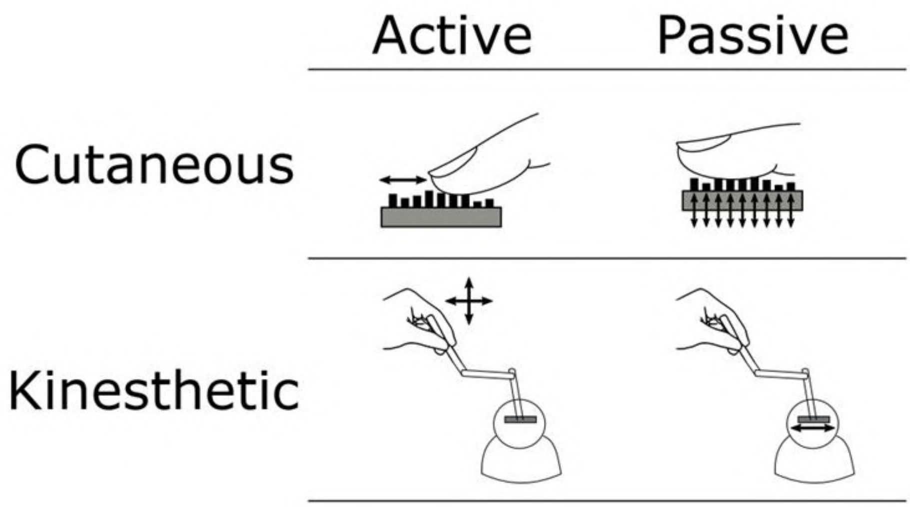


Figure 8. Classification of haptic interaction according to the exploration modality: cutaneous active, cutaneous passive, kinesthetic active, and kinesthetic passive.(Rodríguez et al., 2019)

Texture, as a material property, is inherently passive. It conveys information to be perceived by active touch through movement. However, in wearable contexts, this dynamic may shift when a tactile interface remains in continuous contact with the skin, the perception can become passive, with the user receiving information without deliberate movement. As Rodríguez et al. (2019) note, wearable tactile devices are classic examples of cutaneous passive haptics because they “are in permanent contact with the skin.”
This research primarily examines cutaneous active haptics, which encourage users to actively explore and perceive dynamically changing surface textures. Integrating programmable materials that transform in real time aims to enhance the ways individuals sense, interpret, and emotionally respond to touch.
At the same time, because the device remains in continuous contact, it naturally supports passive cutaneous feedback when the user is not intentionally moving. This hybrid approach brings together the expressiveness of active exploration with the subtle ambient quality of continuous passive touch in wearable systems.

3.4 Texture as Affective Medium in Wearables

Texture, a key quality in material, plays a unique but often underestimated role in wearable interaction. Touching the surface texture is one of the most naturally inviting forms of interaction when first encounter a product. It functions not just as a material finish, but as a sensorial and emotional medium. When running a hand across a surface, the texture communicates subtle emotional and sensory cues.

Previous studies have underscored the critical role of texture in shaping both perceptual and emotional responses. Zuo et al. (2016) highlighted how textures elicit specific emotional reactions, such as a feeling of security with rough, non-slip surfaces or the sense of premium quality evoked by fine, smooth textures. Similarly, Şener and Pedgley (2021) emphasize how tactile attributes influence user satisfaction and hedonic experience.

Texture emerges as a dynamic, co-constitutive medium of embodied interaction. The skin maintains friction, pressure, and thermal exchange with surfaces through bodily movements. Texture guides how users orient themselves physically and emotionally in interaction. It enables a tactile relationship through which the body co-negotiates meaning with material properties over time.

3.4.1 Analysis of Texture in Current Wearables

Despite this potential, most current wearable designs treat texture as a static and functional quality. To examine this limitation, an analysis of contemporary wearable products was conducted, categorizing their tactile texture strategies into three dominant types: Passive Commercial Wearables, Skin Adhesive Wearables, and Textile-based Wearables.

	Passive Commercial Wearables	**Skin Adhesive Wearables**	**Textile-based Wearables**
Material	Plastic, Metal, Glass, Silicone	Silicone, Gel, PU film	Fabric, Conductive yarn
Tactile Feeling	Uniform, smooth, cold	Soft and skin-like	Textured weaves, ridges, and seams
Interaction Quality	Interaction is mainly visual or functional, lacks material interaction	Mainly used as sensors therefore lacks tactile affordance	Invites touch exploration, but lacks responsiveness or expressiveness

Figure 9. Texture characteristics in contemporary wearable devices

Across these categories, a common trend emerges: texture is present, yet remains static, offering little responsiveness or capacity to support tactile communication.

Passive commercial wearables, such as GUI-based smartwatches and fitness bands, typically feature flat plastic or glass surfaces. These designs prioritize visual information but provide minimal surface variation. Skin adhesive wearables like bio-sensors are designed primarily for data collection. Therefore, users rarely touch them directly, so their material presence is treated as invisible rather than expressive. Textile wearables incorporate soft fabrics that feel pleasant against the skin, but their material texture properties are usually fixed and not designed to respond or adapt.

3.4.2 Towards Participatory Material Engagement: Dynamic Texture as Expressive Surface

This gap reveals the need for a new design approach—one that recognizes texture not as a fixed quality, but as an interactive and expressive surface. Dynamic textures can shift in response to bodily movement, emotion, or context, turning the surface of a device into an active co-performer in interaction. However, as of now, no mainstream wearable systems utilize texture modulation to enable affective communication.

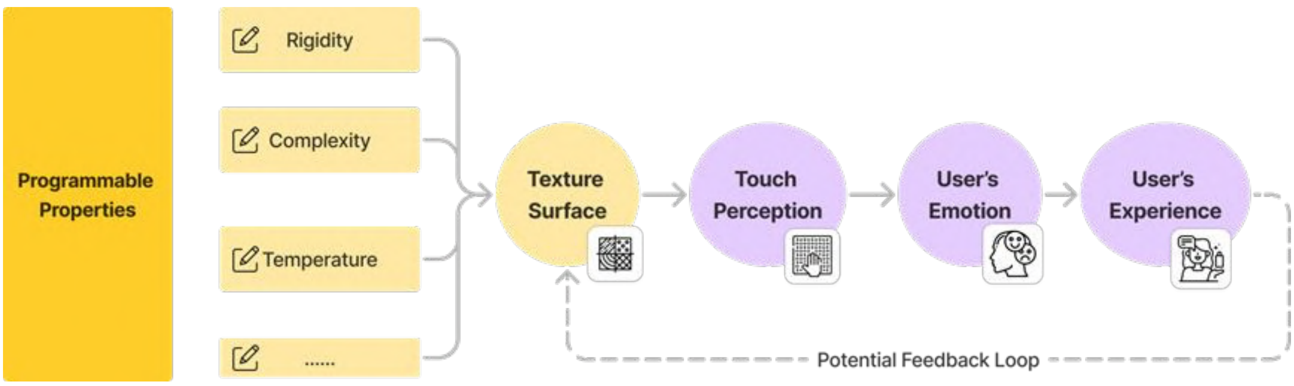


Figure 10. Proposed model of texture-driven emotional interaction in wearables

Bridging this gap requires the development of texture-changing materials capable of modulating their tactile qualities. Exploring such surfaces can make materials more expressive and responsive. By shifting texture in response to bodily interaction and user experience, these materials facilitate mutual engagement and shape how sensations and emotions are perceived, interpreted, and shared.

3.5 Case Studies on Existing Texture changing Methods

3.5.1 Morphing Materials for Tactile Interaction

Morphing materials, capable of dynamically altering their form, have shown significant potential in designing responsive interfaces. There are existing technologies that utilize morphing materials to achieve tactile feedback, moving beyond traditional vibration-based systems to explore alternatives such as shape memory alloys (SMAs) and pneumatics. Hamdan et al. (2019) introduced SMA springs embedded in skin membranes that enable localized shape changes, mimicking sensations like bumps or squeezing. Foo et al. (2019) developed SMA-based garments, such as hug vests, which provide dynamic compression to simulate hugging. Pneumatic systems, such as those designed by Vaucelle et al. (2009), utilize inflatable chambers to create distributed pressure sensations like squeezing or, even hurting feeling if the surface is attached with “teeth”. However, these systems are often bulky, slow, and require external components, making them unsuitable for lightweight and portable applications. Additionally, these technologies primarily focus on large-scale shape changes and are therefore often applied to larger skin surfaces. The potential of morphing materials for fine, micro-scale texture changes, crucial for high-sensitivity areas like fingertips, remains underexplored in research.

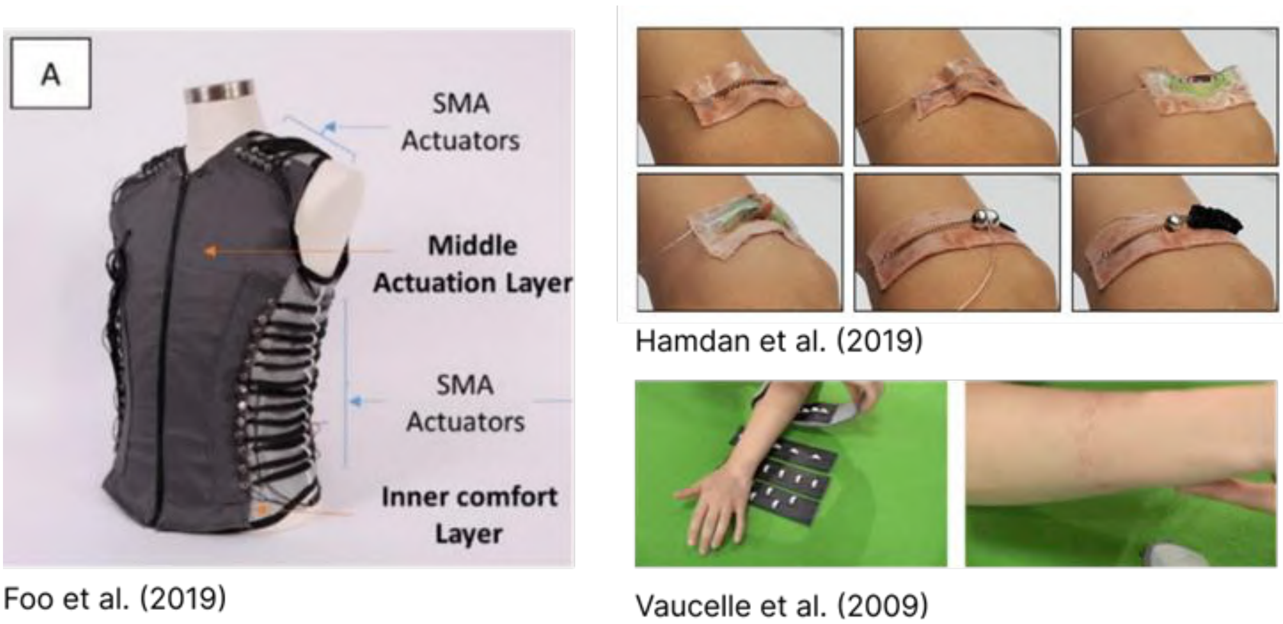


Figure 11. Shape-changing with morphing materials

These limitations highlight a clear research gap: the need for lightweight haptic systems capable of dynamically altering fine surface textures to deliver adaptive and responsive tactile experiences.

3.5.2 Existing Texture-changing Methods

To understand the state of the art of morphing material used in texture-changing interfaces, I analyzed a range of existing technologies described in academic papers. These technologies employ various actuators, such as pneumatics, shape memory alloys (SMAs), electromagnetics, and motorized systems. To systematically evaluate these systems, I mapped their capabilities to Djonov and Van Leeuwen (2011)'s framework, which defines tactile qualities such as temperature, liquidity, viscosity, rigidity, density, relief and complexity. (Seaborn, 2012)

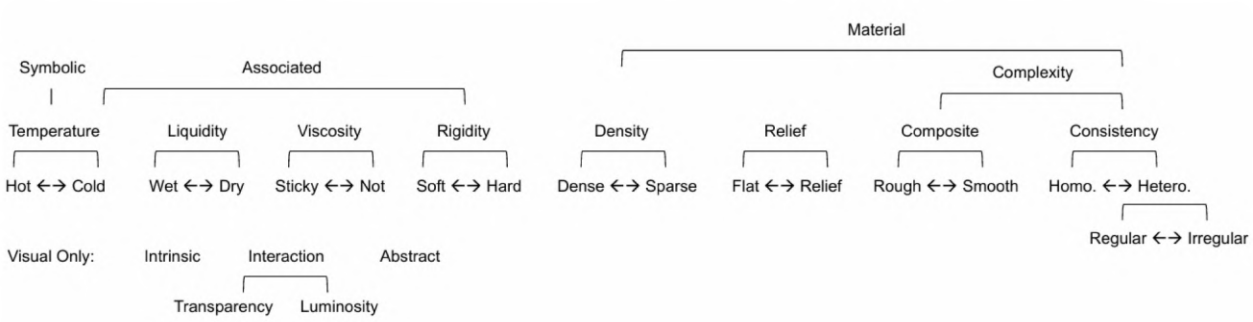


Figure 12. Framework adapted from Djonov and Van Leeuwen's outline of texture qualities (Seaborn, 2012)

Categorized by actuator type, each texture-changing interface paper was matched with the specific texture qualities it manipulates, as illustrated in the following figures. This approach allows for a structured understanding of how different technologies address specific tactile qualities and where opportunities for further innovation exist.

To evaluate the texture resolution of each design, we estimated the number of distinct texture units present within a 10 cm × 10 cm area. This estimation was based on the dimensions and spacing information provided in each paper. By comparing these values, we aim to highlight differences in tactile resolution across actuator types and identify areas for potential innovation.

3.5.2.1 Pneumatic

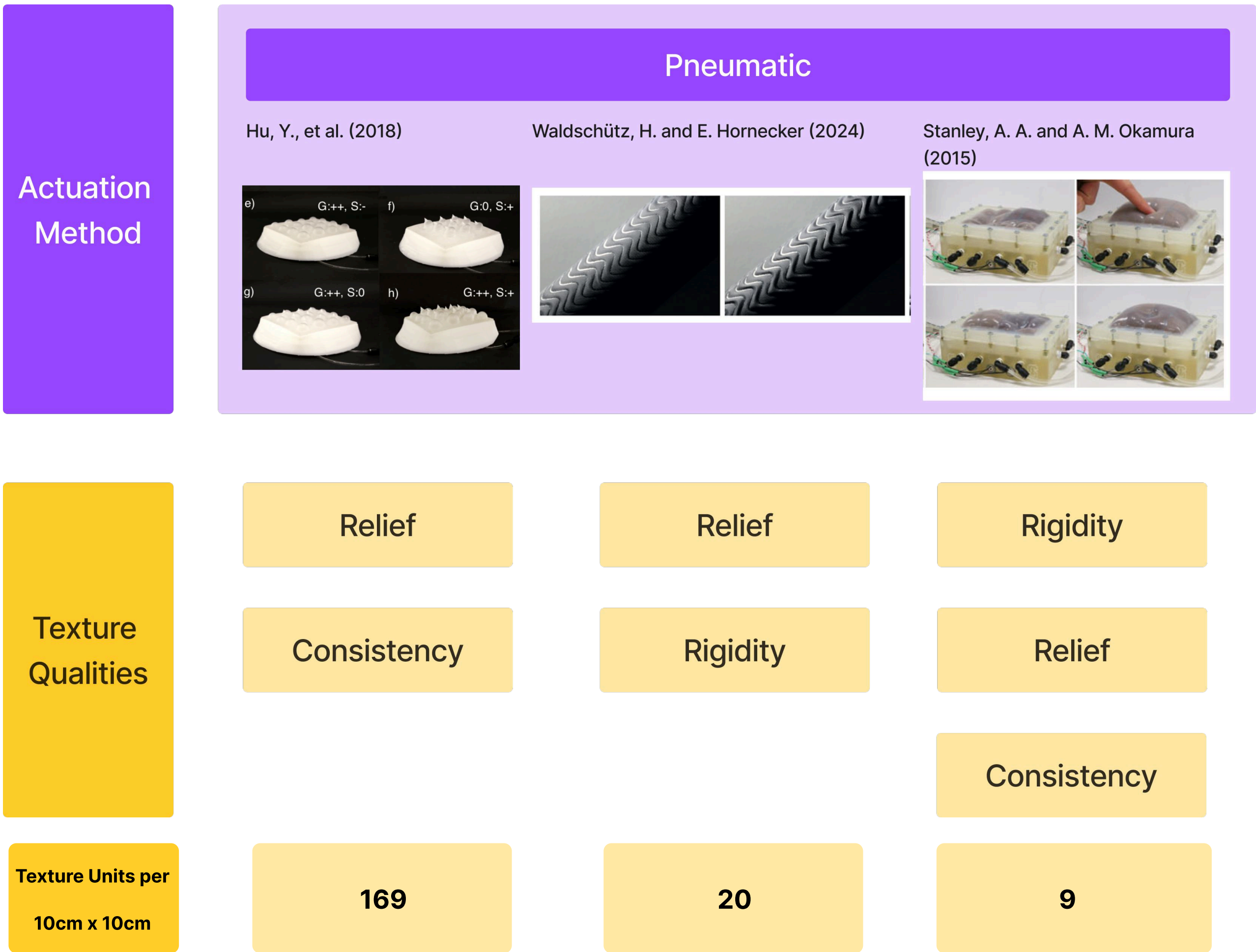


Figure 13. Mapping pneumatic actuated texture-changing interfaces to their manipulated texture qualities

Pneumatics offer advantages like softness and flexibility, making them suitable for creating textures that feel natural and dynamic.

Figure 8. Social Robot that use texture changing to express emotions (Hu & Hoffman, 2019)

Hu and Hoffman (2019) explored the emotional expressiveness of pneumatic textures in social robots by actuating goosebumps and spikes on a robot's skin. These textures were controlled by varying pressure in fluidic chambers, manipulating relief (raised or flat surfaces) and consistency (smooth or sharp textures). Goosebumps were found to convey positive emotions, while spikes evoked negative valence, highlighting the potential of texture changes to communicate emotions effectively through touch. (Hu et al., 2018)

Figure 10. Different Patterns of Inflatable Texture (Waldschütz & Hornecker, 2024)

Waldschütz and Hornecker (2024) introduced "Inflatable Textures," heat-welded pneumatic channels into TPU-coated Nylon to create tactile surfaces with adjustable ridges. By independently controlling these channels, the system modulated relief (ridge height and density) and rigidity (soft to firm textures).

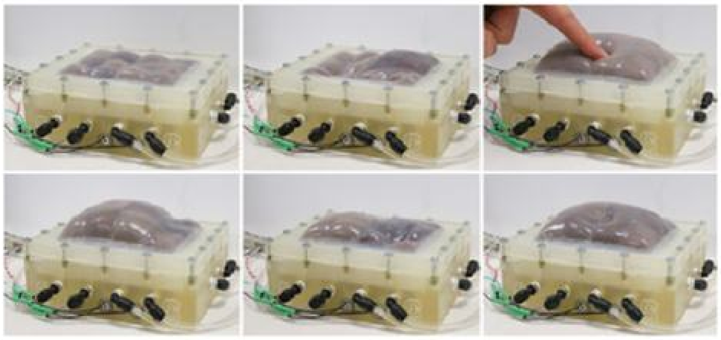


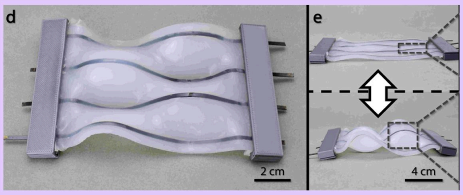
Figure 14. Particle jamming pneumatic interface (Stanley & Okamura, 2015)

Stanley and Okamura (2015) use the mechanism of particle jamming with pneumatics to enable simultaneous control of surface rigidity and shape. Silicone cells filled with granular material were selectively vacuumed to adjust rigidity (soft to stiff states), while pneumatic inflation modulated relief (complex shapes and patterns).

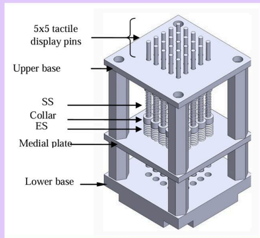
3.5.2.2 Shape Memory Alloy

Shape Memory Alloy (SMA)

Carvajal Loaiza, M. J., et al. (2024)



Mansour, N. A., et al. (2012)



	Carvajal Loaiza, M. J., et al. (2024)	Mansour, N. A., et al. (2012)
Texture Qualities	Relief	Rigidity
	Consistency	Relief
		Consistency
Texture Units per 10cm x 10cm	**6**	**400**

Figure 15. Mapping SMA actuated texture-changing interfaces to their manipulated texture qualities

Shape Memory Alloys (SMAs) enable dynamic and responsive textures through reversible phase changes. Carvajal Loaiza et al. (2024) developed a morphing surface using NiTi SMA wires embedded in silicone, designed to transition between flat and raised shapes in response to heat or electrical current.

Mansour et al. (2012) applied SMA technology in a tactile display for biomedical applications, allowing users to experience both the shape and stiffness of human organs. The device used SMA-actuated pins to adjust relief and consistency (creating surface contours), rigidity (varying softness and hardness). This system provided sophisticated tactile experience, simulating biological textures like soft tissue and abscesses. However, the complex and rigid structure of the system makes it difficult to adhere to product surface.

3.5.2.3 Electromagnetic

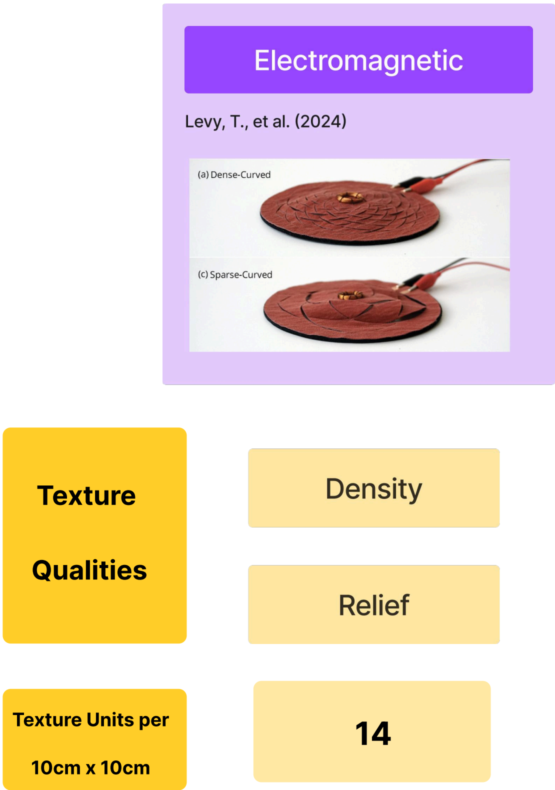


Figure 16. Mapping electromagnetic actuated texture-changing interfaces to their manipulated texture qualities

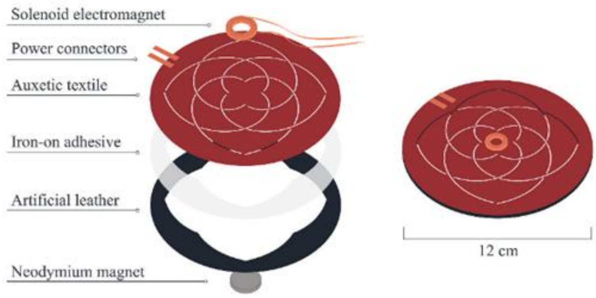


Figure 17. Structure of the morphing metamaterial (Levy et al., 2024)

Electromagnetic actuators are compact, lightweight, and suitable for integration into thin materials. One study demonstrated the use of embedded wires and magnets within fabric to create metamaterials, enabling lifting and shape transformation through laser-cut auxetic patterns (Levy et al., 2024). However, the solenoid system tends to overheat during continuous operation, which might limit its use for sustained shape change in wearable applications.

The research focused on two key parameters of texture patterns: Density (dense vs. sparse) and Geometry (curved vs. angular). Results showed that texture patterns significantly influence emotional responses. Dense and curved designs evoke positive emotions like calmness and happiness. In contrast, sparse and angular patterns are associated with negative emotions such as unease and distress. Therefore, the pattern of texture should be carefully considered regarding the emotion influence.

3.5.2.4 Motor

Figure 18. Mapping motor-actuated texture-changing interfaces to their manipulated texture qualities

Motor-driven texture-changing interfaces stand out for their innovative structures, which offer valuable inspiration for programmable textures. For example, origami-inspired designs, like the ex-CHOCHIN system, demonstrate how folding mechanisms can dynamically alter texture depth. (Ohira et al., 2022)

Similarly, pin-based systems, such as the Relief display, use motorized pins covered with materials like Lycra to create smooth, continuous surfaces. The Lycra covering not only hides the mechanical structure but also allows the pins to form cohesive, natural-feeling textures. (Leithinger & Ishii, 2010)

3.5.3 Reflection on Case Studies

Most texture-changing interfaces using morphing materials achieve transformation by altering relief and rigidity. The relief-based approach, where patterns are raised or altered on the surface, has been shown to influence emotional responses in studies by Hu and Hoffman (2019) and Levy et al. (2024). This suggests that exploring and adopting similar approaches to modify users' emotional perceptions of products is a promising direction.

Most texture-changing interfaces focus on creating one specific texture pattern or shape, often toggling between the presence and absence of one texture (e.g., Waldschütz & Hornecker, 2024; Carvajal Loaiza et al., 2024; Levy et al., 2024; Ohira et al., 2022). These systems typically embed a single pattern into the structure, which is then revealed or actuated by the mechanism. For instance, Levy used an auxetic structure, while Ohira employed origami tessellations. Exploring more unique structural designs like origami could unlock new possibilities for texture modulation.

An alternative approach involves systems that create multiple individually controllable units. Each capable of being adjusted to form various textures. This method, seen in the works of Stanley and Okamura (2015), Mansour et al. (2012), and Leithinger and Ishii (2010), offers greater flexibility and diversity in texture creation. However, it also demands more sophisticated and precise control systems, which can significantly increase complexity and cost.

