Sentura: Understanding the Cognitive Affordances of Silicone Microtextures in Tangible User Interface Design

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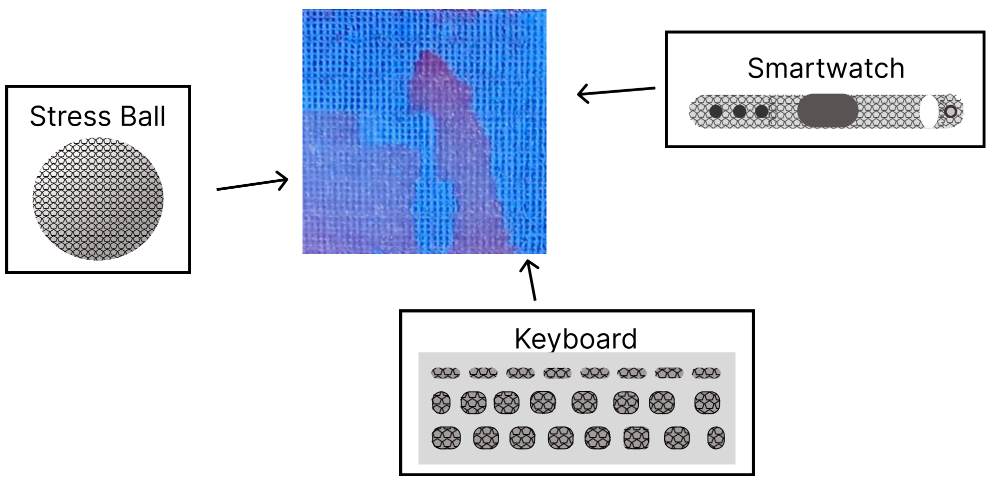

Figure 1: The Pits Texture. The Pits texture, made from cast silicone, features depression geometries of 0.53 mm by 0.5 mm and a spacing of 1.06 mm apart. A tap gesture was one of the preferred methods of stimulation, for which it was perceived as smooth, soft, silky, and fuzzy. Value could be found in applications such as wearable devices, haptic devices, and sensory devices.

ABSTRACT

Silicone has long been an influential material in haptic design due to its durability, flexibility, and versatility. However, its flat and smooth surface restricts potential applications. Using microtextures, we can improve on earlier designs by exploiting microtextured silicone's sensory perception and influence on users' emotions and feelings. In this paper, we explore the applications and benefits of microtextures in haptic design. We conduct a between-subjects psychophysics experiment to characterize the sensory perception of each texture using an adapted form of the Geneva Emotion Wheel. We also report the results of a card sort elicitation task to better understand how textures can improve and influence user actions for tactile user interface applications. Finally, we analyze the results and discuss the unique features of each silicone sample that contributed to users' experiences, as well as potential future implementation in textiles, wearable devices, and robotics.

CCS CONCEPTS

• **Human-centered computing Human computer interaction (HCI)**; *Haptic devices*; User studies.

KEYWORDS

digital fabrication, craft, design tools, molding, casting, laser engraving, haptic interfaces, microtexture

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1 INTRODUCTION

We evaluate silicone microtextures to explore their influence on users and potential applications in haptic design. Traditional uses of silicone have taken a variety of forms, from sensors to model organs to wearable garments. These designs can be improved with the use of microtextures since they allow designers and users to think beyond its utility and consider the enhanced sensory experience and cognitive affordances it can create. We use the Castura micro molding technique [6] to create silicone samples for use in haptic design. In this paper, we conduct a user study to understand its applications in haptic design and how silicone geometries can inform gestures.