While the case studies demonstrate innovative approaches to texture modulation, they also reveal key limitations when considered in the context of wearable interaction. Many prototypes are too rigid or bulky to be comfortably worn on the body. Their structures are often mechanically complex, and the materials lack the flexibility required to conform to the curved, moving surfaces of human skin. Others offer very coarse or low-resolution textural feedback, generating only basic geometric transformations such as spikes, folds, or inflating bumps. These limitations prevent them from supporting nuanced tactile variation.

In case of texture resolution, While a few systems—such as Mansour et al. (2012) with 400 units/10cm² and Hu et al. (2018) with 169 units/10cm²—demonstrate high tactile resolution, the majority of texture-changing interfaces remain relatively low-resolution, often offering fewer than 20 units per 10cm². Examples include Stanley and Okamura (2015), Levy et al. (2024), and Ohira et al. (2022), whose designs prioritize mechanical transformation over spatial density.

This limitation becomes particularly critical in wearable contexts, where human skin is highly sensitive to fine-grained tactile variations. A low-resolution texture field is often insufficient to convey nuanced sensations or evoke meaningful emotional responses through touch. Therefore, future research should prioritize high-resolution, body-conformable tactile displays that better match the perceptual capabilities of the skin, enabling richer and more expressive interactions.

These technical constraints highlight a key gap: current systems struggle to provide soft, thin, high-resolution, and emotionally expressive textures suitable for wearables.

A suitable mechanism for texture-changing must meet several criteria. The material should be flexible and thin enough for seamless integration into garments or skin-worn surfaces. The system must support high-resolution texture modulation and allow for straightforward fabrication and programmability, enabling efficient prototyping of diverse tactile experiences. Additionally, it should possess emotional communicative potential to influence users' affective states through touch. These requirements inform the criteria for the subsequent stage of design research.

Summary

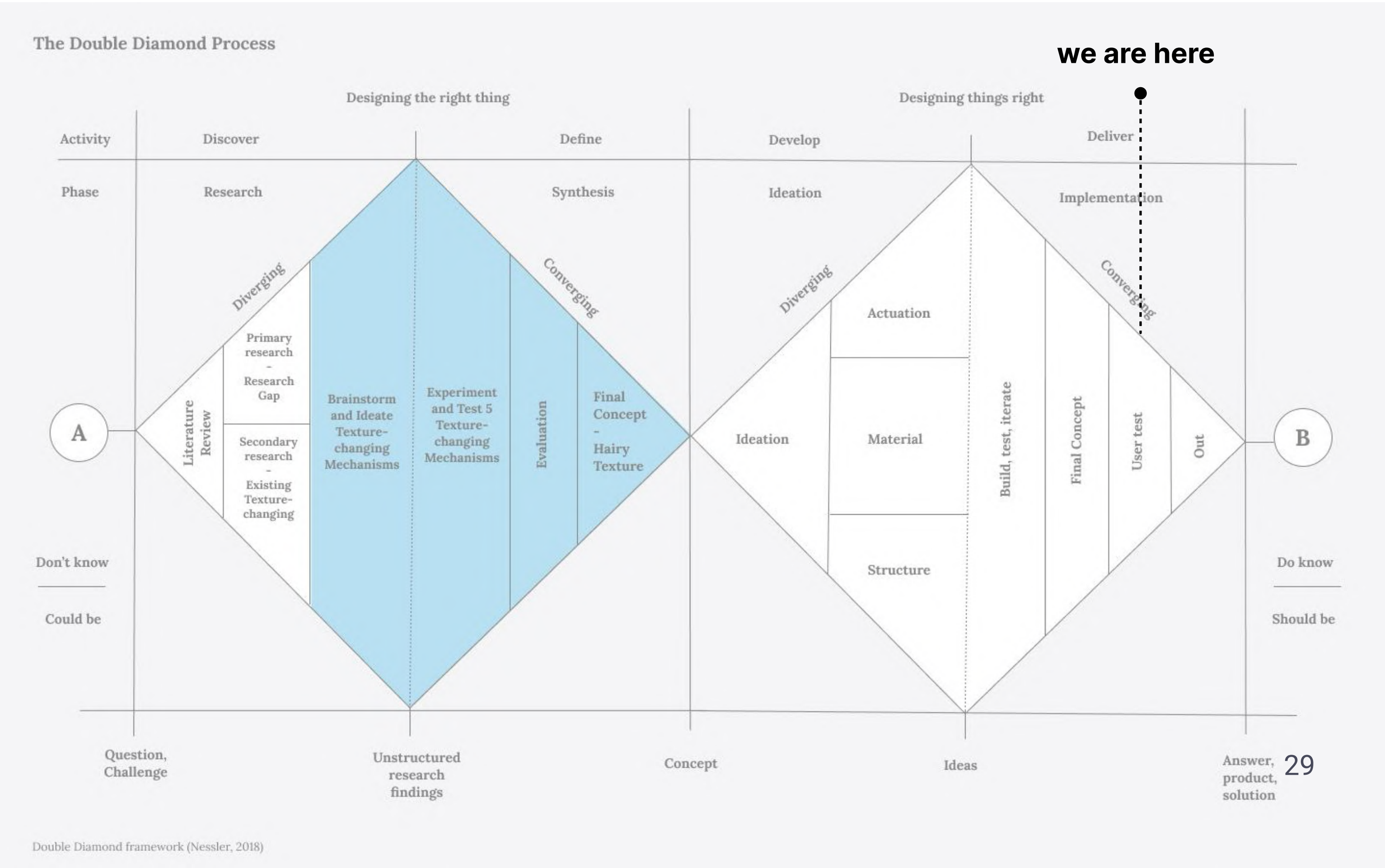
This chapter reviewed tactile interaction and texture in wearable devices, showing that current systems remain dominated by static materials or low-resolution transformations, offering limited bodily engagement. Texture, however, is not merely a surface finish but a sensory and emotional medium. While existing approaches demonstrate potential, they fall short in flexibility, wearability, and resolution. Future research should therefore pursue thin, flexible, high-resolution, and programmable textures that enable wearables to act as intimate tactile media for embodied and emotional communication.

Chapter 4

Exploration 1: Texture-Changing Mechanism

This chapter explores a range of mechanisms for realizing texture-changing surfaces, with the aim of identifying a feasible approach for wearable haptic applications. Building on the research gaps highlighted in the literature review, five directions were developed and tested: Hairy Texture (lateral shifting), Hairy Texture (vertical exposure), Embedded Fiber in Pneumatic Silicone, Vacuum-driven Origami, and Fabric/Knitting Structures. The following sections provide an overview of each method and introduce a performance matrix framework for comparing their strengths and limitations, ultimately leading to the convergence on the most promising concept for further development.

Figure 19. Roadmap of design process (based on Double-Diamond)



4.1 Overview of Explored Methods

This project seeks to develop a texture-changing mechanism that is soft, thin, high-resolution, emotionally expressive, and suitable for wearable applications, addressing gaps identified in the literature review. Five concept directions were generated and prototyped to meet these requirements: Hairy Texture (lateral shifting), Hairy Texture (vertical exposure), Embedded Fiber in Pneumatic Silicone, Vacuum-driven Origami, and Fabric/Knitting Structures. Each method employs distinct principles and material systems to achieve dynamic surface transformations.

Small-scale experiments, material tests, and technical studies were conducted to evaluate each concept's ability to produce distinct tactile differences and emotional expressiveness, while also considering flexibility, thinness, and fabrication feasibility. The following sections provide an overview of the explored methods and a performance-based comparison between them.

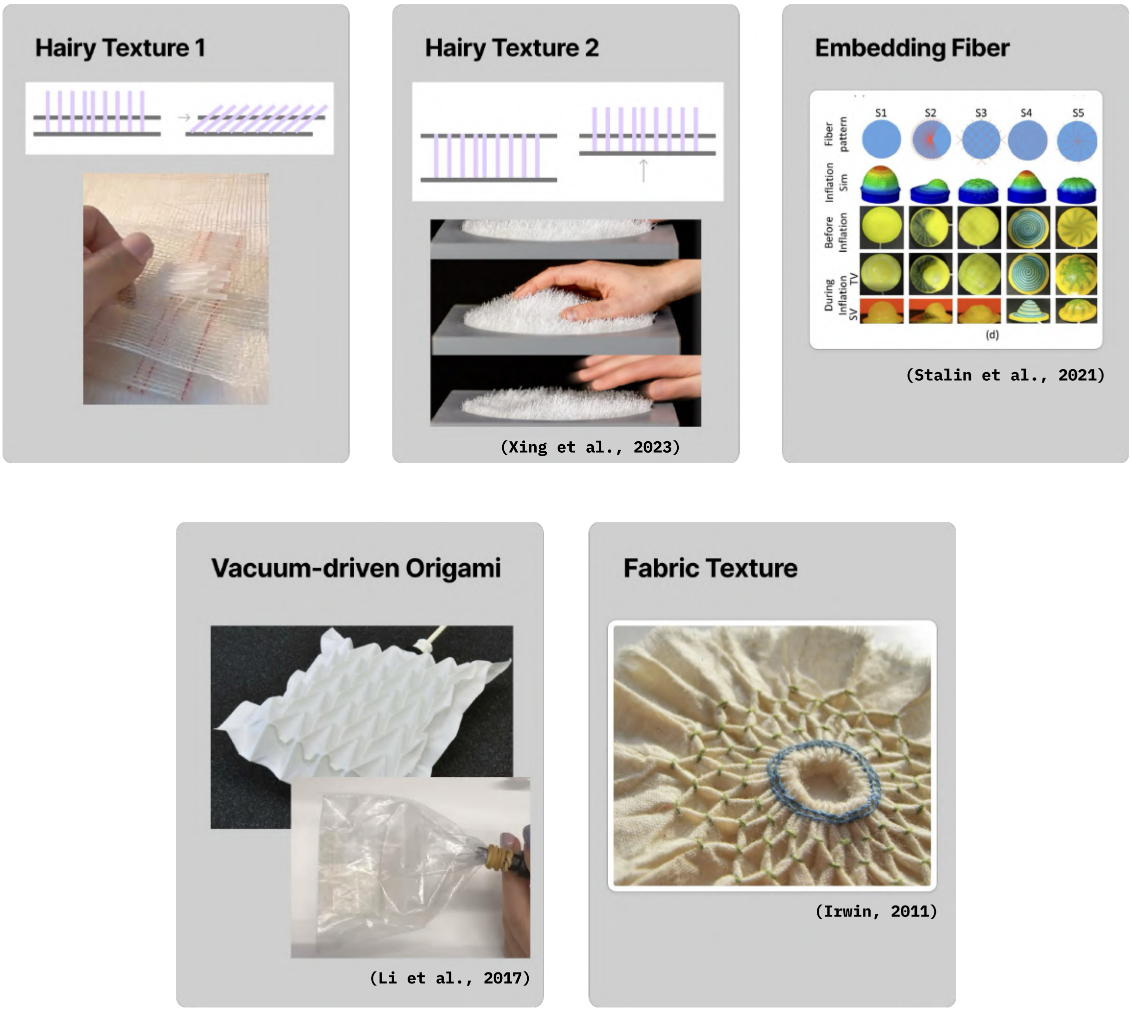


Figure 20. Five texture-changing concepts

4.1.1 Hairy Texture

4.1.1.1 Hairy Texture 1

The initial exploration focused on a hairy texture mechanism inspired by the visual and tactile changes observed in animal fur during various emotional states. For example, a cat's fur stands on end to signal alertness or fear.

The mechanism consists of a double-layer structure: a layer of flexible hairs (thin, hair-like filaments) anchored through a grid-like mesh (a network of interwoven flexible material). By sliding the position of the upper mesh layer relative to the base, the direction and orientation of the hairs can be altered. This allows the surface to switch between a fluffy texture to a flat, smooth one.

Figure 21. Hairy texture 1 (Lateral Shift)

Different materials were tested, including banana fiber, mesh fabrics, and various bristle types. In one experiment, a mesh was placed over a toothbrush-like surface to observe how lateral shifts could control the bristles underneath. The results demonstrated that the concept could change the tactile feel from fluffy to flat. However, two main constraints emerged. First, the grid layer must be sufficiently rigid to pull or hold the bristles; without adequate structural stability, the mesh deforms and loses control. Second, conventional bristle bundles with many fibers are vertically implanted into a single hole, which limits their ability to bend sideways or rotate reliably.

Figure 22. Toothbrush test

Another test fixed zip ties onto a bamboo fiber grid to assess whether their rotational flexibility could facilitate the transition from flat to upright texture. This confirmed the mechanism's basic functionality but revealed practical issues. Manual attachment of each zip tie is labor-intensive, and the resolution remains low. Identifying a suitable ready-made material is therefore necessary.

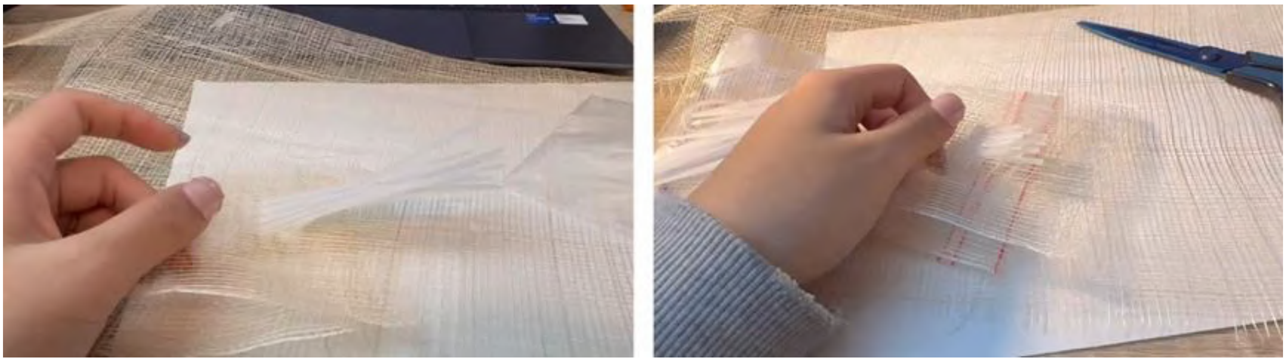


Figure 23. Zip-tie and grid test

In summary, this method demonstrated promising potential for modulating texture in an intuitive, bio-inspired way. However, the tests highlighted the need for careful structural design and material selection to ensure consistent, controllable transformations.

4.1.1.2 Hairy Texture 2

In addition to the sliding mechanism, another concept related to Hairy Texture was explored. This variant uses the same double-layer structure but relies on a vertical shifting principle. The top layer contains a grid of slits or holes, while the bottom layer holds flexible spikes or hairs that can pass through these openings. Moving the top layer up and down changes the amount of exposed hair, shifting the perceived texture from smooth to spiky.

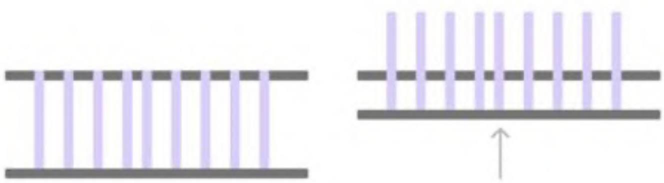


Figure 24. Hairy texture 2 (vertical movement)

This concept was inspired in part by pet brushes, which often feature retractable needle bristles beneath a sliding plastic plate. This mechanism enables rapid transitions between flat and protruding textures with minimal displacement.

4.1.2 Embedded Fiber in Pneumatic Silicone

Another explored mechanism involves embedding low-stretch fibers within a flexible pneumatic silicone structure. This approach takes inspiration from natural tissues, which can locally restrict or guide expansion. By embedding fibers or patterned elastomeric inserts into a stretchable silicone matrix, local deformation can be programmed. When the structure is inflated, fiber-constrained areas expand less, while unconstrained regions bulge more. This creates controlled surface topologies that feel like distinct textures.

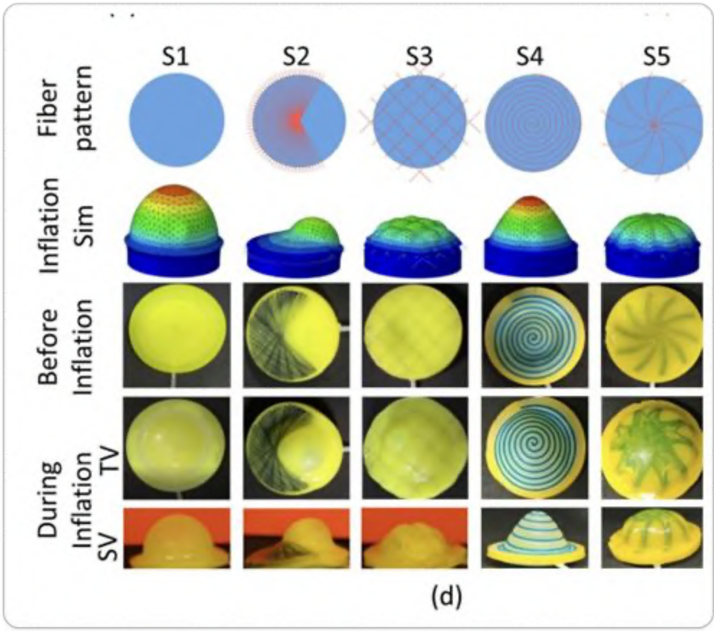


Figure 25. Embedding fiber in pneumatic silicone (Stalin et al., 2021)

The design draws on methods such as Automated Fiber Embedding and programmable texture voxels for stretchable morphing skins. These studies demonstrate that precise placement of fibers using techniques such as direct ink writing or laser-cut templates can influence the stiffness and bending properties of soft actuators. The present concept explores embedding fibers, ropes, or patterned elastomeric sheets into silicone chambers to achieve differentiated textures upon inflation. This principle allows for adjustable height variation and potentially high-resolution shape change.

4.1.3 Vacuum-driven Origami

The third method explores an origami-inspired pneumatic structure for texture changing. This mechanism combines a foldable origami skeleton with a flexible membrane that encloses the structure. When the internal air is evacuated, a negative pressure pulls the membrane tightly around the origami folds. This transforms an initially flat surface into a faceted texture, showing the creases and edges of the origami pattern.

This concept builds on studies of vacuum-driven origami actuators (Li et al.; Li et al., 2017). Inspired by origami designs such as Miura-ori, this mechanism drives the folding process by vacuuming air, creating dynamic surface features.

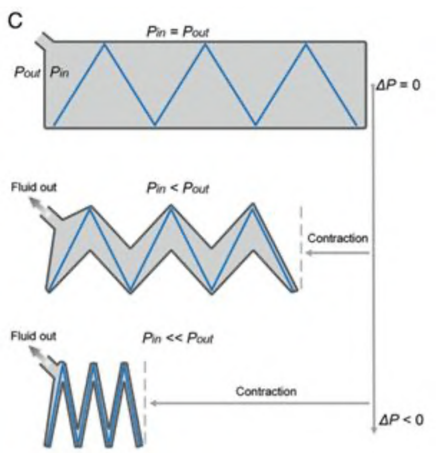


Figure 26. Vacuum-driven origami (Li et al.; Li et al., 2017)

Figure 27. Vacuum-driven origami test

Initial experiments tested this idea using a simple zigzag fold constructed from thin plastic sheet. The folded sheet was enclosed in an air-tight plastic bag connected to a tube. The outcomes demonstrated that applying vacuum results in distinct shape changes. These experiments indicated that the internal structure must have certain flexibility and stiffness to both deform and recover its shape.

A Miura-ori pattern was folded with paper to test finer textures. Achieving small, precise folds by hand proved difficult, which limited the texture's resolution. To address this, more advanced fabrication methods may be required. Possible approaches include casting silicone with embedded folds or 3D printing flexible materials such as thermoplastic polyurethane (TPU) to create an integrated origami structure.

Figure 28. Miura-ori origami test

The primary advantage of this method is its lightweight construction and capacity to achieve substantial shape changes with minimal input. However, maintaining vacuum pressure requires careful sealing. Precise fabrication of fold patterns is also necessary to ensure repeatable and reliable actuation.

4.1.4 Fabric/Knitting Structure

A fourth explored method uses fabric-based structures, such as knitting or weaving techniques. This concept benefits from the textile's internal structure. Embedded or inlaid tendons, shape-memory yarns, or elastic fibers can locally alter the fabric's shape. By integrating actuatable threads during fabrication, designers can induce programmed bending, gathering, or pleating.

This approach draws inspiration from traditional techniques like Canadian Smocking, which generates localized puckering and dimensional surface patterns. Recent work on machine knitting can embed horizontal and vertical tendons. This enables fabric to morph between flat and three-dimensional states when tension is applied.

This method provides high wearability and aesthetic, making it suitable for wearable haptic interfaces. However, achieving precise motion control could be challenging. The resolution is determined by the scale of the internal textile structure.

(Irwin, 2011)

(Albaugh et al., 2019)

Figure 29. Inspiration for textured textiles

4.2 Performance Matrix Comparison

To systematically select among the five proposed texture-changing mechanisms, a performance matrix approach was adopted, inspired by methods described in related design research (Wang & Chortos, 2024). This tool enables evaluation of each method based on criteria directly linked to the research goals and practical constraints.

The performance matrix was adapted to include five key dimensions relevant to this study: **Emotional Difference, Wearability, Texture Resolution, Thickness, and Ease of Making (Figure 30).** These criteria reflect both theoretical and practical considerations. Emotional Difference is crucial, as the design aims to influence the user's emotional state through tactile changes. Wearability assesses whether the mechanism can integrate into garments or skin-worn devices. Texture Resolution addresses the need to create fine, detailed tactile variations, which is a gap in prior work. Thickness pertains to creating a soft, thin interface that does not add bulk. Ease of Making considers that designers are the primary users, so the solution should be easy to prototype without excessive barriers.

For each dimension, scores from 0 to 5 were assigned based on experimental findings, material tests, and critical reflection on each method's feasibility and expressive potential. This quantifiable comparison provides a transparent foundation for selecting the most suitable mechanism for further development.

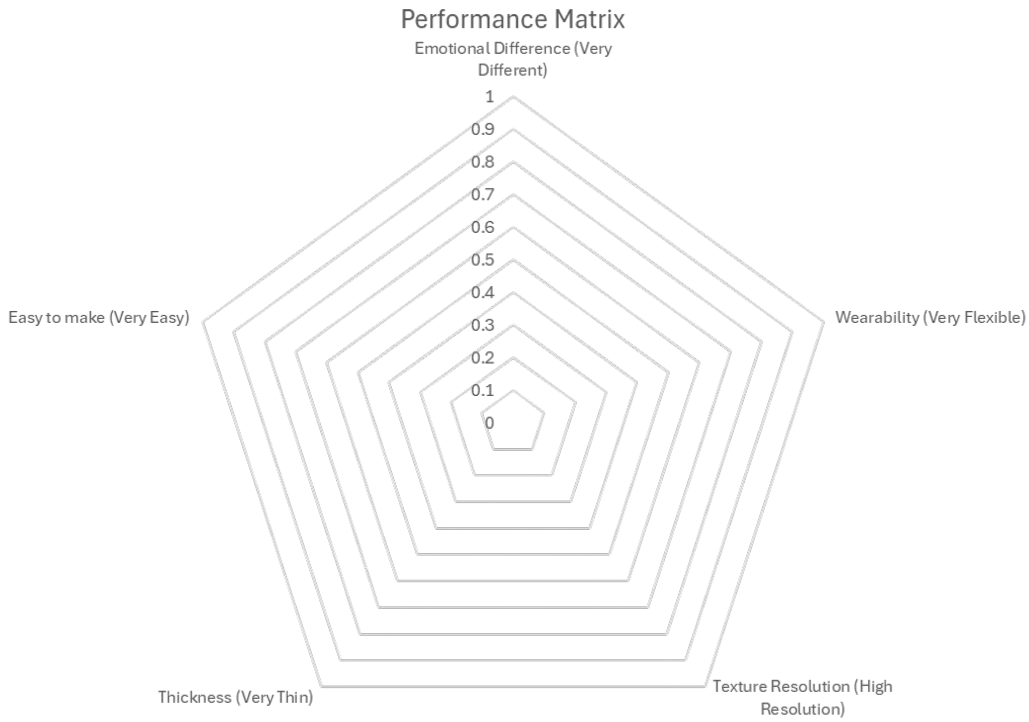


Figure 30. 5 criteria for performance matrix

4.2.1 Comparing Different Mechanism

Based on the scores in the performance matrix, each mechanism was assessed individually to understand its trade-offs.

Hairy Texture 1 (Lateral Shifting)

This approach scored very high overall. It enables a clear Emotional Difference by shifting between a fluffy, upright texture and a smooth, flat one. Its Texture Resolution is high because of the fine hair elements. The mechanism also remains thin and flexible, which supports good Wearability. The sliding grid must be carefully designed to maintain structural stability, but its Ease of Making is acceptable, especially when using ready-made hairy materials.

Hairy Texture 2 (Vertical Shift)

This approach scored very high overall. It enables a clear Emotional Difference by shifting between a fluffy, upright texture and a smooth, flat one. Its Texture Resolution is high because of the fine hair elements. The mechanism also remains thin and flexible, which supports good Wearability. The sliding grid must be carefully designed to maintain structural stability, but its Ease of Making is acceptable, especially when using ready-made hairy materials.

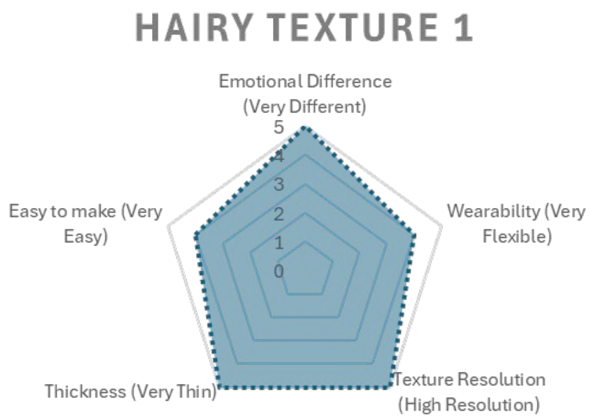


Figure 31. Hairy texture 1 (lateral shift)

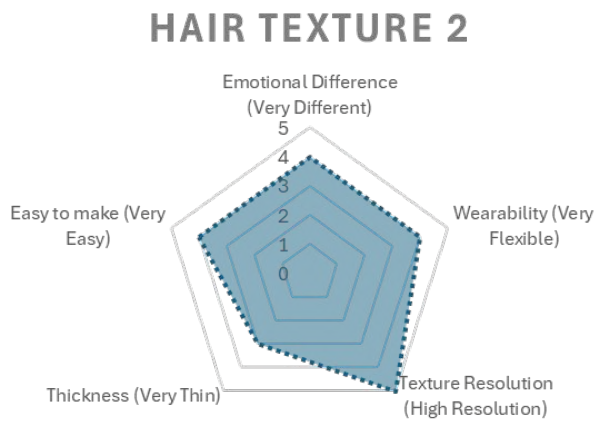


Figure 32. Hairy texture 2(vertical shift)

Embedded Fiber in Pneumatic Silicone

This method has clear potential for shape change, but its Texture Resolution is moderate. Embedded fibers can create local variations but do not produce strong emotional differences. The layered silicone structure tends to be thicker, which reduces wearability for garments. Fabrication also involves airtight chambers, which can cause difficulty in the making process.

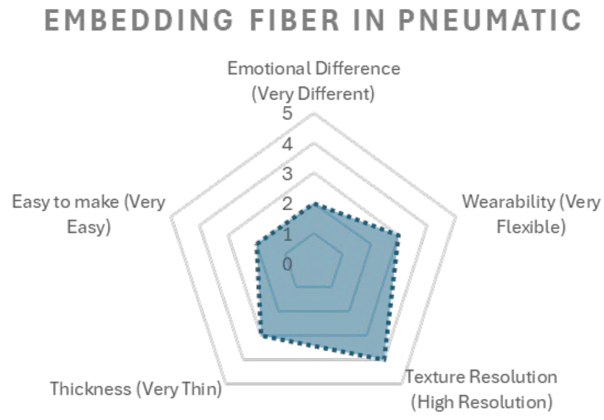


Figure 33. Embedding Fiber in Pneumatic

Vacuum-driven Origami

Origami structures offer a dramatic shift in surface form, giving this method relatively high Emotional Difference. However, experiments showed practical constraints. Achieving high-resolution folds is technically demanding. Thickness may increase due to folded layers. Ease of Making is low without specialized machines or advanced casting or printing methods.

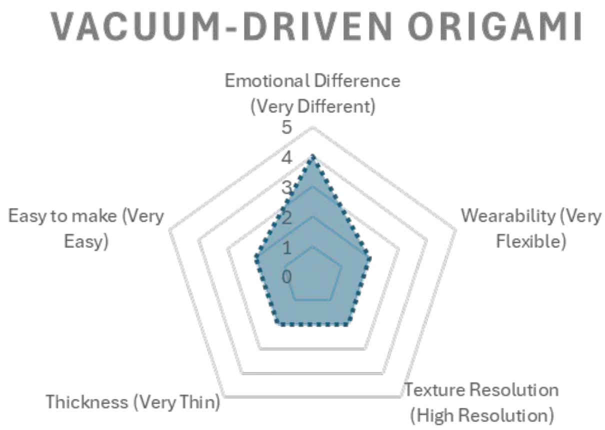


Figure 34. Vacuum-driven origami

Fabric/Knitting Structure

This approach is naturally flexible and thin, making it excellent for wearability. However, its main limitation is Texture Resolution. The scale of shape change in knitted structures is coarse, which limits fine tactile variation. Because the fabric remains soft throughout, the Emotional Difference is modest compared to mechanisms that create dramatic shifts between soft and spiky or soft and rough.

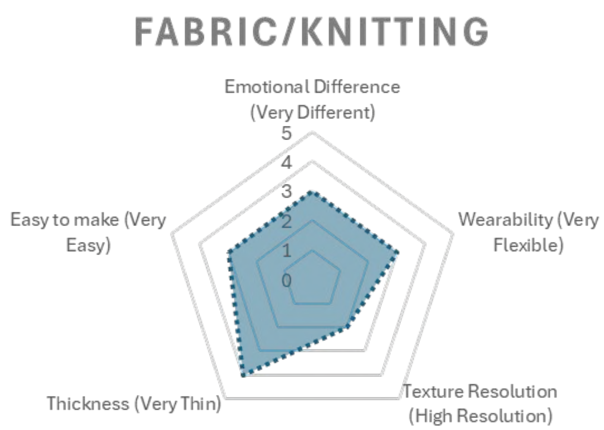


Figure 35. Fabric/knitting

4.2.2 First Convergence: Choosing Hairy Texture

In summary, the comparison indicates that hairy texture mechanisms consistently outperform the other options in Emotional Difference, Texture Resolution, Wearability, and Thinness. Pneumatic concepts are limited by fabrication complexity and thickness, reducing their suitability for wearable devices. The fabric and knitting approach offers softness and ease of production but does not provide the required emotional textural change for this project.

Therefore, both Hairy Texture 1 and Hairy Texture 2 will be retained for further exploration and prototyping, providing a strong foundation for designing emotionally expressive, high-resolution, and wearable texture-changing interfaces.

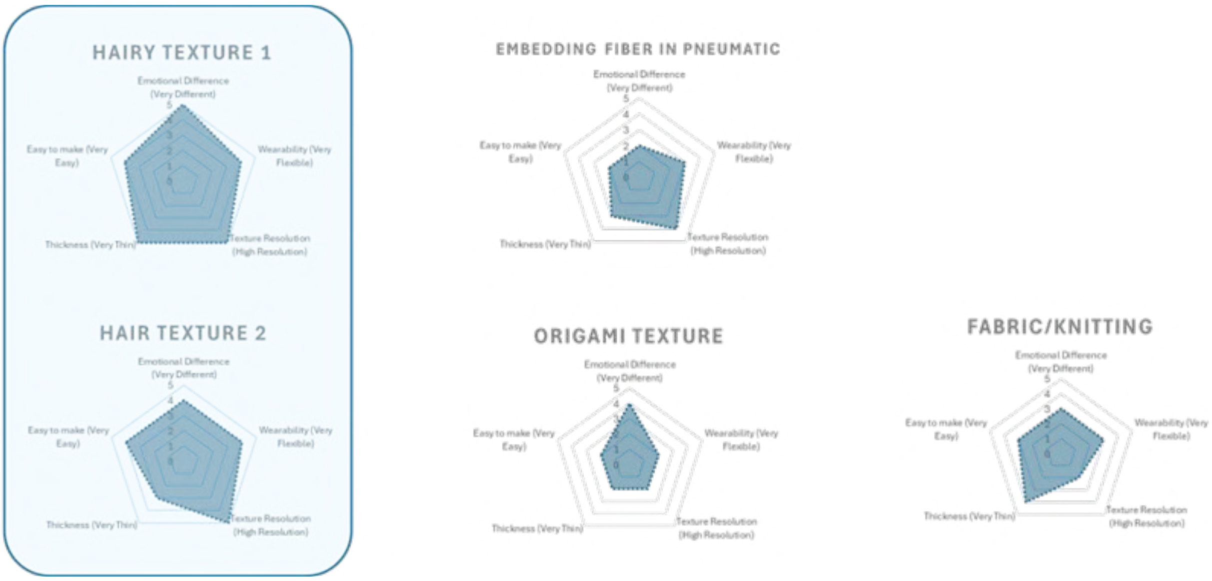


Figure 36. Performance matrix selection

Summary

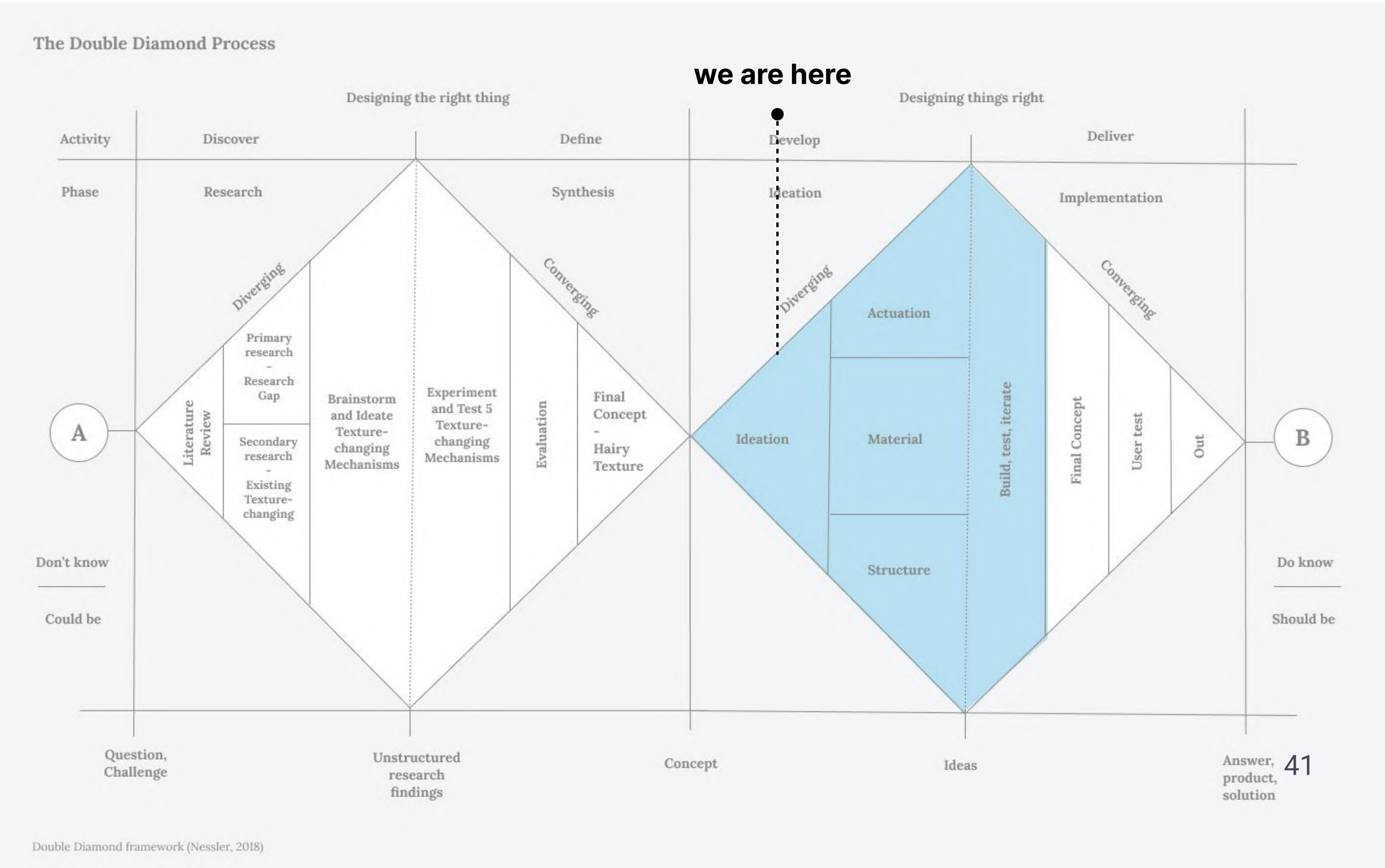
In this chapter, five texture-changing mechanisms were explored and systematically compared using a performance matrix. The evaluation highlighted trade-offs across criteria such as emotional difference, resolution, thickness, and ease of fabrication. While pneumatic and origami-based approaches offered striking visual transformations, they were limited by thickness and fabrication complexity. Fabric and knitting structures provided softness and high wearability but lacked strong emotional variation.

In contrast, hairy texture mechanisms consistently demonstrated high resolution, thinness, and clear affective expressiveness, making them particularly suited for wearable use. Based on these findings, both lateral-shifting and vertical-exposure hairy texture mechanisms were selected as the foundation for subsequent prototyping and implementation.

Chapter 5
Exploration 2: Realizing Hairy Texture

After identifying the Hairy Texture concept as the most promising direction, the next step was to investigate how this idea could be realized in practice. This chapter, therefore, focuses on the transition from concept to implementation. It explores the search for appropriate materials, mechanisms, and structural arrangements that could enable the Hairy Texture to function as a reliable and expressive texture-changing interface.

Figure 37. Roadmap of Design Process (based on Double-Diamond)



5.1 Material Search

5.1.1 Search for "Hairy Material"

First, a systematic material search was conducted to identify commercially available hair-like components and suitable grid or slit layers capable of supporting controlled texture change.

One of the initial directions explored was the use of off-the-shelf brush-like materials, such as sealing brushes commonly used for window frames. These dense bristles were combined with metal mesh fabrics to assess whether effective shifting or protrusion could be achieved.

However, the bristles were too densely packed, with multiple fibers bundled into each hole. This made it difficult to achieve reliable lateral movement for Hairy Texture 1. For Hairy Texture 2, the high density made it challenging to find or fabricate a compatible upper grid or slits layer that could reveal the hairs in a controlled way.

Figure 38. Product image of self adhesive brush strips (Eclat Skincare, n.d.)

Figure 39. Testing with brush strip and grid

To address these limitations, I investigated the possibility of sourcing custom brush strips with more sparse and evenly spaced bristles. Although technically feasible, this approach would require specialized manufacturing. It also presented cost and lead-time challenges that were impractical at this stage.

Figure 40. Custom brush strip (Ultrafab, n.d.)

In parallel, I identified another promising material used in tufting the Gripper Bar, also known as Carpet Fabric Hook for tufting frames. This material consists of a flexible rubber strip with evenly spaced metal needles fixed in place. Compared to standard sealing brushes, this configuration is more open and uniformly distributed, making it more suitable for creating distinct, controllable texture changes in both lateral and vertical directions.

Figure 41. Gripper bar for tufting (zalati, n.d.)

Given these structural advantages, the Gripper Bar, hereafter referred to as the **metal bristle fabric**, proved to be well-suited for the vertical shifting mechanism required for Hairy Texture 2. Its predictable bristle arrangement and fixed dimensions facilitate the design of a matching upper slit layer that can reveal or conceal the bristles in a controlled manner.

In addition, the bristle array offers exceptionally high spatial resolution. The metal bristle fabric used in Hairy Texture 2 contains approximately 300 texture units within a 3×3 cm area, forming a dense and highly regular array, estimating that a 10×10 cm surface could accommodate over 3300 texture units. This resolution is significantly higher than that of most existing texture-changing interfaces, which often offer fewer than 20 units per 10 cm^2.

Based on these insights, further development focused on integrating the material properties with appropriate actuation and structural design to achieve programmable surface changes.

5.1.2 Making process of the matching slit layer

To enable the bristles of the metal fabric to shift vertically in a controlled manner, a second structural layer was required—one that would guide the bristles through fixed openings while allowing them to be selectively revealed or concealed. This layer, referred to as the slit layer, needed to be carefully aligned with the underlying bristle pattern to ensure smooth actuation.

The design process began by analyzing the backside pattern of the metal bristle fabric, which revealed a regular arrangement of gaps between the bristle anchors. These gaps provided a natural reference for generating the openings of the slit layer. Using Grasshopper in Rhino, I developed a parametric model that reproduced this pattern and allowed precise control over the spacing, size, and orientation of the slits.

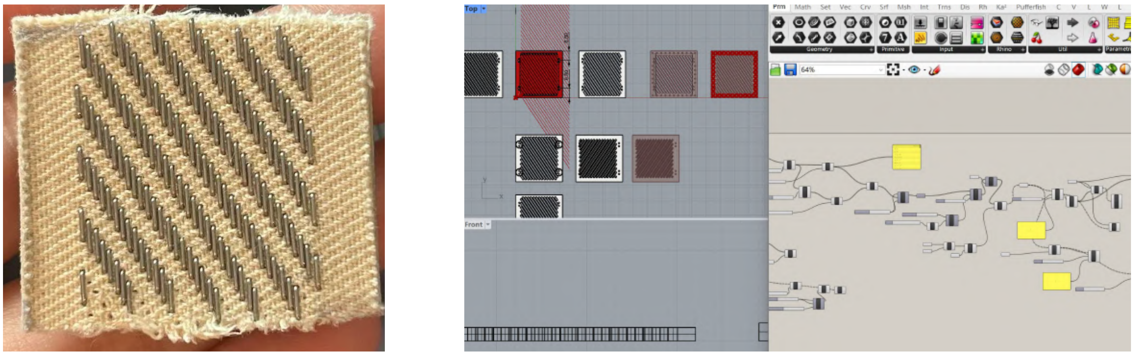


Figure 42. Back pattern and grasshopper script

The optimization of the slit layer involved several iterations. First, I adjusted the spacing of the slits, seeking a balance between minimizing friction and maintaining stable guidance. Next, I refined the thickness of the layer. A thickness of about 2 mm was found to be necessary: if the layer was too thin, the slit layer easily slipped out of alignment. Finally, I addressed the orientation of the slits. While the first prototypes used vertical cut-outs, I discovered that the bristles were not perfectly straight but slightly bent. By matching the slit orientation to this bend angle, the bristles could pass through with minimal resistance.

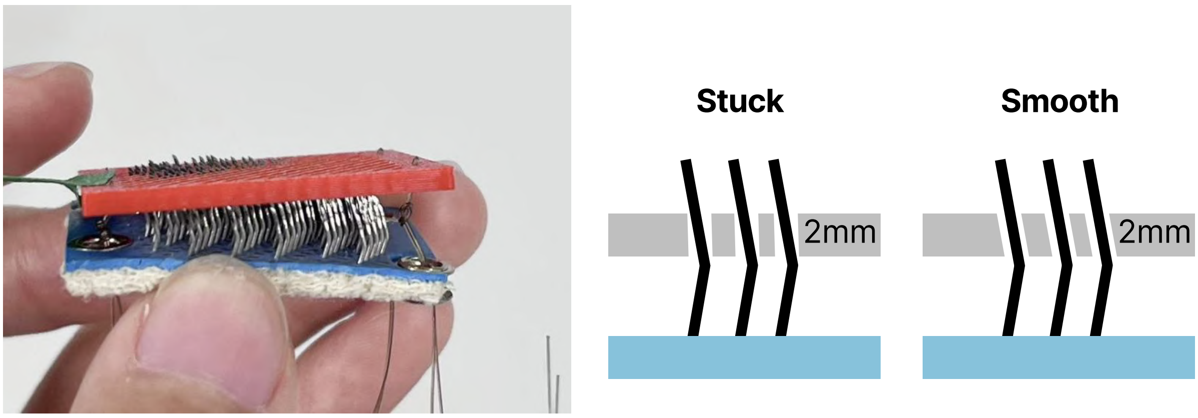


Figure 43. Solving the Bending Needle Problem

After these adjustments, the slit layer achieved a state where it moved smoothly and reliably and would not fall out from the bristles easily.

5.2 External Actuation Mechanism Search

After selecting Hairy Texture 2 with vertical movement, various actuation mechanisms were explored to achieve controlled displacement. The objective was to identify a mechanism capable of reliably lifting or lowering the upper perforated layer, thereby allowing the metal bristles underneath to emerge or retract and modulate the surface texture.

Several actuation methods were considered:

1. **Pneumatic:** Embedding inflatable silicone or film-based air pockets between layers could raise the upper surface smoothly. However, the bulkiness and air supply requirements make it unsuitable for wearable integration.

2. **Lumella structure + SMA tube-guided system:** A Lumella-inspired structure combined with SMA wires in tube guides could deliver linear motion.

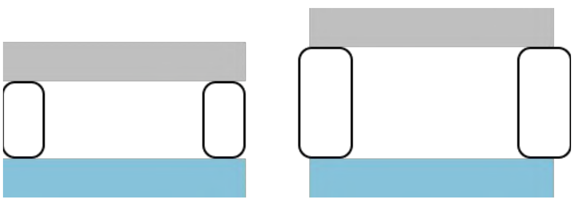


Figure 44. Pneumatic actuation

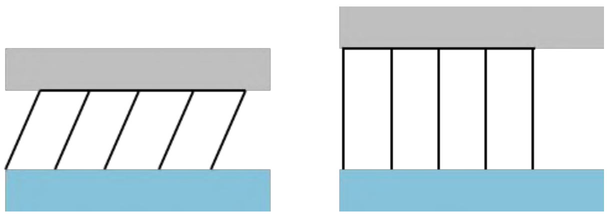


Figure 45. Lumella

3. **Magnetic:** Magnets could attract or repel the surface layer for quick displacement. The motion is too sudden and difficult fit the magnet into the system.

4. **Piezoelectric ceramics:** Piezoelectric stacks generate fine displacements with applied voltage. But their displacement length is limited.

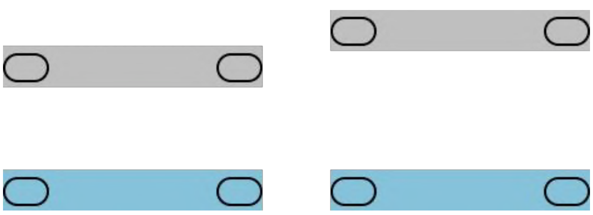


Figure 46. Magnetic

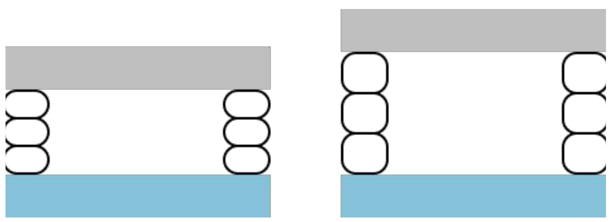


Figure 47. Piezoelectric ceramics

5. String system + SMA tube-guided system: A string system combined with SMA wires to pull the surface layer downward when heated. This option is compact and silent.

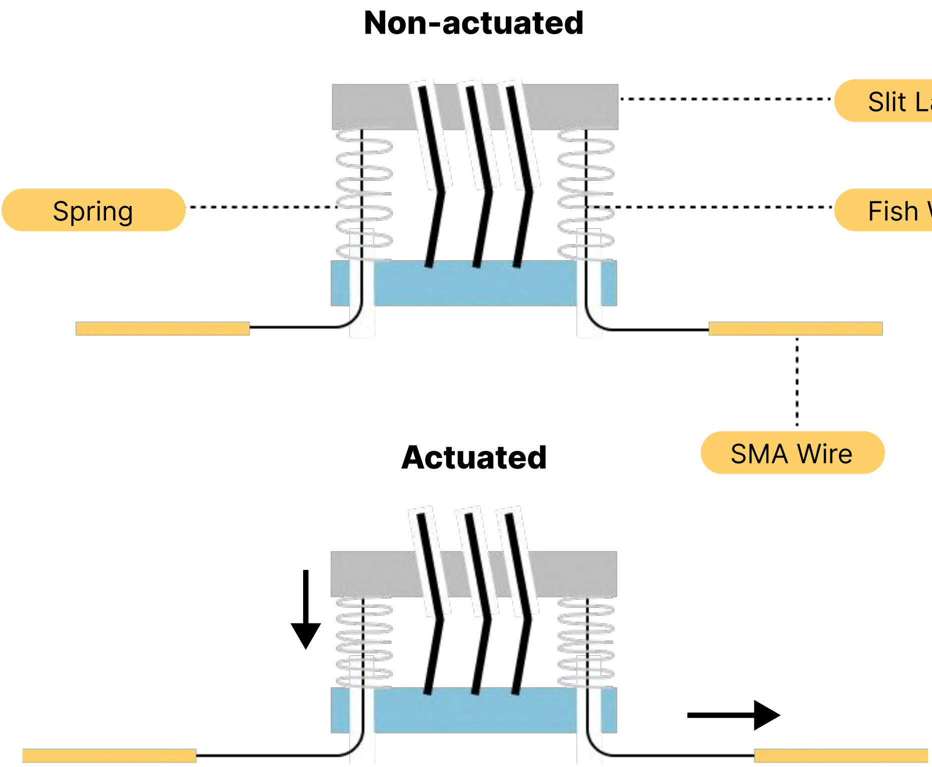


Figure 48. String pulling system mechanism diagram

Through evaluation, a string-based mechanism was ultimately selected. This design uses tensioning or releasing strings to move the upper surface vertically. Shape memory alloy (SMA) wires were chosen as the driving element. When heated, SMA wires contract, pulling the strings and shifting the surface layer downward. Upon cooling, an integrated bias spring provides a counterforce that returns the structure to its original position. This solution offers compactness, low noise, and seamless integration into textile structures.

5.2.1 Actuation System: SMA Tube-guided System

The string-based pulling mechanism requires a stable linear contraction to pull the upper slit layer downward. This can be achieved by integrating a tube-guided SMA system, developed by Qiang Liu in his previous work (Liu et al., 2022). In this design, the SMA wire is enclosed in a flexible but compressively stiff tube, which guides the wire's contraction along a defined path. When the SMA wire is heated, it contracts and pulls the string that shifts the slit layer downward.