2 RELATED WORK

2.1 Haptic Design

Spidey Sense is a wristband that is compatible with Apple Watch devices. It contains a component that gently squeezes a user's wrist to alert them of important notifications [2]. This is a great application for microtextures, as they can evoke sensations in users without the need for other technology.*McKibben Muscles* [1] took this one step further with "wearable choreographers" – a hollow silicone tube of enclosed filaments placed on dancer's legs that contract, expand, and guide their movements as a choreographer would. Such compression-based tools are also employed in medical fields. One example used a prototyping toolkit known as *Compressables* to design inflatable silicone bladders [4]. Our technique could enhance these designs with specific textures used to represent distinct moves and increase comfort for a wearable choreographer, or enable realistic replicas of organs such as bladders.

Some take this into virtual reality (VR). Fang et al. [5], explored the use of objects found in everyday environments to create a VR experience. Their user study found that the haptic feedback provided by these objects enhanced users' experience while playing three games (Whack-a-mole, Pet a cat, and Shoot monsters) with the VR headset engaged [5]. Similarly, HapticLever [7] demonstrated the use of a mechanism based on a pentagraph that gives users the illusion of interacting with objects in VR. The use of textures strategically chosen to emulate the given virtual environment would make these interactions even more realistic.

2.2 Texture Analysis and Representation

Hollins et al. [10] worked to establish a set of scales by which to categorize textures. Using multidimensional scaling, they constructed a model of the texture space using subject's groupings of 17 related textures and ratings along the scales of smooth-rough, hard-soft, slippery-sticky, flat-bumpy, and warm-cool. Their results support the use of no fewer than 3 dimensions to represent a texture space. The first 2 dimensions found to be optimal descriptors were smooth-rough and hard-soft, as they were nearly perpendicular. A third dimension was not clearly identified.

Okamoto et al. [13] identified a consistent usage of similar scales of classification by analyzing 17 texture studies that classified the results of their study on a tactile scale. Among the 5 scales identified, macro and fine roughness (often combined into a singular scale of rough/smooth), warmness (warm/cold), hardness (hard/soft), and friction (moist/dry and sticky/slippery), rough-smooth and hard/soft were, again, most commonly observed.

Given the prevalence of these scales in texture literature and the evidence to support their use, we used them as perpendicular axes within our own Texture Wheel that was used to collect data during our texture study.

3 SILICONE TEXTURES

We leveraged the Castura microtexture fabrication process [6] to generate 10 tactile samples of size 60 mm x 60 mm on 3 mm acrylic sheets. Each texture was cast with silicone (EcoFlex 00-50) into a laser-engraved mold. For the first version of the texture, the silicone was dyed to make the surface topography more visual for later quality comparisons. All subsequent artifacts produced for the study do not use colored silicone.

We chose these specific textures because of and categorize them by their **feature type** and **spatial separation**. Feature type refers to whether it has protrusions or depressions. Spatial separation refers to whether the texture can be described as coarse or fine. These metrics are used because of their influence on tactile perception.

4 SENTURA TEXTURE WHEEL RATING INSTRUMENT

If you ask someone to describe how something feels, their ability to align their feeling to semantics is difficult [16]. In the context of a psychophysics study, the need to assess whether a collection of haptic descriptors aligns to a user's perception can be tedious.

To this end, we adapted the Geneva Emotion Wheel [14] to capture data on textures. The Geneva Emotion Wheel is a study instrument that allows users to report their emotional responses in an easy-to-use and concise interface. It combines two self-reporting mechanisms: discrete emotion labels (using labels to describe emotional states) and dimensional approach (organizing emotions by valence, arousal, and tension). It places twenty emotion words from a set of twenty emotion families around a circle, or "wheel", organized by the dimensions of valence and power [14]. These dimensions give the ability to differentiate between distinct emotion families and to categorize an emotion by both pleasantness or unpleasantness, and intensity. Radiating from the center of the wheel is a five-point scale with the size of the selection bubbles corresponding to the intensity of the emotion [14].

When creating our Texture Wheel (Fig. 3), we chose anchors found in natural languages and used in everyday conversation since people struggle with brainstorming or using words that can appropriately describe the feel of a texture. To help solve the issue of coming up with descriptors for the textures in the study, we developed the word list for our texture Wheel using ChatGPT and prompt engineering. We finished by checking the list for and removing duplicates both within and between clusters. [13].