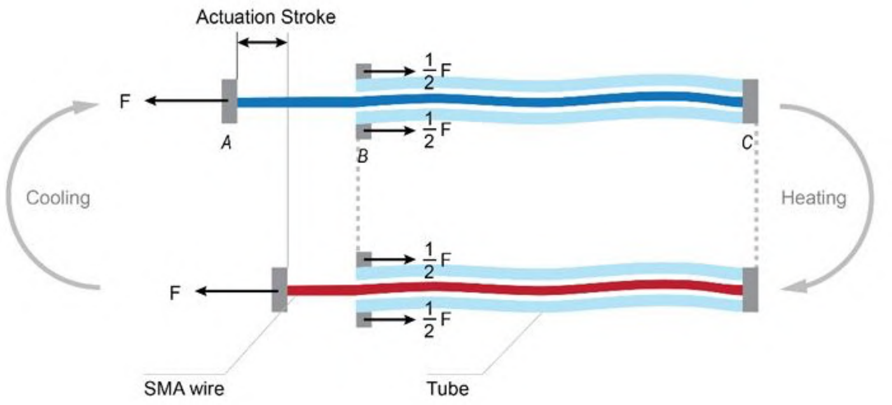


Figure 49. Configuration and activation process of the tube-guided SMA actuator. The actuation is between points A and B, whereas most of the actuator length is in the flexible tail BC. (Liu et al., 2022)

The tube transfers the counterforce generated during SMA contraction back along the tube walls. This prevents buckling and ensures that the pulling motion remains stable and linear. As a result, it is possible to generate a clear, repeatable displacement even when the actuator is integrated into a soft or flexible wearable structure.

This design principle enables the system to utilize thermally activated SMA wire to produce a repeatable, programmable pulling motion that meets the requirements of the Hairy Texture 2 structure.

5.3 Internal Structural Prototyping

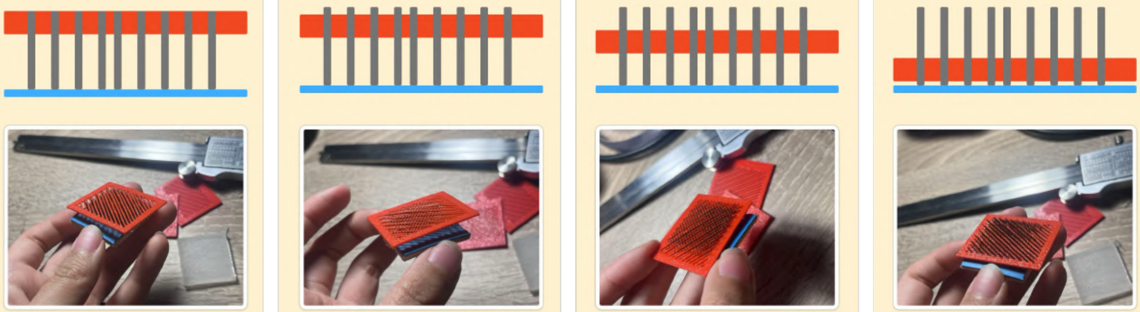
The main goal of this stage was to test whether the proposed two-layer structure—combining a metal bristle fabric with an upper slit layer—can reliably produce controlled surface texture changes. This included exploring what specific structural design elements, such as bristle spacing, slit placement, and layer thickness, are needed to ensure that the bristles can shift smoothly between concealed and exposed states.

The metal bristle fabric consists of densely arranged rigid bristles that can protrude through the top slit layer to create a distinct spiky surface or remain hidden underneath to form a smooth texture. To ensure that the two layers work together precisely, I first analyzed the spacing and density of the bristles on the selected material. I then used a computational design approach in Grasshopper to model the slit pattern for the upper plate, ensuring that each bristle aligns with a corresponding slit and can pass through smoothly when actuated.

The slit layer was prototyped using PLA 3D printing. For improved flexibility in future iterations, TPU or other elastomeric materials may be used. The thickness of this layer proved to be a critical parameter: it needs to be thin enough for the bristles to move freely, yet thick enough to hold them in place when retracted, maintaining a flat surface without unintended exposure. Testing showed that a thickness of approximately 2 mm provides a good balance between concealment and reliable actuation, preventing the bristles from slipping out unintentionally.

To validate the effectiveness of this design, I tested whether shifting the slit layer could indeed modulate the surface texture and alter the haptic interaction. I defined and evaluated four positions—highest, mid-high, mid-low, and lowest—each corresponding to a different degree of bristle exposure. In its fully covered state, the surface feels smooth and flat, similar to plain plastic. When the bristles are slightly revealed, the texture becomes rougher, resembling sandpaper. With greater exposure, the sensation grows distinctly aggressive, similar to a metal brush. When the bristles are fully extended, the surface feels sharp and needle-like, creating an intense, spiky touch.

	Highest	Mid-High	Low-mid	Lowest



Needle Exposure	Fully Covered	Mostly Covered	Partially Exposed	Fully Exposed
Tactile Feeling	Smooth and flat Flat plastic	Coarse and buzzy Sandpaper	Rough and stinging Metal Brush	Sharp and aggressive Needle

Figure 50. Four states of surface texture

This experiment demonstrates that the internal structure can generate a wide range of tactile sensations, from smooth to sharply spiky. Such clear variation supports the concept's potential to deliver strong emotional contrasts through surface touch.

Summary

In this chapter, a systematic search for materials, actuation mechanisms, and structural solutions was conducted to realize the Hairy Texture 2 concept. Through material exploration, the metal bristle fabric used in tufting frames was identified as a suitable candidate, offering predictable spacing and rigidity while enabling controllable transitions between smooth and spiky textures. A matching slit layer was computationally designed and iteratively optimized, with thickness and slit orientation found to be critical factors for reliable performance.

Several actuation approaches were evaluated, including pneumatic, magnetic, and piezoelectric options. However, these were limited by bulkiness, abrupt motion, or insufficient displacement. Ultimately, a string-based system driven by tube-guided SMA wires was selected, as it provided compactness, low noise, and stable linear contraction suitable for wearable integration.

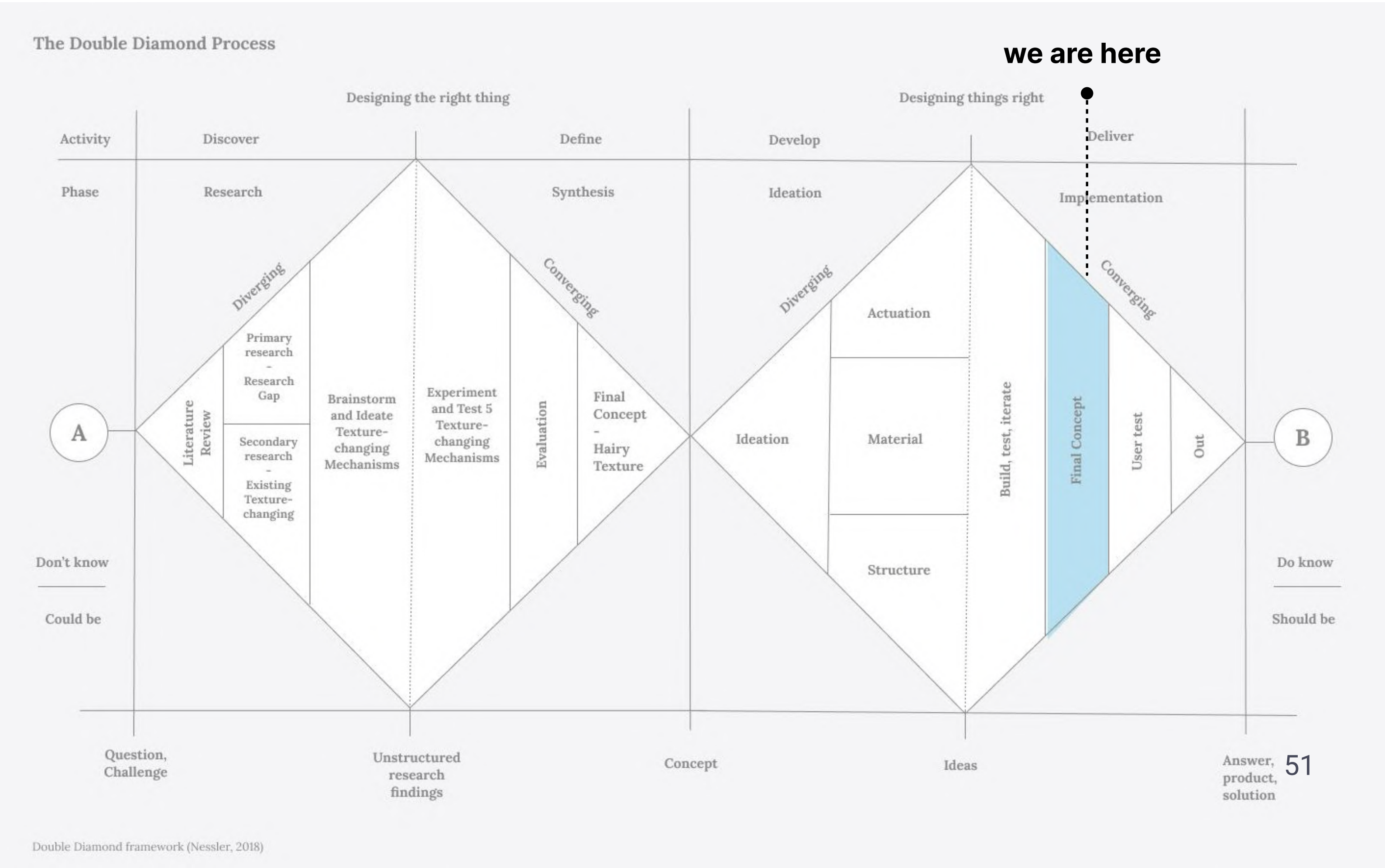
The integration of material properties, actuation stability, and structural precision sets the stage for prototyping a fully wearable texture-changing interface in the next phase of the project.

Chapter 6
Final Concept

Building upon the outcomes of the previous explorations, including material search, structural prototyping, and actuation method evaluation, this section presents the final integrated concept.

The chapter introduces the final concept and its prototype, explaining how the system was constructed, how it operates, and what findings were revealed through the process of making and testing.

Figure 51. Roadmap of Design Process (based on Double-Diamond)



6.1 Final Design

To clearly explain how the system functions, the following sections are divided into two parts:

- Texture-Changing System – describing the layered structure that produces different tactile states.
- Actuation System – outlining the SMA-based mechanism that drives and resets the texture transitions.

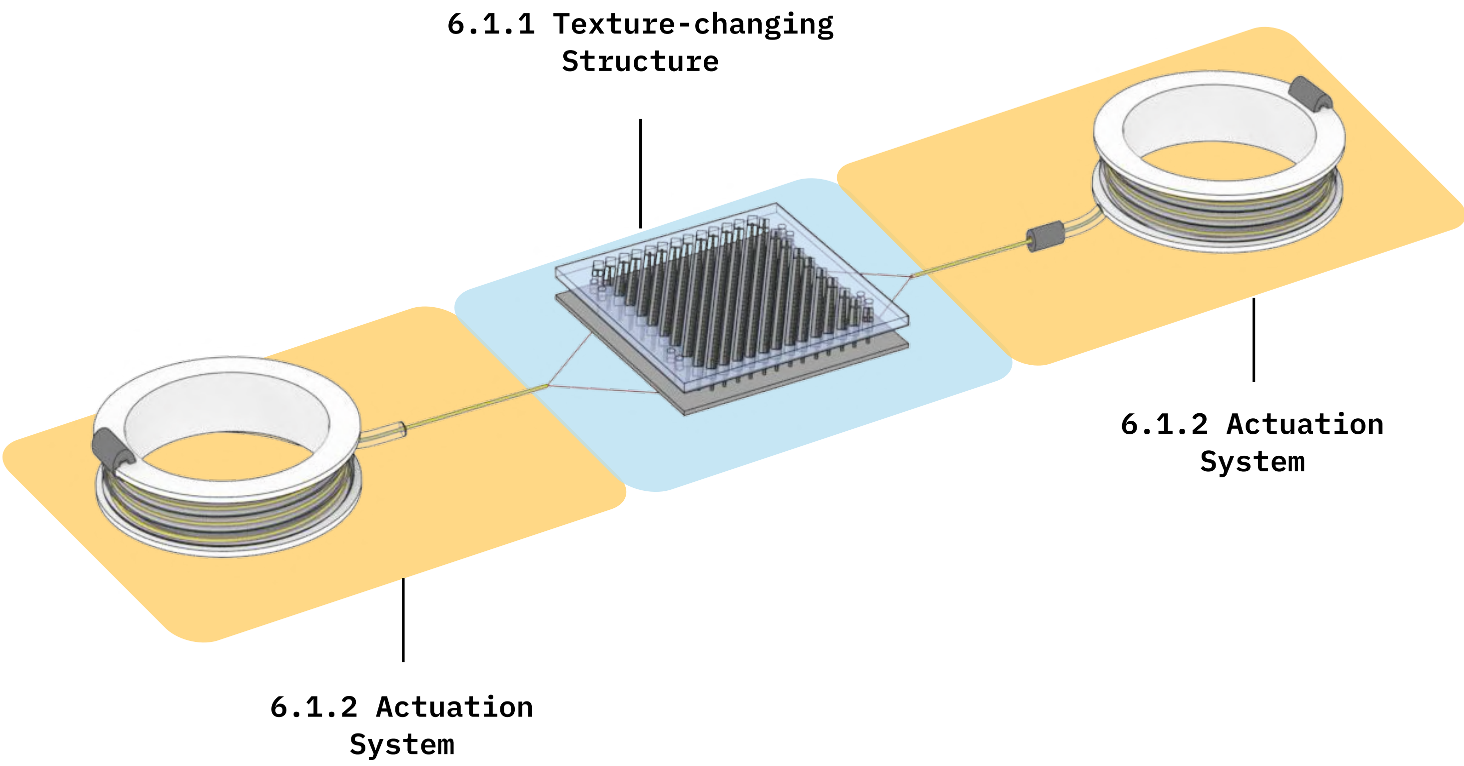


Figure 52. Division of the two main components

6.1.1 Texture-changing Structure

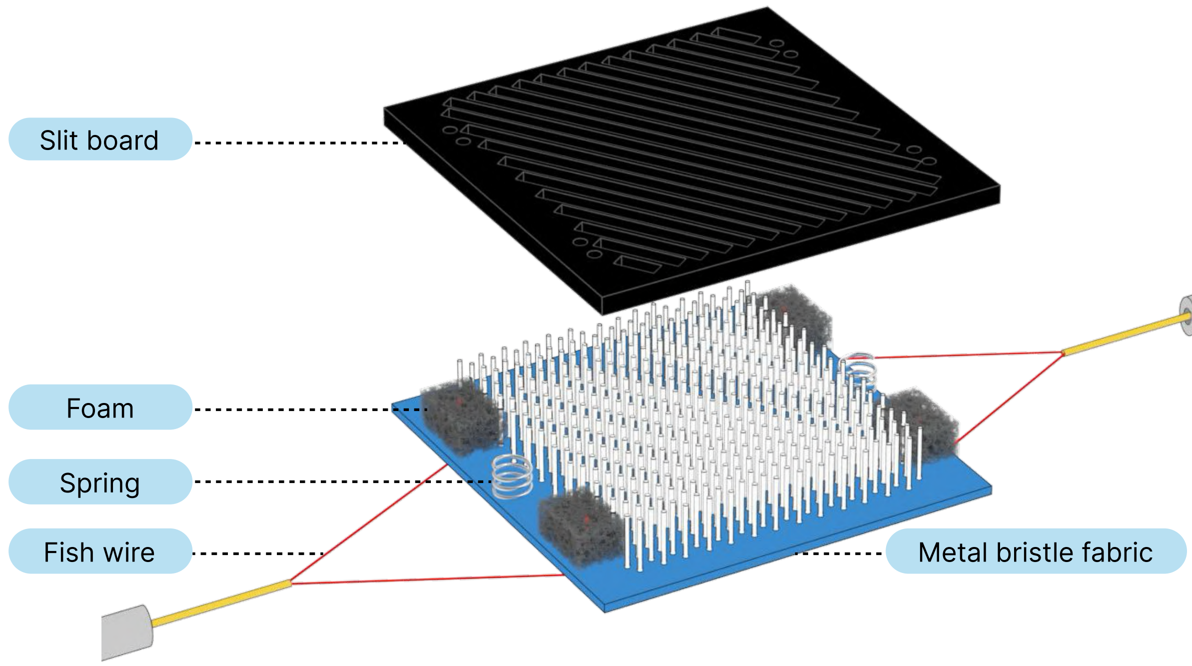


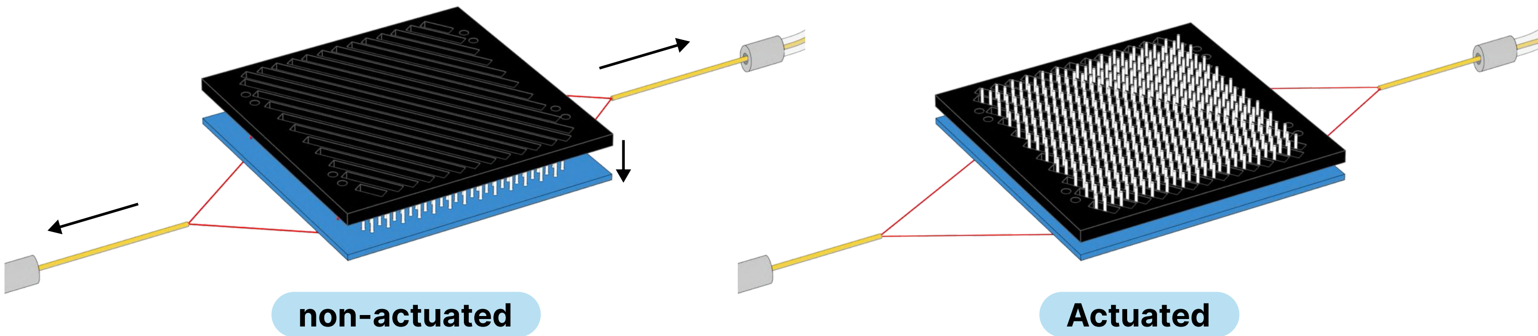
Figure 53. Texture-changing Structure Diagram

The texture-changing structure, illustrated in the accompanying Structure Diagram (Figure 53), integrates multiple layers and components to achieve controlled, programmable texture change.
The top layer is a 3D-printed PLA plate with precisely designed slits. These slits align with the bristles of the metal bristle fabric beneath it, allowing the bristles to pass through or retract to create different tactile states.

Between the slit layer and the metal bristle fabric, a combination of sponges and springs is embedded. This intermediate structure ensures that when the SMA wires cool down and relax, the elastic elements provide the counterforce necessary to return the slit layer to its original position.

To actuate the movement of the slit layer, fish wires are threaded through the top layer and the bristle fabric underneath. These strings extend outward and attach to the tube-guided SMA system, which generates the pulling force needed to shift the slit layer vertically (Figure 54).

Figure 54. Mode transition



6.1.2 Actuation System

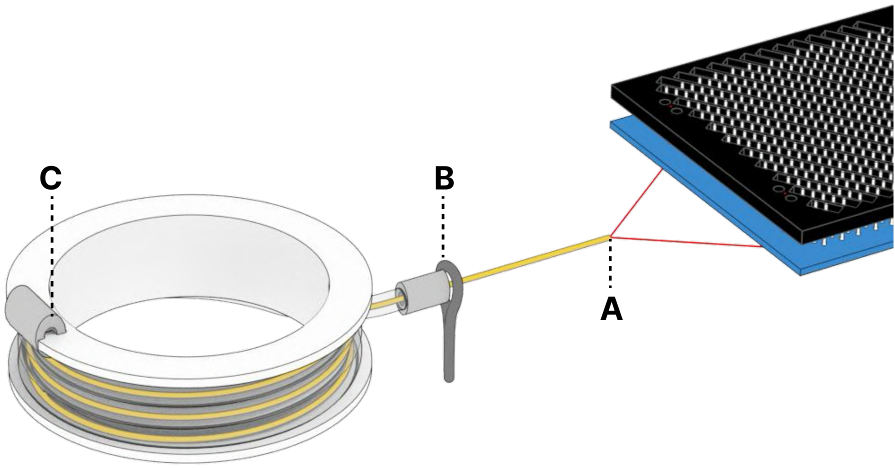


Figure 55. Actuation System Structure Diagram

The actuation system works by transferring the contraction of the pre-stretched Shape Memory Alloy (SMA) wire into a linear pulling motion that shifts the slit layer up or down. As illustrated in the diagram, the system includes three critical points: A, B, and C.

- Point A is the connection where the fish wire is attached to the SMA wire. This point is free to move horizontally when the SMA contracts or relaxes.
- Point B fix the Teflon tube end to a fixed surface and provides the necessary counterforce. It prevents the tube from moving backward while allowing the SMA wire inside to slide and generate tension.
- Point C is a fully fixed end that clamps both the Teflon tube and the SMA wire using a metal cable clamp. This ensures that the contraction force is transmitted effectively along the wire's length.

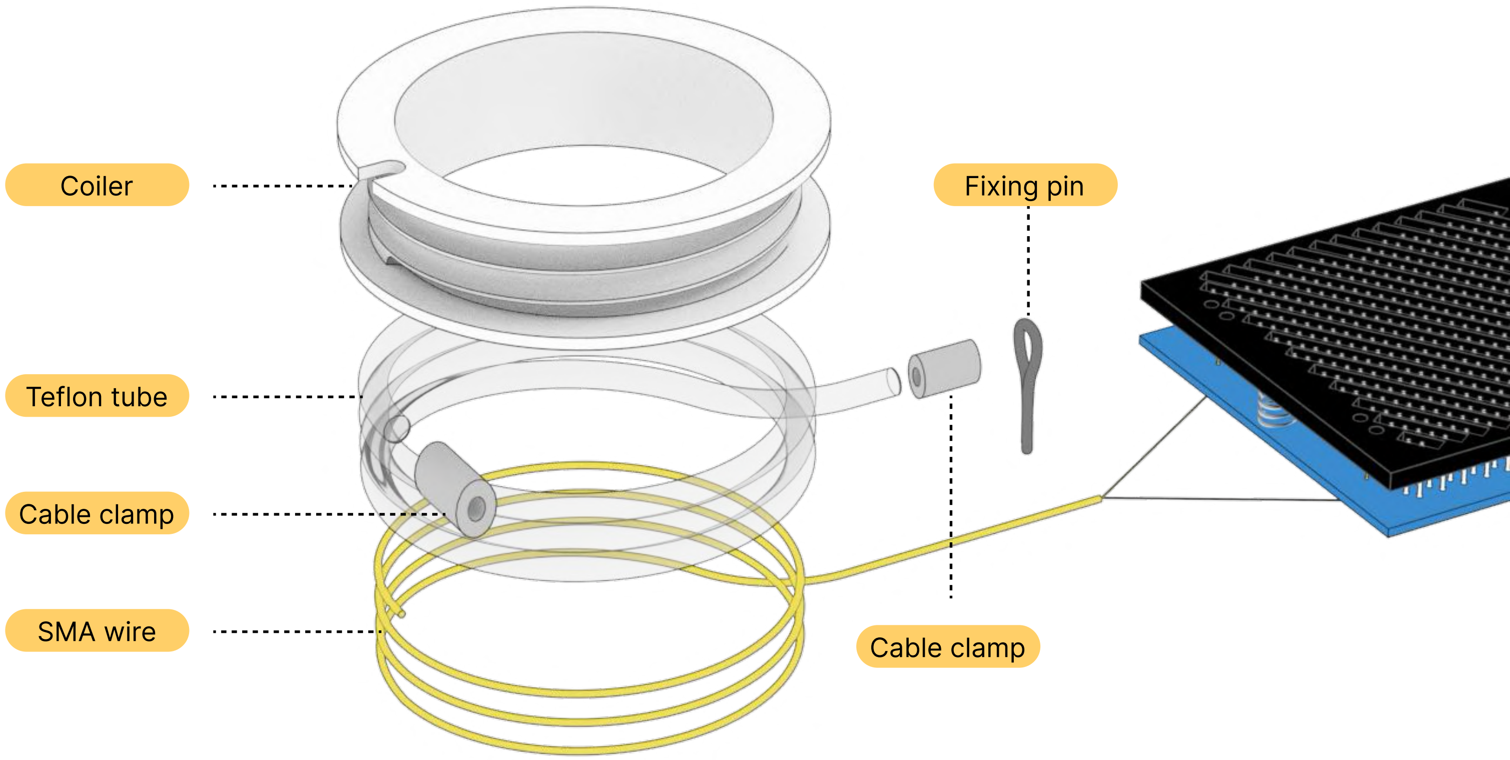


Figure 56. Actuation System Components

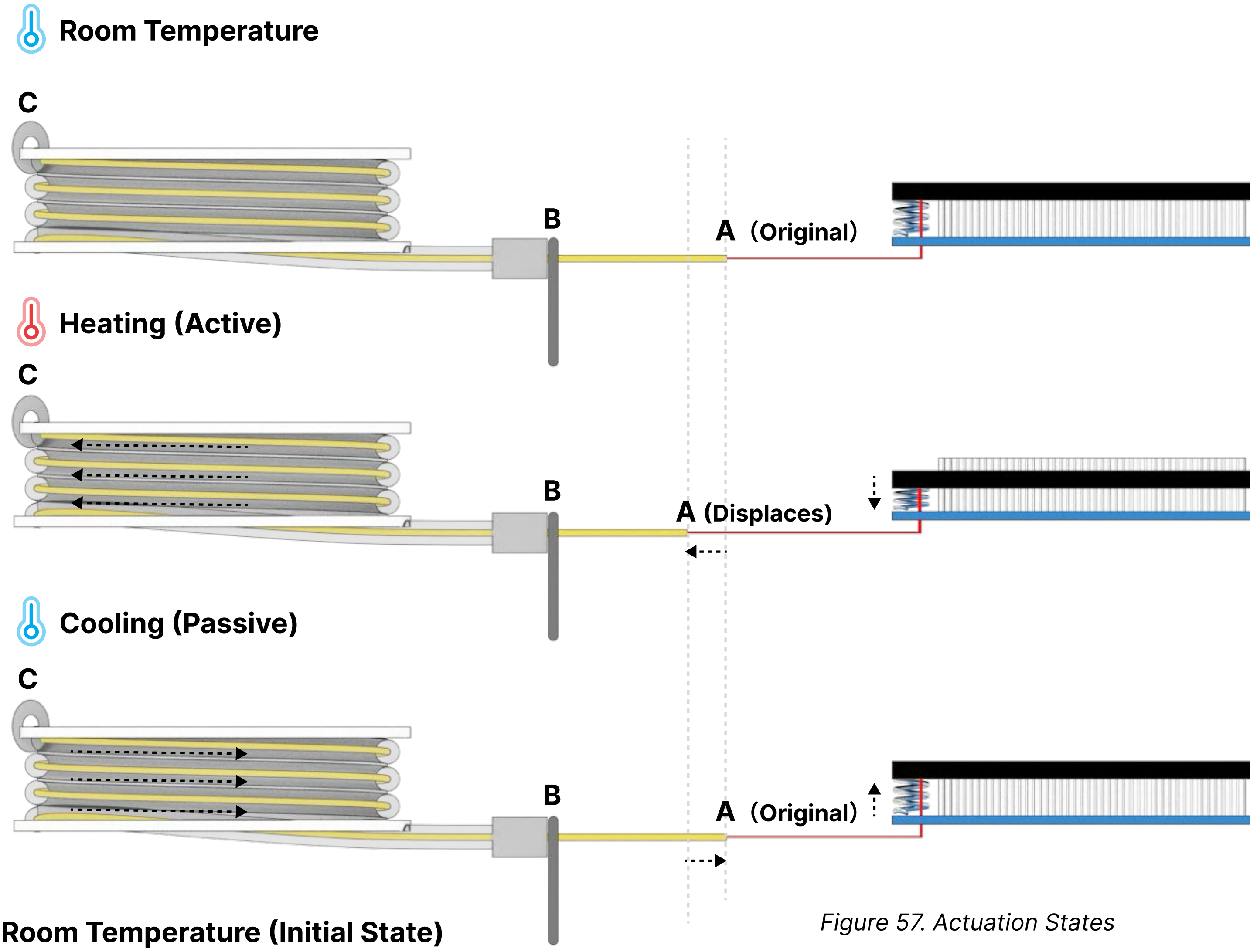


Figure 57. Actuation States

Room Temperature (Initial State)

At room temperature, the SMA wire (between Point A and Point C) remains in its pre-stretched state. Point A is positioned at its original location, while the slit layer is held in its default position. The springs beneath the slit layer are relaxed, keeping the bristles mostly concealed.

Heating (Active Actuation)

When electrical current is applied, the SMA wire heats up and actively contracts toward its shorter memorized length (Liu et al., 2022). This contraction displaces Point A horizontally, pulling the fish wire and lowering the slit layer by approximately 2–3 mm. As the slit layer moves down, more of the metal bristle fabric becomes exposed. At the same time, the springs beneath the slit layer compress, storing elastic potential energy.

Cooling (Passive Recovery)

The SMA wire relaxes and need to extend back to its pre-stretched state for repeatable actuation. The stored elastic energy in the springs pulls Point A back to its original position, lifting the slit layer and concealing the bristles once again.

6.2 Prototyping

6.2.1 Prototype Set-up

The experimental prototype was assembled to test the complete actuation and recovery cycle of the two-layer texture-changing structure. The structure is slightly elevated at the center and fixed securely onto a corkboard to provide a stable base.

On either side of the top layer, two tube-guided SMA systems are connected to the fish wire strings, enabling symmetrical pulling forces when current is applied.

At Point B, which acts as the fixing point for each tube-guided system, small pins are used to anchor the Teflon tubes to the cork board with zip-ties. This prevents unwanted backward movement of the tube while allowing the SMA wire inside to slide freely and deliver a stable pulling force to the slit layer.

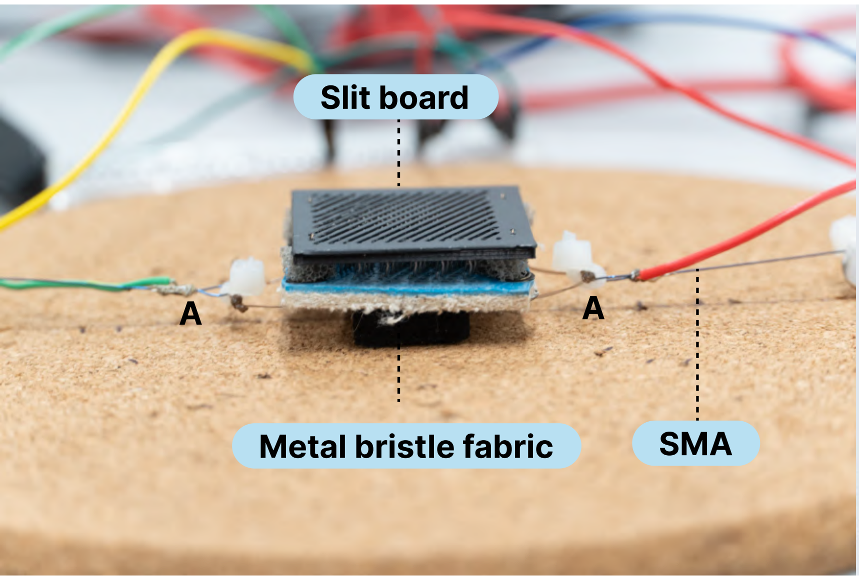


Figure 58. Texture-changing structure

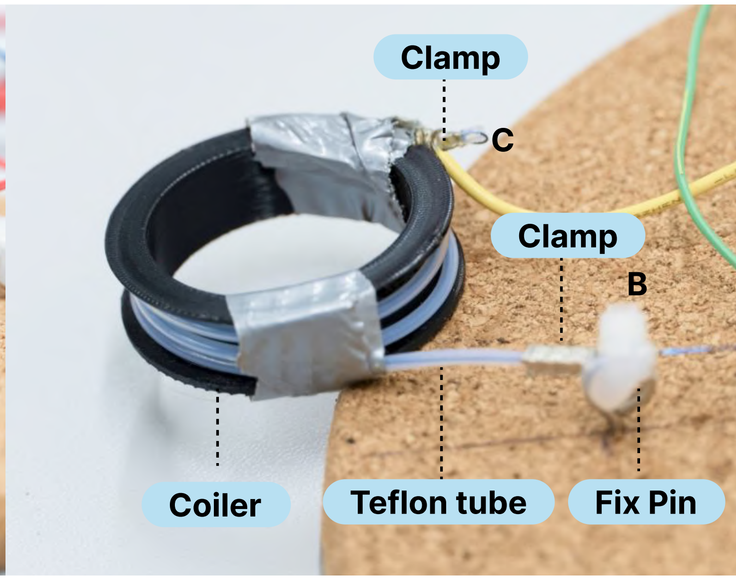


Figure 59. Actuation system

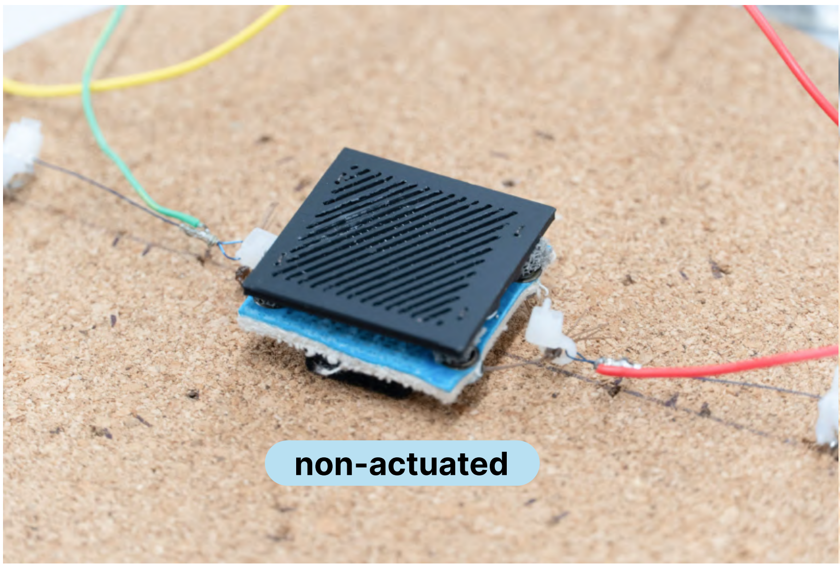


Figure 60. Non-actuated mode

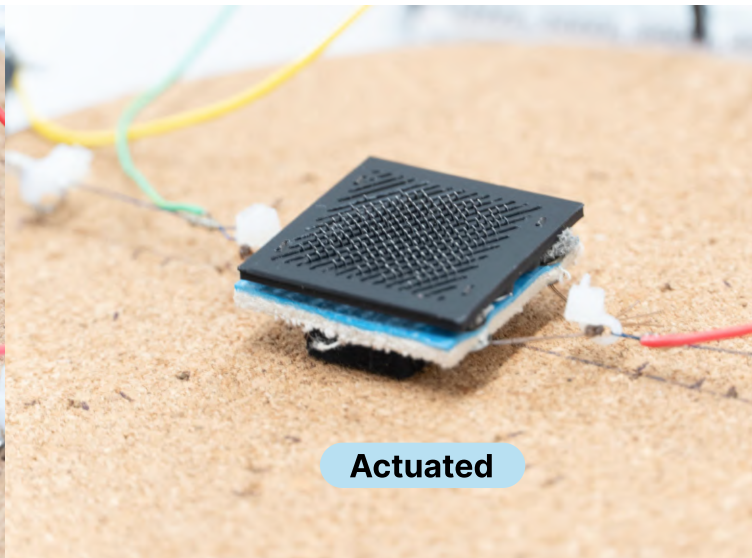


Figure 61. Actuated mode

6.2.2 Prototype Insights

During the prototyping phase, I encountered several critical challenges working with Shape Memory Alloy (SMA) wire and the tube-guided system.

A. Balancing Actuation and Recovery
For the prototype to function reliably, it was essential that the system could both actively actuate and fully recover in a repeatable cycle. The Shape Memory Alloy (SMA) wire had to contract upon heating to displace the slit layer downward, and then be re-extended during cooling so that it returned to its pre-stretched state. This pre-stretch is critical: without sufficient elongation (around 4% of its original length), the SMA would fail to produce the necessary contraction during the next cycle.

The restoring force for this recovery was provided by springs. However, maintaining the right balance between the SMA contraction force and the spring restoring force proved challenging. If the springs were too stiff, the SMA could not generate enough force to compress them, resulting in insufficient displacement of the slit layer. Conversely, if the springs were too weak, they failed to re-extend the SMA wire, leaving it under-stretched and causing incomplete recovery of the surface height.

To resolve this, I conducted multiple trials adjusting three key variables in combination:

1. Spring stiffness – testing different spring types and sizes.
2. Length of the SMA wire – influencing contraction displacement.
3. Diameter and cross-sectional area of the SMA wire – determining the achievable contraction force (see Figure 62).

Through these experiments, I identified a configuration that repeatedly produced a displacement of 3–4 mm. The final setup employed two miniature pen springs placed on each side of the slit layer, combined with an SMA wire of 0.012 inches (0.31 mm) diameter and 30 cm length. Although the datasheet specifies that a 4% pre-stretch is required for optimal contraction performance (Dynalloy, Inc., n.d.), in practice part of the SMA's contraction was resisted by the restoring springs, which reduced the effective displacement. Nevertheless, this balance is important, as it ensures actuation and recovery.

Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Heating Pull Force* pounds (grams)	Cooling Deformation Force* pounds (grams)	Approximate** Current for 1 Second Contraction (mA)	Cooling Time 158°F, 70°C "LT" Wire*** (seconds)	Cooling Time 194°F, 90°C "HT" Wire*** (seconds)
0.008 (0.20)	0.74 (29)	1.26 (570)	0.50 (228)	660	3.2	2.7
0.010 (0.25)	0.47 (18.5)	1.96 (891)	0.78 (356)	1050	5.4	4.5
0.012 (0.31)	0.31 (12.2)	2.83 (1280)	1.13 (512)	1500	8.1	6.8

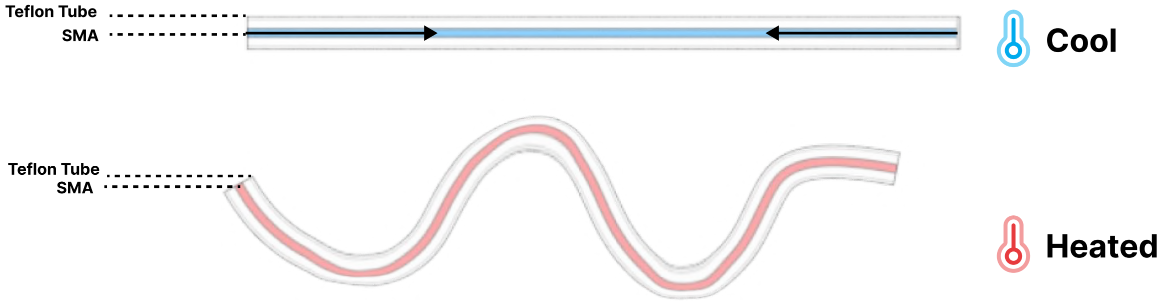
Figure 62. Configuration for 0.31mm Diameter SMA

B. Fixation and Pre-Tension at the Anchor Point

Another insight was the importance of precise pre-tension and stable fixation at each connection point. This fixed point B must hold the SMA wire in slight tension, ensuring that when activated, the contraction immediately pulls the fish wire and shifts the slit layer. Any slack in this anchor connection can reduce effective displacement and lead to incomplete bristle exposure.

C. Path Constraint for Effective Contraction

Another finding concerned the importance of constraining the actuation path of the SMA wire. I initially assumed that a longer SMA would generate greater total contraction, but experiments showed that without proper constraint of the route of the wire, the displacement can get lost in the Teflon tube.



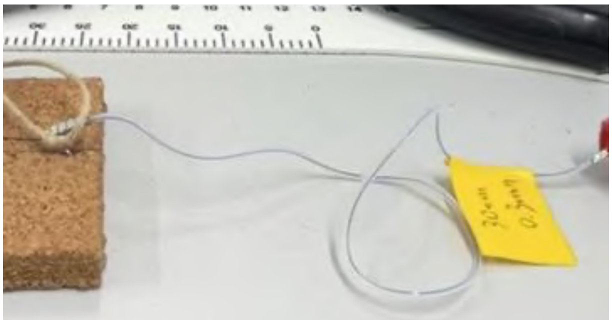


Figure 63. Behavior of snake shape when heated

When the Teflon tube is left unconstrained, the SMA wire inside shortens upon heating while the tube itself maintains its original length. This mismatch causes the tube to deform into a snake-like shape, absorbing the contraction internally instead of transferring it to Point A. As a result, much of the SMA's stroke is lost, and the external displacement becomes negligible.

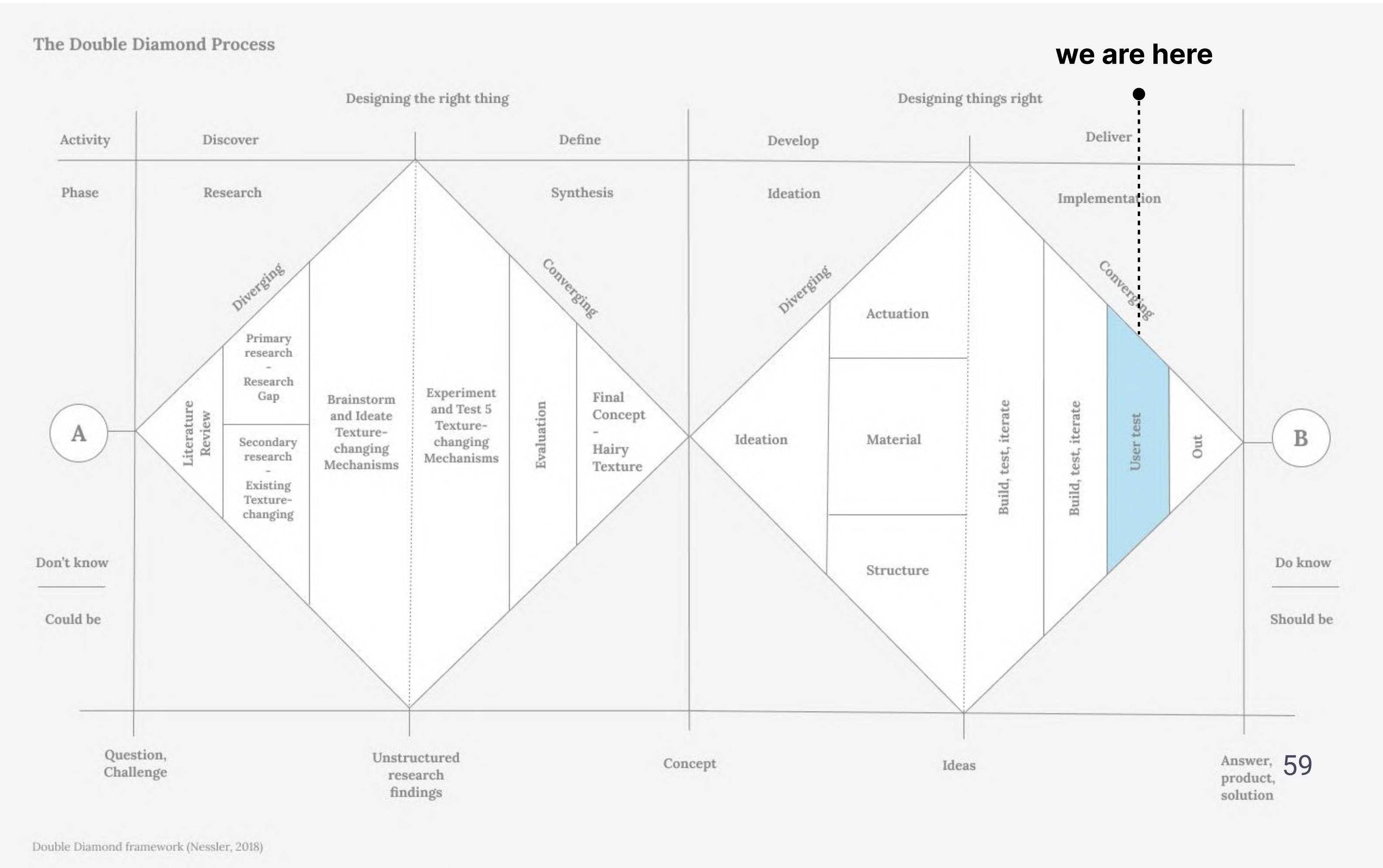
To address this, I introduced a coiler that defined a fixed path for the tube. The coiling structure is also beneficial for cooling. This optimization significantly increased the effective displacement.

Chapter 7
User Test

To evaluate how the dynamic texture-changing surface influences user perception and emotion, a user study was designed based on the Material Experience Framework (Karana et al., 2015). I invited participants to engage with the material and reveal what kinds of emotional and tactile experiences it may evoke. The study focused on performative, sensorial, affective and interpretative levels — to systematically examine how users interact with, describe, and emotionally respond to the material.

The findings from this study further serve as generative input for imagining potential application scenarios and refining the design direction.

Figure 64. Roadmap of Design Process (based on Double-Diamond)



7.1 Research Questions and Hypothesis

This study investigates how a dynamic, texture-changing surface mediates emotion and perception across time.

We address the following research questions:

- **RQ1:** How does the surface influence users' emotional states at different moments in time (before, during, and after actuation)?
- **RQ2:** How do users interpret the meaning or character of the surface as it changes?
- **RQ3:** What kinds of application scenarios or design directions can be inspired by their emotional and interpretive responses?

We evaluate two key hypotheses:

- **H1:** The texture-changing surface will elicit significant differences in users' sensorial and emotional perceptions between the pre-actuation and post-actuation phases.
- **H2:** The dynamic property of the material will shape users' interpretations and emotional reactions in ways that are distinct from static conditions.

These hypotheses serve as a foundation for identifying the expressive affordances and communicative potential of dynamic material systems.

7.2 Theoretical Framework

7.2.1 Material Experience Framework

This study adopts the Ma2E4 Toolkit-Experiential Characterization of Materials proposed by Camera & Karana (2018), which offers a comprehensive model for understanding how people perceive, feel, and make sense of materials in context. Moving beyond a purely technical assessment, this framework articulates material experience through four interrelated levels: **performative, sensorial, affective, and interpretive.**

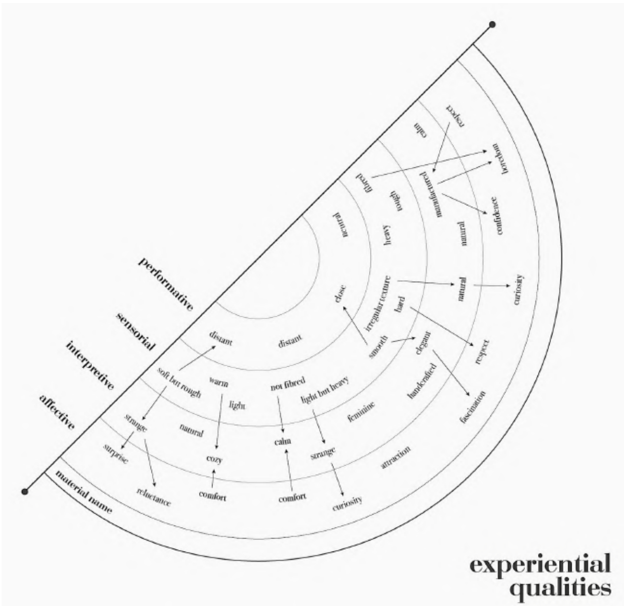


Figure 65. Mapping of the materials' experiential qualities at the four levels (Camera & Karana, 2018)

At the **performative level**, the material is understood through physical interaction—how users touch, manipulate, or respond to its changing states.

The **sensorial level** focuses on the immediate tactile qualities perceived during interaction.

The **affective level** addresses users' emotional responses elicited during tactile engagement.

At the **interpretive level**, attention is given to the meanings users ascribe to materials. Participants projected associations, metaphors, and narratives onto the interface, revealing the symbolic and cognitive dimensions of material experience.

Together, these four layers provide a holistic lens to evaluate material experience. This framework guided the structure of user evaluation in this study.

7.2.2 Modification of the framework

The Material Experience framework was originally developed to evaluate user engagement with static materials, whose tactile and visual qualities remain constant over time. In contrast, this study focuses on a dynamic, texture-changing surface, in which tactile properties evolve during interaction. This temporal and transformational character introduces two distinctive challenges:

1. **Haptic surface texture:** The study centers on haptic qualities of the material's surface rather than its overall structural or compositional attributes.
2. **Temporality:** The material's perceptual and emotional impact changes as it transitions between states.

7.2.2.1 Adaptation for Temporality

The material was categorized into four modes:

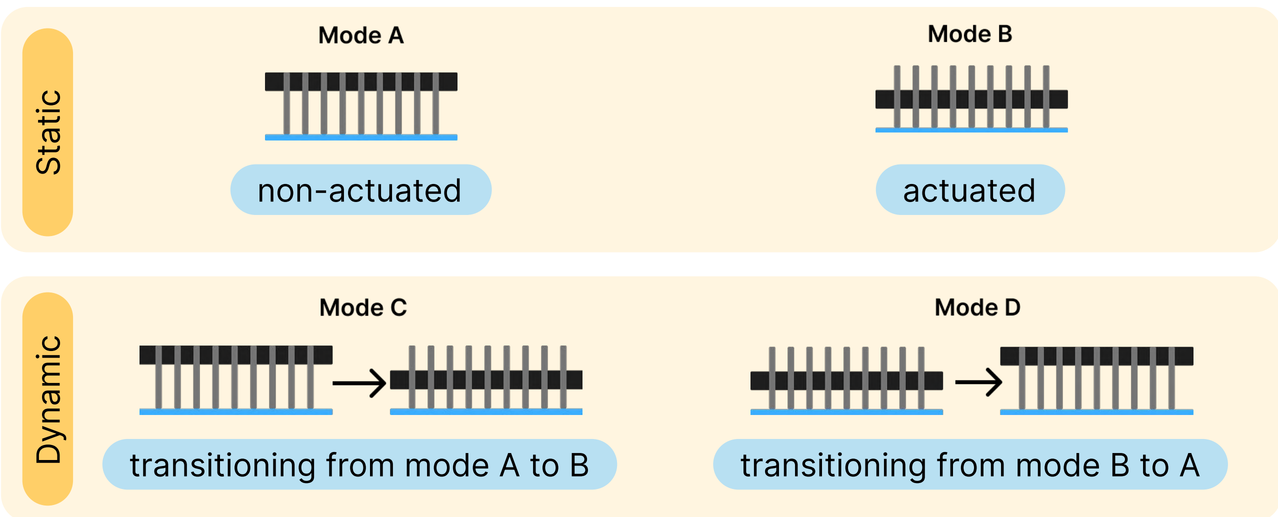


Figure 66. Four modes

The evaluative focus across the four levels of material experience (performative, sensorial, affective, interpretive) was distributed strategically:

- For the two static states (Mode A: non-actuated and Mode B: actuated), users were evaluated on **performative, sensorial, and affective levels.**
- For the two dynamic states (Mode C and Mode D), emphasis was placed on **performative and affective levels**, recognizing the difficulty of extracting a consistent sensorial evaluation during motion.
- The interpretive dimension was assessed holistically, focusing on how participants understood the material's capacity to change—e.g., as responsive, alive, playful, or expressive.

This temporal segmentation enabled a more holistic assessment of the dynamic material.

7.2.2.2 Other Adaptations

Other details of the test were also tailored to the context of this project. (Full questionnaire Appendix D)

- **Performative** experience was captured primarily through video recordings, allowing for later analysis of hand gestures and movement. This unobtrusive method minimized participant's burden.

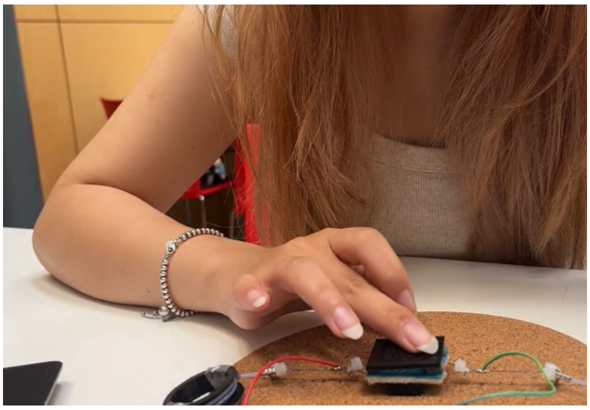


Figure 67. Participant touching the surface

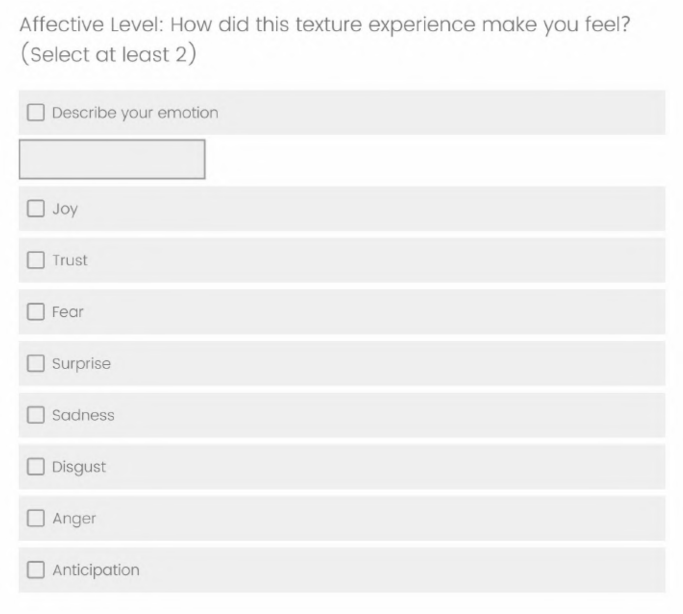
- For the **sensorial level,** given the project's focus on haptic interaction with surface texture, I chose 5 related texture qualities from the Djonov and Van Leeuwen's framework (2011).


Sensory Level: How would you describe your tactile sensation of the surface in the non-actuated phase?

Smooth	○ ○ ○ ○ ○	Rough
Soft	○ ○ ○ ○ ○	Hard
Dense	○ ○ ○ ○ ○	Sparse
Flat	○ ○ ○ ○ ○	Relief
Regular	○ ○ ○ ○ ○	Irregular

Figure 68. Sensorial Questionnaire - Texture qualities rating

- Regarding **affective** level, while the original Material Experience toolkit emphasizes open-ended word selection for qualitative study. I want to aim for both qualitative and quantitative analysis. Participants either described their emotional responses freely or selected from a curated set of core emotional words based on Plutchik's 8 Primary Emotions (1988) (Figure 70). All responses were later mapped onto Russell's circumplex model to derive valence and arousal values.


Affective Level: How did this texture experience make you feel? (Select at least 2)

- [ ] Describe your emotion
- [ ] Joy
- [ ] Trust
- [ ] Fear
- [ ] Surprise
- [ ] Sadness
- [ ] Disgust
- [ ] Anger
- [ ] Anticipation

Figure 69. Affective level questionnaire

Figure 70. Plutchik's 8 Primary Emotions (University of West Alabama [UWA], 2019).

7.3 Testing Procedure

7.3.1 Test Set-up

The user test was conducted in a controlled setting. The moderator was positioned near the power source to operate the actuation, switching the dynamic texture on and off according to the test protocol. A video camera was placed to record the participants' hand movements and interaction behaviour for later performative analysis. A consent form was provided on the table for participants to review and sign prior to the test.

Participants were seated in front of the material sample, which they could freely touch and explore during each condition. After each tactile interaction, they completed a questionnaire on a laptop to evaluate their experience before proceeding to the next mode.

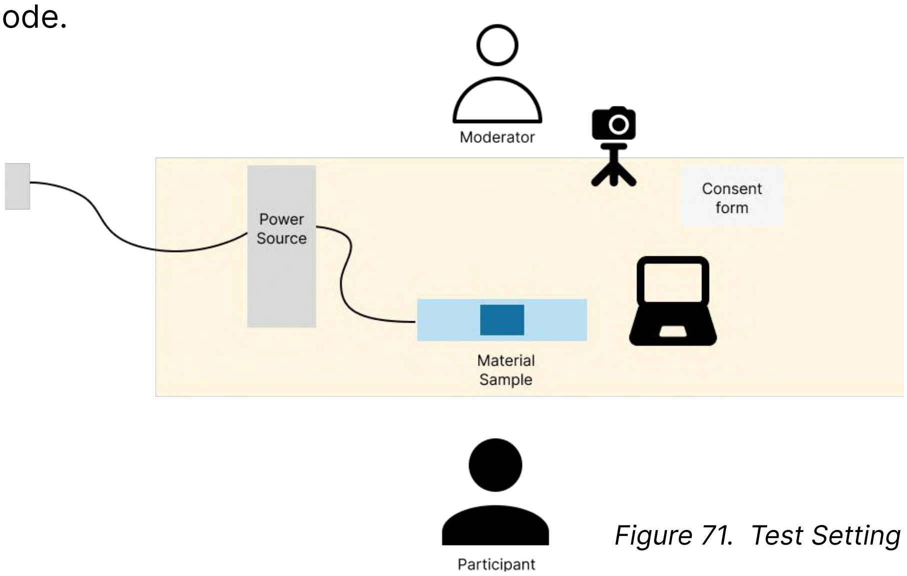


Figure 71. Test Setting

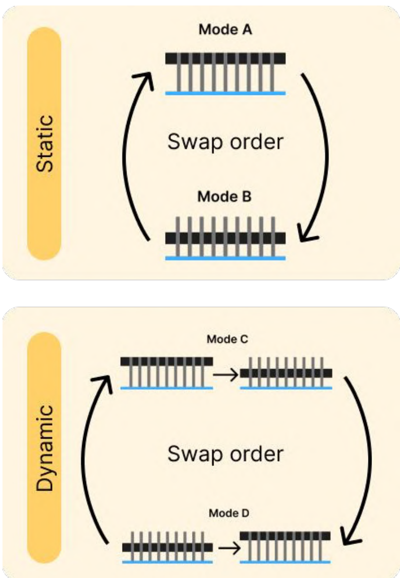


Figure 72. Swapping Testing Order

7.3.2 Testing Order

To avoid the results being affected by the order in which the textures were experienced, the test used a **Latin square counterbalancing** method. In this study, the static textures (A and B) were always tested together as one block, and the dynamic textures (C and D) were tested together as another block, to prevent mixing the two categories during the session. Within each block, the order of the two textures was swapped for different participants. Across the twelve participants, all four possible orders were used the same number of times. (Appendix. C)

7.3.3 Test Process

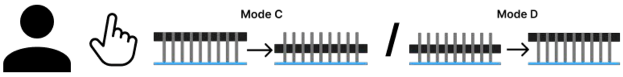
Each session lasted around 10-15 minutes. Participants first arrived at the testing area, where they were welcomed and given a brief explanation of the study's purpose and structure. After signing the consent form, the video recording was started to capture their interaction throughout the session.

	Step 1 - Intro (1 min)	**Step 2 - Static Mode A&B (3 min each)**
		Mode A / Mode B
Participant	1. Walk in the room 2. Brief Intro of the project and testing process 3. Fill in Consent form	1. Touch and play the material for 20-30s (Performative level) 2. Fill in the Sensory level & Emotional level questionnaire
Material	1. Consent form and pen	1. Camera & Tripod 2. Material in Mode A/B 3. Laptop with questionnaire
Backstage (Facilitator)	1. Welcome participant 2. Introduce the project and test(bullet point in script) 3. Help participant with the consent form (remember number the participant) 4. Start Recording	1. Leave user 20-30s to explore the material, encourage them to think out loud 2. Explain the questionnaire
Data	1. Filled consent forms	1. Video record of the performance with the material → Analyze into performative data 2. Sensory & Emotion level data from questionnaire

Figure 73. Journey map of testing process

They were then invited to explore four material modes in sequence—two static textures (A and B) and two dynamic textures (C and D). Each mode was experienced for about 20-30 seconds of free tactile interaction. After exploring each mode, participants completed a short questionnaire: for the static textures modes, they rated five tactile qualities on a Likert scale; for all four modes, they selected one or more emotions.

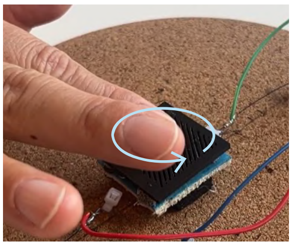
Finally, participants took part in a short interview in which they discussed their interpretation of the material and suggested potential applications.

Step 3 - Dynamic Mode C&D (3 min)	**Step 4 - Interview (5 min)**
	
1. Touch and play the material while it is changing(Performative level) 2. Fill in the Sensory level & Emotional level questionnaire	1. What does this texture-changing material remind you of? 2. If this material were to be, what kind of product or scenario would feel most appropriate?
1. Camera & Tripod 2. Material in Mode C/D 3. Laptop with questionnaire	1. Camera & Tripod 2. Laptop with questionnaire
1. Turn on/off the current 2. Leave user 30s to feel the changing of material, encourage them to think out loud 3. Explain the questionnaire	1. Explain the questions and ask follow-up questions when needed
1. Video record of the performance with the material → Analyze into performative data 2. Sensory & Emotion level data from questionnaire 	1. Interview Answers 

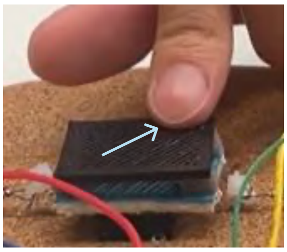
7.4 Data Analysis & Testing Results

This chapter presents the methods used to analyze the data collected from 12 participants who took part in the user study. Both quantitative and qualitative approaches were applied to examine how participants perceived, interacted with, and emotionally responded to the dynamic texture-changing material.

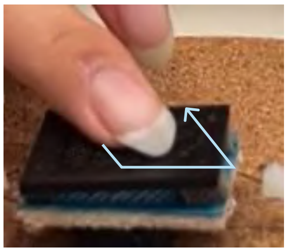
7.4.1 Performative Level



Single-Finger Rub



Single-Finger Slide (single direction)



Single-Finger Slide (different direction)

Single-Finger Tap

Single-Finger Press

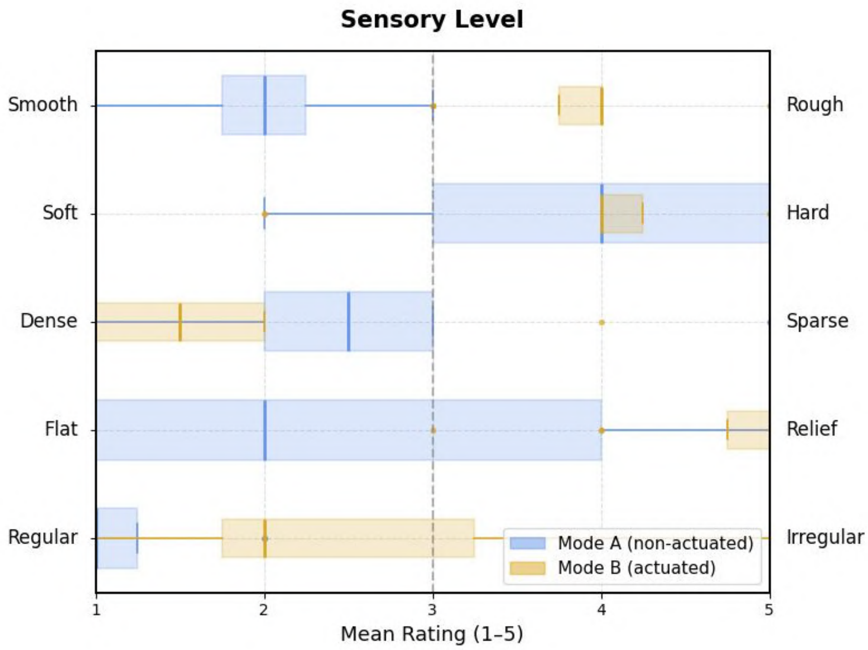
Single-Finger (two hands) Slide

Figure 74. Different Interactions with Texture

> *"You can feel different texture in different directions"*
>
> *"It really feels rough on this side, but smoother when touched the other way around"*
>
> *"When I press it, it becomes a bit spiky"*

Participants employed a variety of gestures to explore the material, such as rubbing, sliding, and tapping. In the static mode, their exploration tended to be more experimental and diverse, involving multiple types of hand movements. In contrast, under dynamic conditions, participants often adopted more restrained interactions, relying primarily on static touch or repetitive gestures like sliding and rubbing.

7.4.2 Sensorial Level



Texture Quality	Mode A (Mean ± SD)	Mode B (Mean ± SD)	p-value	Significance	Effect Size (r)
Smooth:Rough	2.00 ± 0.74	3.92 ± 0.67	0.0028	**	0.883
Soft:Hard	3.83 ± 1.03	3.92 ± 1.00	0.7135	ns	0.442
Dense:Sparse	2.75 ± 1.22	1.67 ± 0.89	0.0080	**	0.770
Flat:Relief	2.42 ± 1.44	4.67 ± 0.65	0.0048	**	0.883
Regular:Irregular	1.25 ± 0.45	2.50 ± 1.31	0.0106	*	0.883

Figure 75. Data Analysis of Sensorial Level

On Smooth–Rough, the two modes show almost no overlap: Mode A is consistently rated smoother, while Mode B is rated rougher, with a significant difference and large effect size. By contrast, Soft–Hard reveals nearly identical means and largely overlapping distributions, with no significant difference ($p = 0.7135$). Dense–Sparse shows a significant shift ($p = 0.0080$, $r = 0.770$), with Mode A perceived denser and Mode B sparser, though the broader variance for Mode A indicates stronger individual differences. The Flat–Relief dimension exhibits the strongest separation: Mode B is consistently judged as more relief-like (4.67 ± 0.65), while Mode A remains flatter but with high variability (2.42 ± 1.44), suggesting that minor surface features or slits may have influenced participants' interpretation of "flatness." Finally, Regular–Irregular ratings are overall biased toward regularity, yet Mode B shifts significantly toward irregularity (A = 1.25 ± 0.45, B = 2.50 ± 1.31, $p = 0.0106$, $r = 0.883$). Taken together, the system effectively altered perceptions of roughness, relief, regularity, and density, while its impact on hardness remained limited.

7.4.3 Affective Level

7.4.3.1 Emotion Transition

Participants' reported words were mapped to eight basic emotions. The proportion of each emotion was then calculated for every mode to identify which emotions were most prominent in each condition.

The analysis revealed that anticipation, fear, joy, surprise, and trust were consistently more prominent across modes. In contrast, anger, disgust, and sadness appeared with proportions close to zero (Full data refer to Appendix F).

Based on these findings, the five most significant emotions were selected for further comparison across the four modes. Bar charts were used to highlight the relative differences in how each mode elicited these emotional categories.

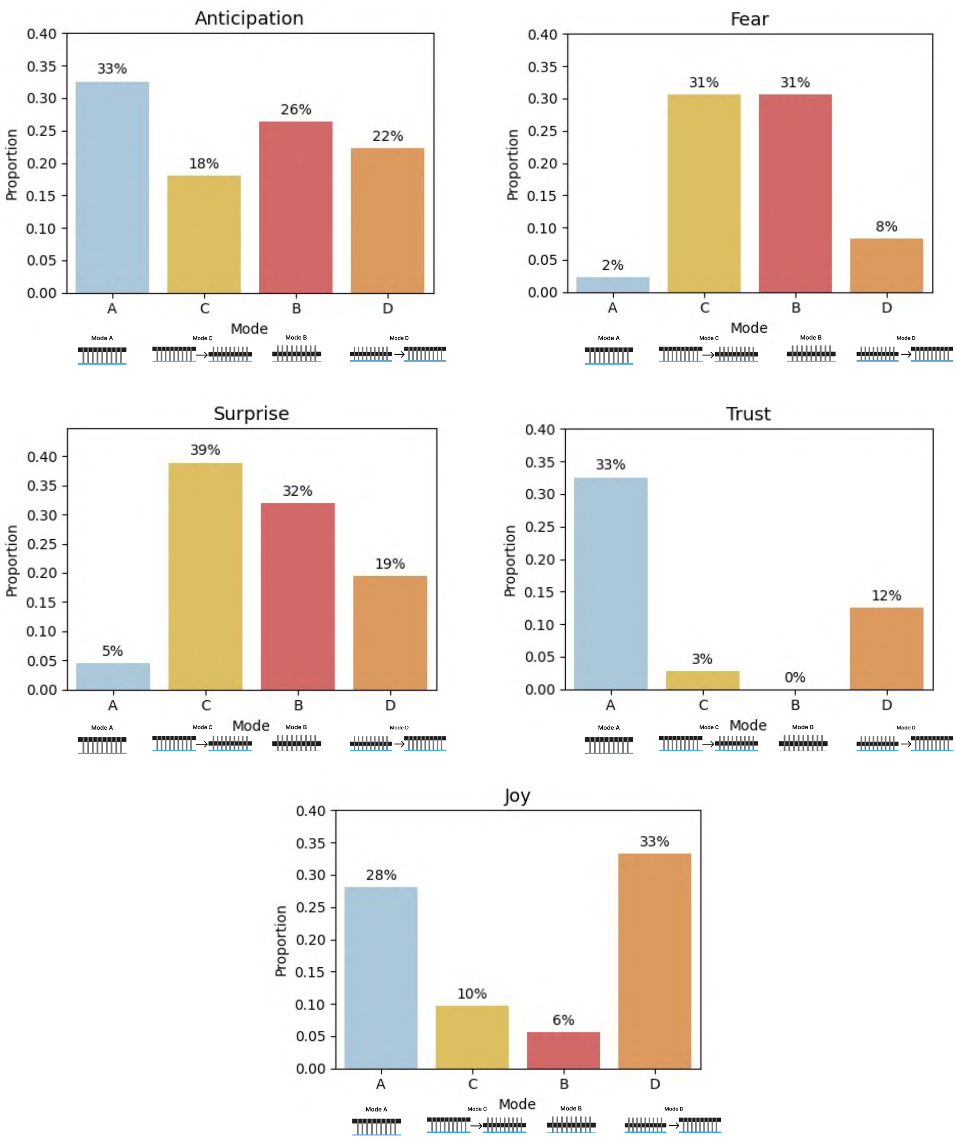


Figure 76. Bar chart for each emotion in time order

Overall anticipation remains high in all modes. Fear shows a clear spike around the "spike-rising" phase—peaking in C and staying high in B—and then drops in D. Surprise rises sharply at C, decreases in B, and further attenuates in D, matching the momentary novelty of spikes followed by adaptation. Trust is highest in A (flat, safe baseline) and D (return-to-flat/recovery), suggesting greater perceived safety at the start and during smoothing. Joy is strong in A and reaches its maximum in D, where the surface gradually flattens during stroking, creating a pleasant relief.

7.4.3.3 Word Cloud for Each Mode

Figure 77. Detailed Emotion for Each Mode

The word clouds reveal the emotional trajectory across interaction modes.
In Mode A, participants felt trust, calm, and anticipation, indicating safety and readiness. In Mode C, as the texture spiked, surprise, fear, and discomfort became dominant, reflecting heightened arousal. Mode B, with sustained spikes, continued to evoke fear and surprise, along with mixed terms like curious and goosebump. Finally, Mode D shows a return of trust and joy, alongside relief, suggesting emotional release as the surface flattens.

7.4.4 Interpretive Level

Half of participants (6/12) described the material as “alive”, “naturally alive”, or “unnaturally alive”. Notably, this perceived aliveness was not isolated from artificial qualities—3 of these 6 also used the word “mechanical” in the same sentence or phrase, suggesting a co-existing perception of biological and technological attributes.

> *“Between alive and mechanical, tension & relief.” – P1*
> *“Playful, intimate, alive, mechanical, protective.” – P12*
> *“Like Velcro, unnaturally alive.” – P2*

Some also suggested that re-designing the appearance of the material sample and hiding the electronic parts can also increase the aliveness.

Furthermore, 4 participants (4/12) used the word “playful,” often in combination with dynamic property and aliveness. These descriptors imply that users perceived the material as possessing intentionality, expressiveness, and even emotion, reinforcing its potential as an affective interface rather than just a responsive surface.

> “Playful, dynamic, alive, only a little bit of aggressive.” – P11
> “Tongue of a cat; alive; teasing.” – P10

In contrast, 3 participants (3/12) associated the material with feelings of discomfort or distrust, using terms like “aggressive,” “suspicious,” and “unnatural.” While less frequent, these responses suggest that dynamic texture change—particularly when sudden or sharp—may evoke defensive or ambiguous emotional associations.

> “Aggressive, suspicious, unnatural.” – P8
> “A needle hidden in cotton, like Chinese martial art.” – P9

These findings highlight that participants did not interpret the dynamic surface merely as a functional material, but as something expressive, intentional, and full of character. The material’s temporal transformation encouraged users to engage in symbolic and emotional meaning-making.

Overall, users attributed rich, multi-layered interpretations to the surface, suggesting that dynamic texture can serve not only as a tactile feature but also as a medium for emotional and social expression. This reinforces the potential of texture-changing materials to function as communicative interfaces in future design applications—capable of conveying mood, intention, and interaction cues through their physical behavior.

7.4.5 Potential Applications

Participants proposed a diverse range of application scenarios for the texture-changing surface, which can be grouped into three main thematic categories:

1. Warning & Defensive Feedback

7 out of 12 participants envisioned the surface as a tool to warn, defend, or deter, particularly in situations requiring safety or awareness. The texture's ability to shift dynamically was understood as an implicit language to signal danger, prevent access, or enforce boundaries.

> *"On the surface of potentially hazardous objects... the surface texture changes to alert them."*
> *"This serves a defensive function, creating fear or deterrence in others."*
> *"A designer's screen that activates a defensive mode when someone tries to point at it."*

These ideas suggest that texture change can act as a non-visual, physical alert system, conveying urgency or restriction without relying on sound or light.

2. Emotional Expression & Communication

4 participants associated the surface with expressive or affective uses, such as regulating emotional states or conveying interpersonal signals. The material's responsiveness was seen as a medium to communicate feelings or create subtle atmosphere shifts.

> *"It can express certain emotions through touch interaction."*
> *"In a long-distance relationship... to express emotions remotely."*
> *"Light mood & vibe; haptic alarms."*

Here, the surface moves beyond functionality to become an intimate emotional interface, useful for affective computing, wearable feedback, or therapeutic support.

3. Notification and Behavior Nudging

Several responses imagined contextual applications where the texture change provides feedback or shapes behavior.

> *"Snack box during diet... to alert and make the user a bit discomforted."*
> *"Focus mode (like phone)."*

> *"Anti-theft pocket device."*
> *"Rest intervention for office seating cushions."*

These use cases reflect the belief that dynamic texture can serve as a subtle nudge, reinforcing behavior or enhancing physical interaction based on context.

7.4.3 Analysis of the User Test Findings

7.4.3.1 Material Experience and Applications

Application	Key Material Traits	Related Experience Insights
1. Alert & Defensive Signaling	High contrast; sudden change; spiky exposure (Mode B/C)	Affective: Surprise, fear, discomfort Sensorial: Smooth → Rough , Flat → Relief
2. Emotional Expression & Regulation	Gradual, reversible transitions (Mode A/D)	Affective: Joy, trust, calm, relief Performative: Stroking, sliding Interpretive: "Feels alive"
3. Behavioral Modulation	Subtle cue; nudging; context-aware guidance (Mode C/D)	Affective: Anticipation, slight discomfort Sensorial: significant difference Performative: Multi-direction slide, posture shift

Figure 78. Application, material traits and related experience

1. Alert & Defensive Signaling
The sudden shift from smooth to spiky textures was consistently linked to defensive or alarming reactions. One participant described it as "It feels a bit like goosebumps, or like skin tensing up when it gets chills," while another emphasized the discomfort: "It gave me a slightly tense feeling, but at the same time it made me curious and want to keep touching it." These reactions show how high-contrast and abrupt transitions trigger immediate attention, making the material particularly suited for warning or protective applications.

2. Emotional Expression & Regulation
Gradual and reversible transitions were perceived as expressive and even alive. One user commented: "I feel relief when the surface becomes smooth" This suggest that the material's temporal morphing can embody emotional states, offering a medium for affective communication. The interpretive layer—"feels alive"— making it effective for emotional expression and interpersonal communication.

3. Behavioral Modulation
Subtle yet perceivable changes in friction and resistance encouraged participants to adjust their behavior. Texture variation can guide users unconsciously, serving as a tactile nudge for behavioral modulation in contexts such as focus, attention, or ergonomic posture adjustment.

7.4.3.2 Qualities of the Material

The user study revealed three key qualities of the material: temporality, contrast, and agency.

Contrastive describes the material's ability to create sharp sensory differences between actuated and non-actuated states. At the sensorial level, this opposition was consistently recognized by participants.

When contrast occurred over time, the experience became a process rather than a static property. Transitions such as smooth to prickly or sharp to soft created a tactile story that participants could feel, and each shift brought out different emotions.

Together, contrastive and temporality converged at the interpretive level to give rise to agentive perceptions. Participants no longer regarded the material as a passive surface but described it as "alive," "playful," "protective," or even "aggressive." In this way, agentive is not an inherent property of the material but the emergent outcome of sensory contrasts experienced through time, embodied in action and infused with emotional meaning.

Importantly, this agentive quality is dynamic and diverse. For some, it appeared as a playful, responsive partner; for others, it signaled rejection or defense. This multiplicity demonstrates that the material's diverse expressiveness is dependent on context.

In summary, the material acts as a temporal performer of tactile contrast, expressing, signaling, and relating. It invites users into an ongoing interaction where meaning is created together.

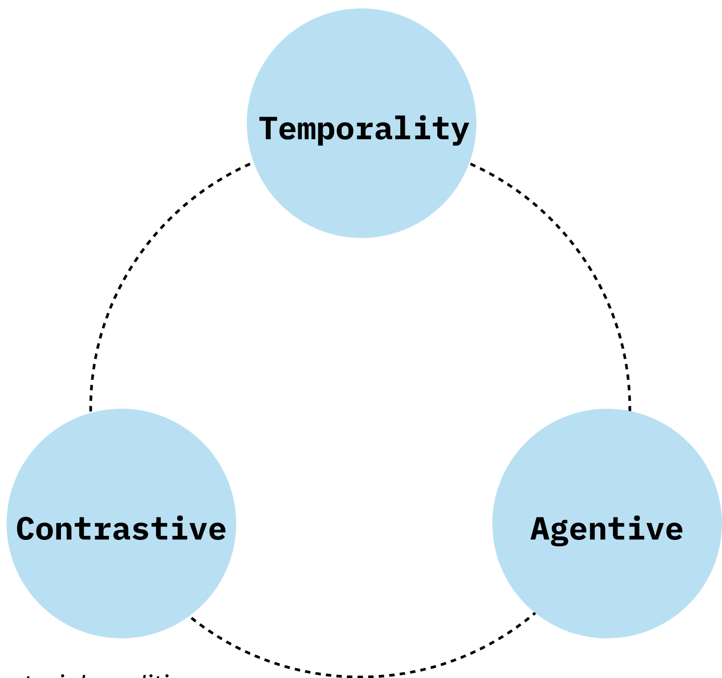


Figure 79. The three material qualities

7.4.3 Reflection on User Test

Conducting this user study raised several methodological challenges that are worth reflecting on. The first difficulty concerned the adaptation of the Material Experience framework to a dynamic material. The original framework was developed for static materials, whereas my prototype introduced temporality and transformation as core characteristics. Integrating these aspects into a structured analysis required me to expand the framework and consider how changes over time shape perception, affect, and interpretation. This adjustment provided valuable insights, but also demonstrated the need for refined tools to study dynamic and evolving materials.

Another limitation was that in Mode D, the material required a longer recovery period before returning to its initial state (about 20s). This sometimes disrupted the flow of the test and may have influenced participants' responses compared to other modes. A potential improvement for future studies would be to refine the actuation control—using circuits to better regulate the speed, duration, and frequency of the texture changes. So that the temporal qualities of the material can be tested more systematically.

The emotional mapping also presented methodological considerations. Initially, I intended to use Russell's circumplex model to analyze valence and arousal (Appendix E). However, the vocabulary provided to participants was not evenly distributed within this model. Instead, I used a categorization based on Plutchik's eight basic emotions. These two frameworks rely on different logics of emotional analysis, which led to a partial mismatch between data collection and analysis. While the use of basic emotions still enabled meaningful results, a more consistent alignment between framework and measurement tool would strengthen future studies.

Overall, the test highlighted both the potential and the complexity of studying dynamic texture-changing materials. It showed how temporality and contrast can significantly affect interpretation, but also revealed the need for tailored research methods that match the unique characteristics of dynamic materials within interaction design.

Summary

This chapter described a user study exploring the expressive potential of a texture-changing surface. Participants' responses were analyzed using the Material Experience framework, covering performative, sensorial, affective, and interpretive aspects.

Emotional responses matched the material's changes: fear and surprise peaked during spike-rising (Mode C), trust and joy were strongest during smoothing (Mode D), and anticipation persisted throughout. Participants could clearly distinguish between smooth and spiky textures, confirming the effects of texture modulation. Participants often described the material as “alive,” “playful,” or “mechanical,” attributing agency to it.

These interpretations show that the material's changes encouraged symbolic and emotional responses.

Participants suggested applications in three areas: alert and defensive feedback, emotional communication, and behavioral nudging.

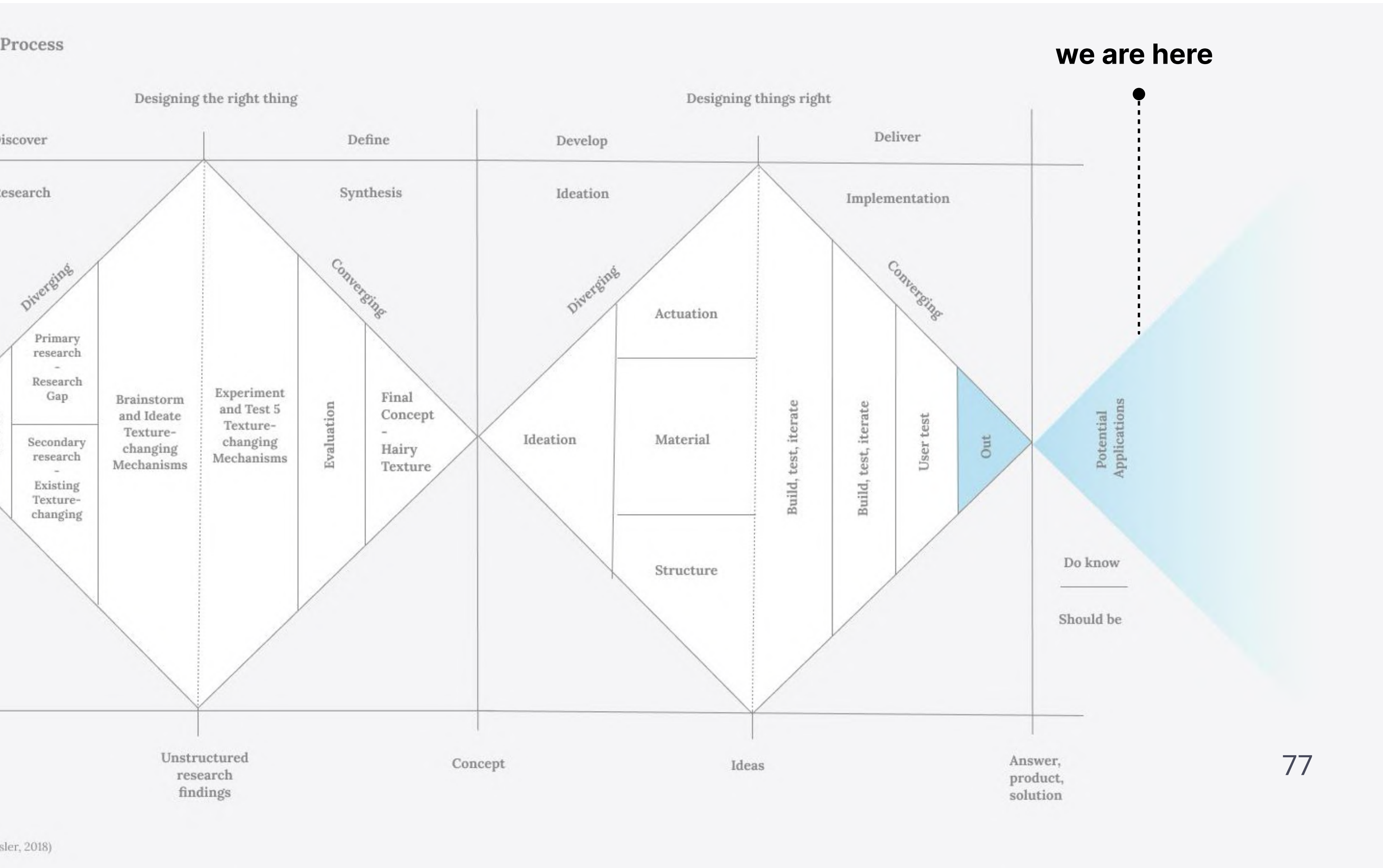
These results support the idea that dynamic textures shape perception and emotion, and that changes over time increase interpretive richness. Overall, texture-changing materials can act as communicative and affective interfaces

Chapter 8

Potential Applications

Building on the user study results, this chapter explores how the identified material capabilities can be translated into concrete applications. Four distinct capabilities—Tactile Contrast, Temporal Morphing, Surface Simulation, and Passive Guidance—capture how the texture-changing material can evoke affective responses, communicate meaning, and subtly guide behavior. Each capability is illustrated through speculative application scenarios that demonstrate its potential in everyday, social, and immersive contexts.

Figure 80. Roadmap of Design Process (based on Double-Diamond)



8.1 Material Capabilities

Based on the results of the user study, a set of core material qualities was identified, reflecting how participants experienced and interpreted the dynamic texture across different interaction stages.

Drawing from this data, I identified four material capabilities. These abilities describe what the material is particularly suited for, and how it can be deployed in diverse interaction contexts.

1. Tactile Contrast: Characterized by a sudden shift between smooth and sharp states, this property enables the material to produce surprise, discomfort, or aversion. It is particularly effective in contexts requiring alert, defense, or boundary reinforcement.
2. Temporal Morphing: When changing from sharp to smooth, this property evokes affective responses such as calmness, trust and relief. It supports applications focused on emotional expression, mood regulation, or affective communication.
3. Surface Simulation: This property enables the material to reproduce different surface textures. It is applicable in learning, storytelling, or immersive environments.
4. Passive Guidance: Through subtle modulation of the tactile feeling, the material can influence physical perception and behavior. This ability lends itself to behavioral nudging, posture correction, or attention management.

In the following section, each category is elaborated through illustrative examples.

Material Ability	Behavioral	Core Capability	Potential Applications
1. Tactile Contrast	Sudden transition from smooth → spiky	Strong contrast interrupts continuity and triggers surprise	Defense, warning, boundary enforcement
2. Temporal Morphing	Gradual transformation over time	Temporal flow evokes a sense of life or companionship	Emotion regulation, affective communication
3. Surface Simulation	Reproduction of different textures	Simulates material texture in digital world	Immersive experience
4. Passive Guidance	Subtle but perceivable tactile nudges	Changes in friction/grip subtly alter micro-behavior	Behavior correction, attention guidance

Figure 81. Four Material Capabilities

8.2 Tactile Contrast for alert or defence

8.2.1 Privacy Spike (outward texture)

Privacy spike is a wearable interface embedded in the upper back or shoulder area of clothing. It is designed to signal the wearer's need for personal space in shared environments, such as libraries, studios, or classrooms.

When someone enters a predefined proximity—such as reaching to tap the wearer's shoulder—the system activates and triggers a sudden texture change on the surface. The patch shifts from smooth to spiky within a localized area, creating a physical barrier that discourages further approach.

It provides a non-verbal, physical signal to others without talking. The system can be used to prevent interruptions during focused work, maintain social distance, or reinforce spatial boundaries in public or semi-public settings.

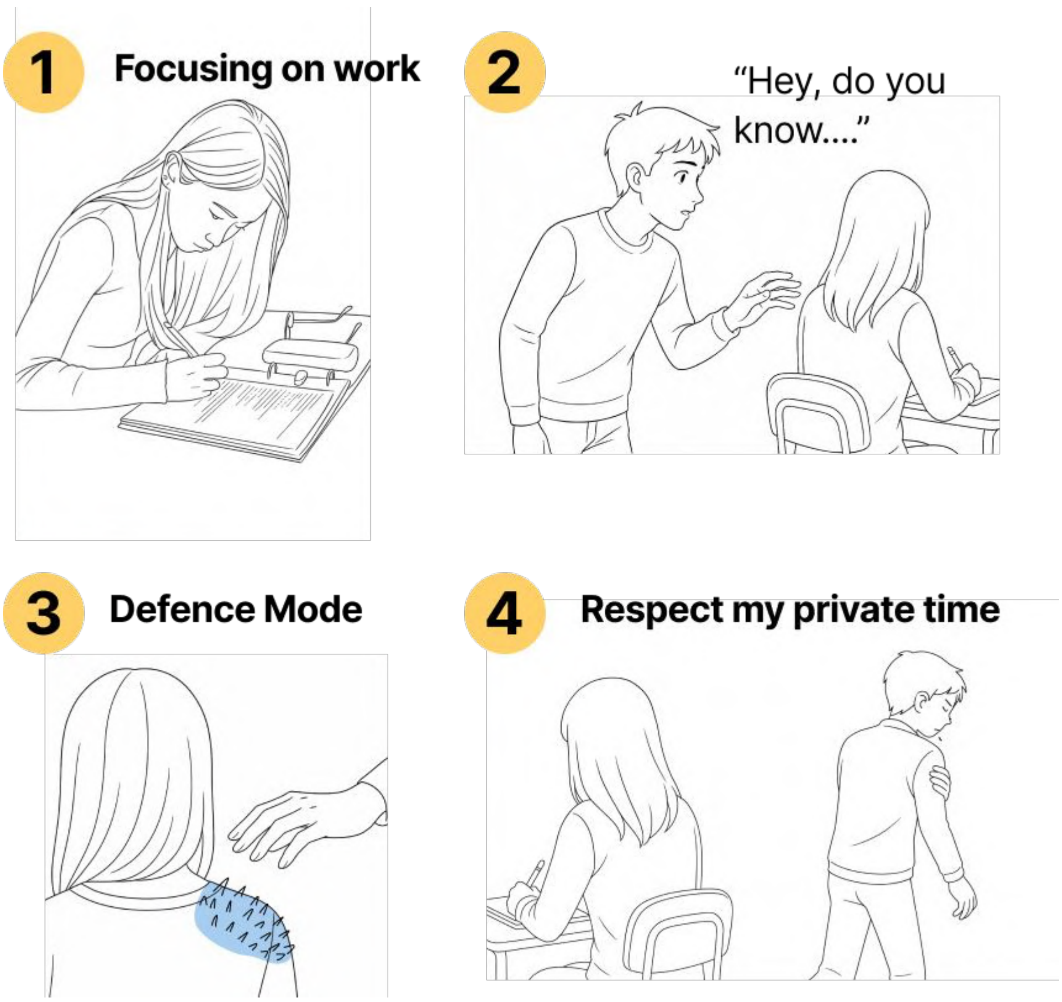


Figure 82. Privacy spike concept

8.2.2 Focus Band (inward texture)

Focus band is a wearable device designed to support concentration in tasks that require sustained attention, such as studying or attending lectures. The device takes the form of a thin, flexible band worn on the wrist or neck.

When the user is sleepy, the surface begins to change from smooth to spiky. The band poke the user frequently to alert the user to pay attention. This sensation serves as a physical prompt to refocus attention without relying on visual or auditory signals.

When the user adjusts their posture or resumes active engagement, the texture returns to its original state. The device provides a direct, embodied feedback mechanism for managing lapses in focus in quiet or shared environments.

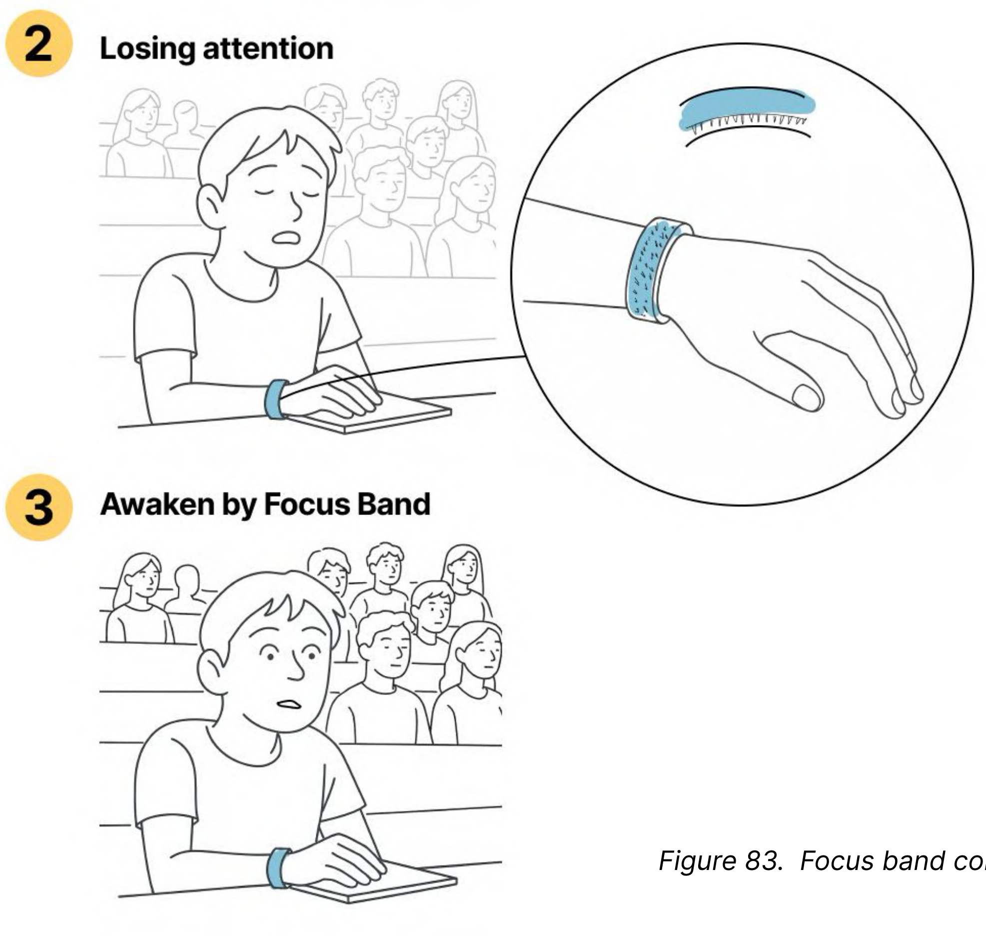


Figure 83. Focus band concept

8.3 Temporal Morphing for emotional communication

8.3.1 Stroke me, soothe me

Stroke Me, Soothe Me is a bidirectional tactile interface designed for emotional expression and interpersonal regulation in long-distance relationships. The system consists of two paired devices, each embedded with a texture-changing surface that responds to emotional input and touch interaction.

When one partner experiences emotional distress—such as anger, frustration, or withdrawal—the surface of their device transitions from smooth to raised, forming a coarse or spiky texture (like cat getting scared). This change is transmitted in real-time to the paired device, alerting the other partner through a non-verbal, tactile cue.

The receiving partner can then respond by gently stroking the surface. As continuous, calming touch is applied, the texture gradually returns to a smoother state. The texture slowly returns to smoothness, reflecting the calming of emotions.

This system supports mutual emotional communication in contexts where direct touch is limited.

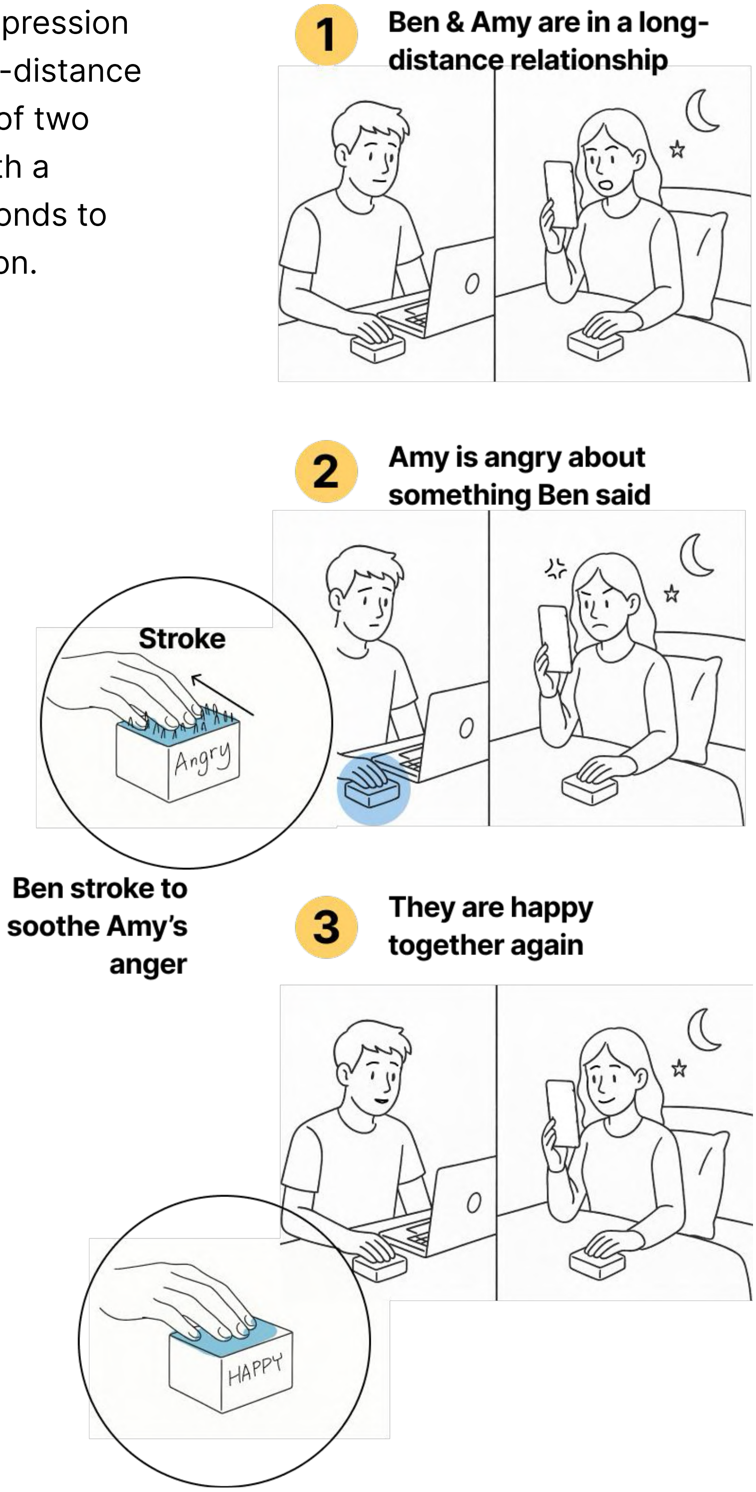


Figure 84. Temporal Morphing Concept

8.4 Tactile Simulation

8.4.1 Texture simulation in Virtual Reality

In virtual environments, visual and auditory stimuli predominate, while the lack of tactile feedback constrains realism. Texture-changing surfaces address this limitation by simulating contact with otherwise intangible virtual elements. For example, as a user navigates a virtual forest, a wearable surface can transition from smooth to rough, replicating the sensation of branches or rocks. This conversion of virtual cues into physical sensations increases immersion and fosters a more embodied sense of presence.

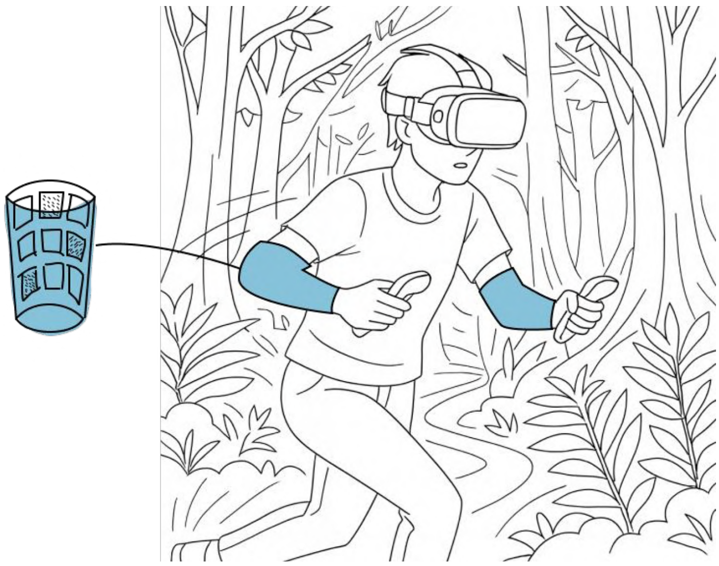


Figure 85. Tactile simulation in VR game

8.4.2 Texture simulation for Education

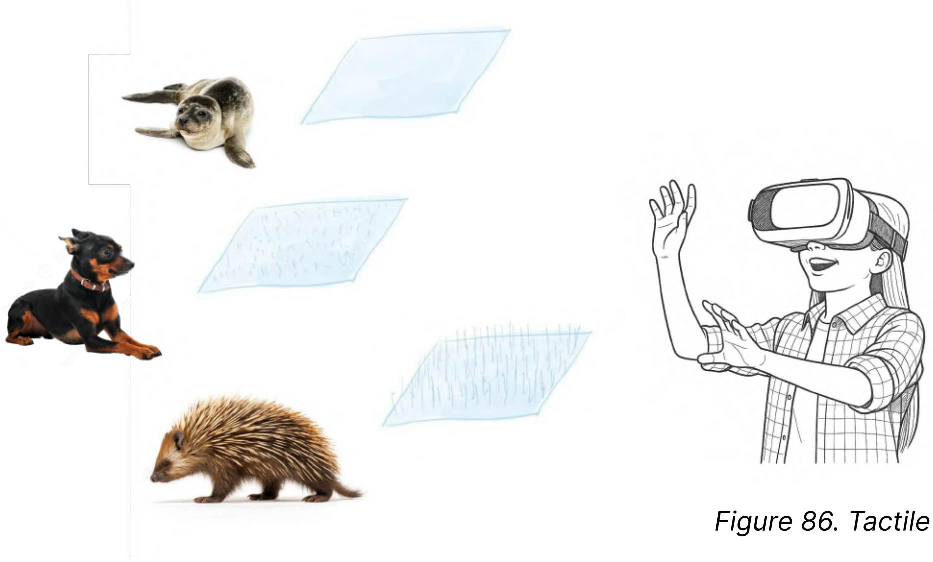


Figure 86. Tactile simulation in VR education

In educational settings, texture-changing materials provide tangible references for abstract or inaccessible concepts. For instance, when students study animals, the surface can reproduce different texture of fur.

8.5 Passive Guidance for behavior change

8.5.1 Break Reminder

Break Reminder Surface is a tactile interface designed to support healthy work rhythms by providing non-intrusive cues for rest. The device takes the form of a touchpad coated with a texture-changing layer.

If you are working too long, the surface gradually shifts from smooth to increasingly coarse to remind you to take a break. This change creates a growing sense of resistance and discomfort when the user continues to work.

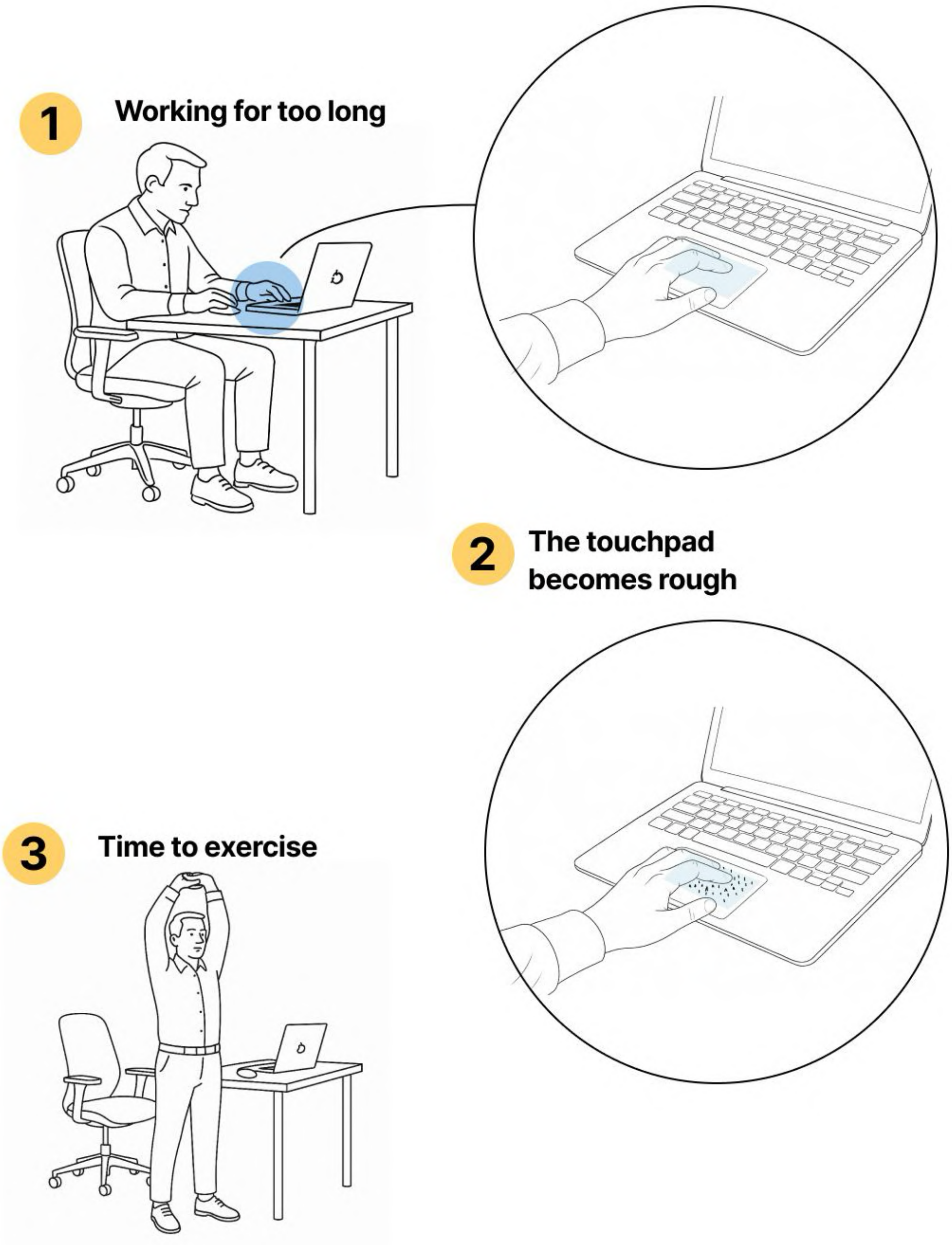


Figure 87. Break reminder concept

Summary

This chapter demonstrated how the core material capabilities identified through user studies can be mapped onto diverse application domains.

Tactile Contrast enables sudden, defensive signals for alertness or personal space management.

Temporal Morphing supports emotional communication by translating shifts in texture into affective cues.

Surface Simulation extends the material into immersive and educational contexts, enhancing realism and tangibility.

Finally, Passive Guidance shows how subtle tactile modulation can nudge behavior, such as promoting rest or sustaining focus.

Together, these applications illustrate the wide-ranging expressive and functional potential of texture-changing materials, positioning them as a promising foundation for future wearable and interactive systems.

Chapter 9
Discussion & Future Work

8.1 Material Advantage

Thinness and High Resolution

This project demonstrates the clear advantages of the developed texture-changing surface over existing systems. Unlike bulky, multi-layered structures, this design is thin, lightweight. Its external actuation mechanism eliminates the need for embedded thick structure underneath the surface. The fine, hair-based resolution enables subtle, perceivable texture changes that conventional large-scale systems cannot achieve.

Silent and Non-mechanical Actuation

The interaction is also improved through a tube-guided shape memory alloy (SMA) system, which operates silent actuation. This makes the surface suitable for a wider context, such as wearable devices in work or study settings, and allows it to blend unobtrusively into daily life.

Accessible Fabrication

The fabrication process also offers significant benefits. Because the structural components, such as the slit layer, can be rapidly prototyped through 3D printing. Designers can adjust spacing, thickness, or orientation according to their “hairy layer”.

Cost-effectiveness

The material system is cost-effective, using mostly readily available components. The only moderately expensive element is the commercially available SMA actuator. This balance keeps costs low while maximizing expressive potential.

8.2 Material Limitations

Response Time

A key limitation of the current prototype is its slow actuation and recovery time. The tube-guided SMA system relies on heating and cooling cycles, resulting in a full activation time of about 10 seconds and a recovery time of 20 seconds. This delay reduces the immediacy of interaction, especially when rapid or repeated tactile feedback is needed. Potential improvements include increasing the current for faster heating, using thinner SMA wires to speed cooling, or redesigning the structure for better heat dissipation. These changes could make the material more responsive to user input.

Multi-state Control

Another limitation is the limited range of controllable states. While the design aimed to produce a spectrum of tactile sensations by varying the slit layer's position, the current system only switches between two states: fully concealed and fully exposed. Achieving more nuanced tactile feedback would require finer control of the SMA's contraction, possibly by modulating current in short impulses in programme.

8.3 Future Work

Prototype Refinement and Integration

Future work will refine the prototype's appearance and attachment methods. Since the current design is fragile and not optimized for integration, subsequent versions may use fastening strategies such as Velcro, clips, or modular housings to improve stability and adaptability. The SMA coiling system also presents opportunities for redesign; planar or alternative coiling geometries could enhance conformity to flat substrates and improve wearability. Additionally, refining program control of SMA heating and cooling could enable more precise and reliable regulation of texture states, maintaining intermediate positions.

Material Variations

Further research may incorporate alternative tactile substrates beyond the current metal bristle fabric. Because the mechanism itself is material-agnostic, substituting hairy, fibrous, or custom-designed textures could enable a broader spectrum of sensations.

Patterned Surfaces

Arranging multiple modules in parallel could facilitate the creation of programmable patterns for guiding touch, forming symbolic imagery, or delivering complex haptic feedback across a surface.

Dynamic Temporal Qualities

Future studies could investigate the influence of temporal rhythms on user perception. As the material is inherently dynamic, aspects such as actuation speed, sequence, or oscillation patterns may elicit novel affective responses. For instance, varying the tempo of transitions could convey soothing or alerting qualities, introducing an additional expressive dimension to the interface.

Integration with Sensing and Context Awareness

A longer-term objective is to integrate the material into interactive systems that respond to user context. Pairing with sensors that detect proximity, physiological signals, or environmental cues, it would allow the material to adapt dynamically to situational needs, functioning as a responsive, intelligent layer within daily environments.

Chapter 10
Conclusion

This thesis set out to address a central gap in wearable haptics: the absence of thin, high-resolution materials capable of dynamic texture change. While existing systems rely on bulky pneumatic or motorized solutions, they remain difficult to integrate into the body as expressive, emotional interfaces. The research asked how texture could move beyond a static property and become a communicative, temporal medium.

Through iterative exploration and performance-based comparison, the work converged on the design of a Hairy Texture mechanism actuated by a tube-guided SMA system. This solution is thin, lightweight, silent, allowing seamless integration into wearable contexts without motors or pumps. User studies confirmed its experiential value: the material produced strong contrast, temporal transitions, and a sense of agency, enabling it to evoke emotions and diverse interpretations ranging from aggressiveness to playfulness. In application terms, the material demonstrated potential for alert and defense, emotional expression, and behavioral guidance.

The main advantages lie in thinness, flexibility, fine tactile resolution, and low-cost fabrication. At the same time, limitations remain. The SMA actuation is relatively slow (≈10s activation, ≈20s recovery), constraining responsiveness. Moreover, the system currently affords only two primary states, whereas richer multi-state control would expand its expressive vocabulary. These tensions reflect both the promise and the current immaturity of the concept.

Future work should optimize actuation improved thermal management, and structural refinements that allow faster cycles and stable intermediate positions. Beyond technical improvements, the material invites speculative directions: modular arrays forming tactile patterns, alternative bristle or hair-like substrates producing diverse sensations, and integration with sensing systems for context-aware interaction. Further studies may also examine how rhythms of change shape affect and communication.

In sum, this project demonstrates a thin, high-resolution texture-changing material that transforms surface touch into an expressive medium, opening new possibilities for wearable haptics.

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Personal Project Brief – IDE Master Graduation Project

Name student Yuxuan Liu

Student number 6008992

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title Texture-changing Wearable Haptic Skin for Emotion and Perception Influence

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

Introduction

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

This project aims to empower designers to view texture as a dynamic and designable element, enabling them to shape tactile sensations and emotional experiences in product design. While surface textures play a critical role in shaping user experiences, existing approaches largely rely on static material properties or vibration technologies, which fail to replicate the complexity of natural textures and rich emotion it brings (Figure 1). However, this research explores how programmable materials can transform textures into interactive, adaptable features, offering designers greater control over the emotions and sensations their products evoke. (Figure 2)
The goal is to develop texture-changing interfaces that allow surfaces to dynamically adjust properties like relief, rigidity, and complexity. By using programmable materials such as pneumatics and shape memory alloys, these interfaces can respond to user interactions or other factors. This opens up new opportunities for products to communicate emotions like comfort, excitement, or calmness, fostering deeper connections between users and products.

→ *space available for images / figures on next page*

introduction (continued): space for images

click to add picture

image / figure 1 Current Process of Texture Design

image / figure 2 Envisioned Process of Texture Design

Problem Definition

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

While tactile sensations are critical in forming emotional connections, the design of texture is often constrained by static material properties. Designers lack tools to create dynamic textures that respond to interaction or convey varied emotional cues, leaving a gap in delivering richer, more immersive tactile experiences.
In the field of morphing materials, research has primarily emphasized macro-scale transformations, such as bending or folding structures. However, micro-level texture modulation, which deals with intricate surface changes that directly influence tactile feedback, has received less attention.
The research aims to result in a toolkit that designers can use to integrate surface texture as a designable and interactive component in their work. By transforming texture into a dynamic medium, this project empowers designers to create products that go beyond static material attributes, fostering deeper user engagement and emotional connection.

Assignment

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

Design a toolkit for creating texture-changing interfaces that empower designers to integrate tactile surfaces as adaptive and interactive components in product design.

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

Literature Review:
Research morphing materials and their role in texture modulation.
Study the emotional connection between touch, texture, and user experience.

Prototyping & Experimenting:
Experiment with technologies to manipulate texture qualities. Compare methods to identify effective solutions for dynamic texture changes.

Conceptualization:
Design and build a system enabling designers to create dynamic, texture-changing interfaces

User Test:
Conduct user studies to evaluate the emotional and sensory impact of the textures-changing interface.

Project planning and key moments

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

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

Kick off meeting	13 Feb 2025
Mid-term evaluation	24 Apr 2025
Green light meeting	19 Jun 2025
Graduation ceremony	17 Jul 2025

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

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

Comments:

Motivation and personal ambitions

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

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

I have always been drawn to the quiet, unspoken dialogue between people and objects—the subtle sensations that arise when your fingers brush against a surface. Touch and tactile experiences hold a special place in my design philosophy. Even as I delved into interaction design, my fascination with the materialization of interactions persisted. I have always valued the dynamic, tangible qualities of physical products and the way they communicate through touch.

I have never seen products as static. It should be inherently “touchable” and "Interactable". I believe that touch is a form of communication. When we touch a product, and it responds to us, an emotional flow is established. I am captivated by the unconscious, subtle feelings that emerge through tactile interactions—the emotions conveyed through the skin as it meets a surface. This is something that we are increasingly losing in the digital age. My passion lies in reclaiming that connection, designing products that foster meaningful, sensory-rich interactions. Through my work, I hope to bring touch back into focus as an essential element of communication and emotional resonance in design.

Appendix A. Test Plan

Exploration

Research Question

1. In what ways does a dynamic texture-changing wearable surface mediate users' tactile interaction, sensory perception, and emotional states across distinct temporal phases (before, during, and after actuation)?
2. What potential application scenarios and design implications can be derived that?

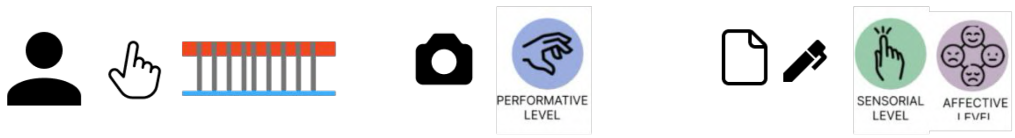
H1: The texture-changing surface will elicit significant difference in users' self-reported emotional states (valence and arousal) between pre-actuation and post-actuation phases.

H2: Temporality of the dynamic texture change will shape how users interpret and emotionally respond to the surface during the actuation process.

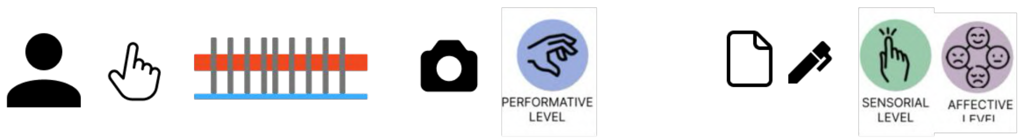
Phase 1 - Experience

Phase 2 - Evaluation

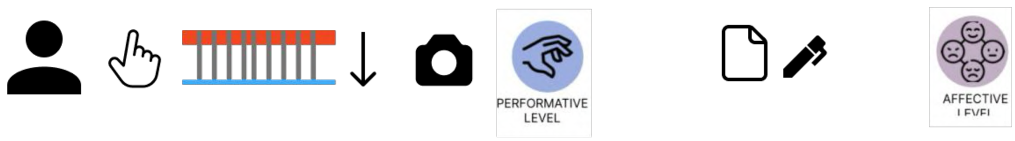
Mode A: Before Actuation



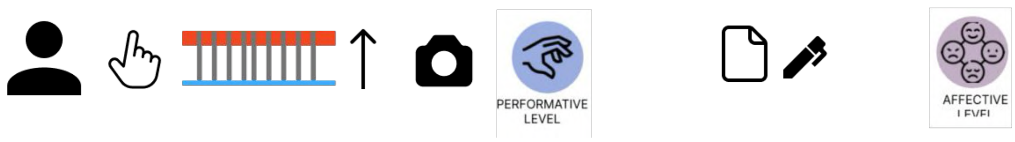
Mode B: After Actuation



Mode C: During Actuation (A→B)



Mode D: During Actuation(B→A)



Phase 3 - Interview

1. "Where do you imagine this texture-changing surface could be useful?"
2. "How did you experience the changing of the texture?"
3. "Would you rather wear it, hold it, or use it in your surroundings?"

Validation

In Exploration phase, we identify the evoked sensory and emotion. We have some hypothesis that we think this texture-changing interface can be useful.

Now we want to explore.
In what ways do shape-changing materials mediate users' affective and sensory engagement with the artifact?

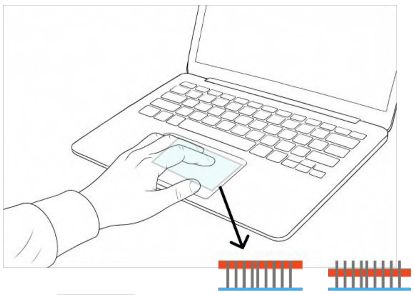
To validate whether the texture-changing wearable surface can reliably evoke specific affective and sensory responses when embedded in designed contextual scenarios derived from exploratory findings.

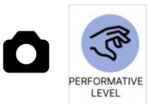
Scenario 1 **Hypothesis 1**

The dynamic texture change will trigger emotion of surprise, alertness

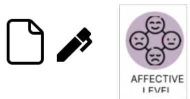
Experience

You are working on your Laptop.





Evaluation



Interview

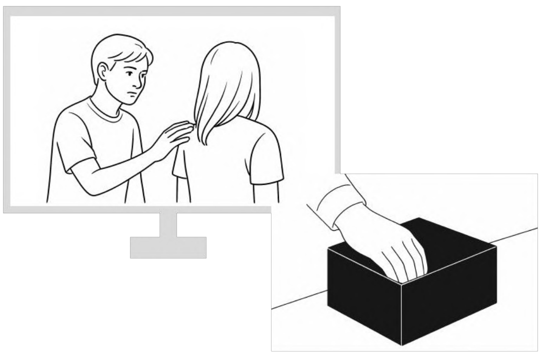
"What do you think it is telling you?"

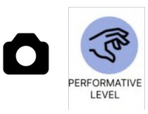
Scenario 2 **Hypothesis 2**

texture-changing surface will evoke feelings of rejection or discomfort

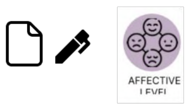
Experience

You are walking towards someone wanting to talk





Evaluation



Interview

"What do you think it is telling you?"

Appendix B. Consent Form

Participant ID: ....

Texture-changing Wearable Haptic Skin for Emotion and Perception Influence

This research is conducted as part of the MSc study Industrial Design Engineering at TU Delft.

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research consists of the following activities:

1. Completing a questionnaire about sensory, emotional, and interpretive responses to different tactile surfaces.
2. Interacting with a texture-changing material while being optionally observed or recorded for research purposes.

I am aware that data will be collected during the research, such as notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. Data will be processed and analysed anonymously (without your name or other identifiable information). The data will only be accessible to the research team and their TU Delft supervisors.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project.

I give permission for using photos and/or video recordings of my participation:
(select what applies for you)

- ☐ in which I am <u>recognisable</u> in publications and presentations about the project.
- ☐ in which I am <u>not recognisable</u> in publications and presentations about the project.
- ☐ <u>for data analysis only</u> and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes.

I acknowledge that no financial compensation will be provided for my participation in this research.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

The researchers take the applicable COVID-19 measures into account. I confirm to respect the COVID-19 measures taken and will follow instruction about these provided by the researchers.

I will receive a copy of this consent form.

______________________	______________________
Last name	First name
___ / ___ / 2024	______________________
Date (dd/mm/yyyy)	Signature

Appendix C. Testing Order

Participant	Static-1	Static-2	Dynamic-1	Dynamic-2
1	A	B	C	D
2	B	A	D	C
3	A	B	D	C
4	B	A	C	D
5	B	A	D	C
6	A	B	C	D
7	B	A	C	D
8	A	B	D	C
9	A	B	C	D
10	B	A	D	C
11	A	B	D	C
12	B	A	C	D

Appendix D. User Test Questionnaire

Guaduation Project

Start of Block: Participant Information

Welcome to the Tactile Interaction Experience Survey Thank you for participating in this study! This research explores how people emotionally and physically respond to dynamic, texture-changing wearable surfaces. Your feedback will help us better understand how tactile textures influence sensory perception, emotional response, and personal interpretation. The study is divided into a few short sections: You will touch and explore **four** different surface conditions. After each interaction, you will be asked to describe your **sensory** impressions (in some cases), and your **emotional** response. At the end, we will ask a few questions about your overall impression, including any **associations, metaphors, or potential application** scenarios that came to mind. There are no right or wrong answers — please respond intuitively based on what you feel. If at any point you feel uncomfortable or wish to stop, you are free to do so without any consequences.

Q1 What is your participant number

____

End of Block: Participant Information

Start of Block: Static Modes

Q2 Which static mode did you experienced?

○ Mode A: non-actuated (1)

○ Mode B: actuated (2)

End of Block: Static Modes

Start of Block: Mode A: non-actuated

Mode A: non-actuated **Mode A: Non-actuated**

Page 1 of 8

A1 Sensory Level: How would you describe your tactile sensation of the surface in the non-actuated phase?

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	
Smooth	○	○	○	○	○	Rough
Soft	○	○	○	○	○	Hard
Dense	○	○	○	○	○	Sparse
Flat	○	○	○	○	○	Relief
Regular	○	○	○	○	○	Irregular

*

A2 Affective Level: How did this texture experience make you feel? (Select at least 2)

- ☐ Describe your emotion (1) ________________
- ☐ Joy (2)
- ☐ Trust (3)
- ☐ Fear (4)
- ☐ Surprise (5)
- ☐ Sadness (6)
- ☐ Disgust (7)
- ☐ Anger (8)
- ☐ Anticipation (9)

End of Block: Mode A: non-actuated

Start of Block: Mode B: actuated

Mode B: actuated **Mode B: Actuated**

Same for Mode B

Q3 Which dynamic mode did you experienced?

- ○ Mode C (1)
- ○ Mode D (2)

End of Block: Dynamic Mode

Start of Block: Mode C

Mode C **Mode C**

C1 Affective Level: How did this texture experience make you feel? (Select at least 2)

- ☐ Describe your emotion (1) ____
- ☐ Joy (2)
- ☐ Trust (3)
- ☐ Fear (4)
- ☐ Surprise (5)
- ☐ Sadness (6)
- ☐ Disgust (7)
- ☐ Anger (8)
- ☐ Anticipation (9)

End of Block: Mode C

Start of Block: Mode D

Mode D **Mode D**

Same for Mode D

Final You've now explored all four surface conditions. In this final part, we ask you to reflect on your experience as a whole — not just how it felt, but what it reminded you of, and where you imagine it could be used.

Q4 **Interpretive Level: What does this texture-changing material remind you of?** What do you associate it with? Does it seem to carry an intention? If it were a metaphor, what would it stand for? *Example: Playful, shy, aggressive, protective, deceptive, cold, intimate, distant, familiar, guarded, mischievous, unnatural, alive, mechanical...*

____

____

____

Q5 **Potential Applications: Where do you imagine this texture-changing surface could be useful?** Would you rather wear it, hold it, or use it in your surroundings?

____

____

____

____

____

Appendix E. Valence & Arousal Mapping

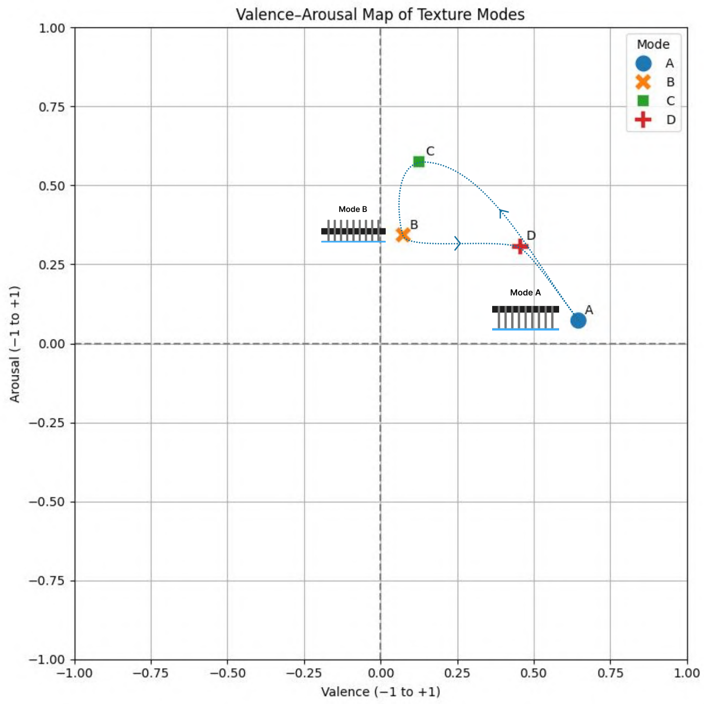


Figure X. Valence-Arousal Map of Texture Modes

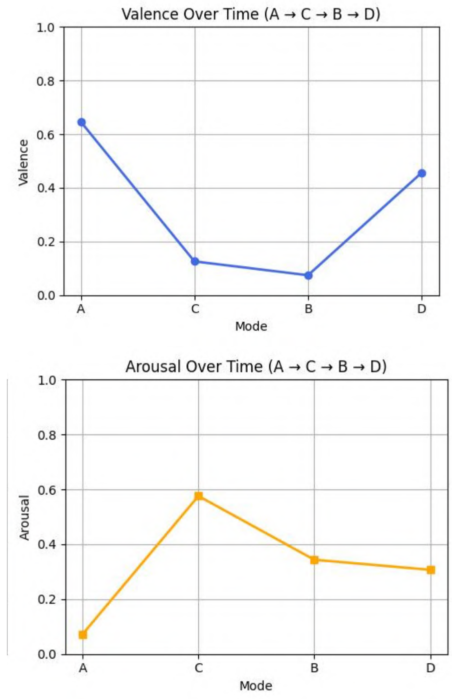


Figure X. Valance and Arousal Over Time

	Mode_Simple	Valence Mean	Arousal Mean	ΔValence	ΔArousal
0	A	0.646278	0.072139	NaN	NaN
1	C	0.125861	0.575806	-0.520417	0.503667
2	B	0.074194	0.343444	-0.051667	-0.232361
3	D	0.456333	0.306833	0.382139	-0.036611

Appendix F. Emotion Distribution Across Modes