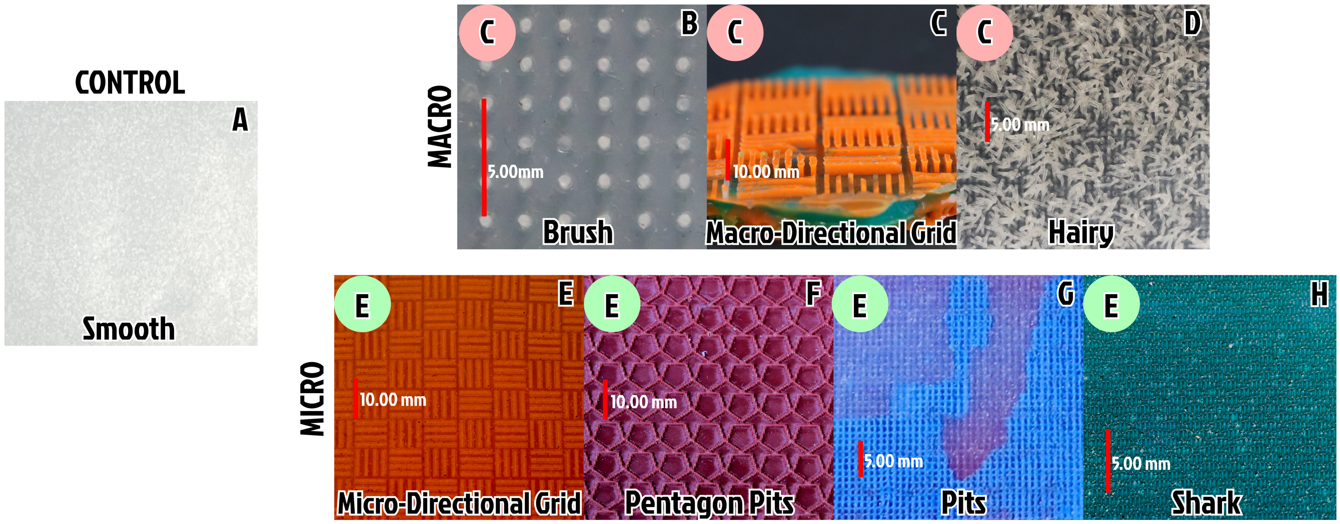


Figure 2: Castura Fabricated User Study Textures. A selection of textures that were fabricated via the *Castura* method. Textures marked with a "C" were fabricated with cut plates, while textures marked with an "E" were fabricated with an etched plate.

5 USER STUDY

In order to evaluate and classify these textures, we conducted a user study with two parts: a texture perception task and a gesture mapping task.

Recruitment and Selection. We selected 15 participants (6 male, 8 female, 1 non-binary) from the Computer Science Department with an average age of 20 years (± 1.51) and proficient to advanced English proficiency levels. Each received a $10 USD gift card as an incentive. The study was approved by our Institutional Review Board on human subjects research.

5.1 Texture Perception Characterization Task

This portion of the user study seeks to formally classify each of the textures based on curated texture words using the Texture Wheel.

Protocol. Interacting with 8 silicone textures could take over an hour and potentially fatigue participants. To minimize user fatigue, each participant was instead assigned a smaller texture group consisting of 4 or 5 textures: Group 1 (textures 10 [Smooth], 11 [Brush], 12 [Macro-Directional], and 13 [Pits]) or Group 2 (textures 10 [Smooth], 14 [Shark], 15 [Pentagonal Pits], 16 [Micro-Directional], and 17 [Hairy]).

Texture terms on the wheel were organized into families of five related words. Participants then selected the word they were most familiar with from each category. Participants performed four gestures on each texture: single finger tap, lateral swipe, vertical swipe, and circular motion. After performing each gesture, the participant rated textures on a 5-point scale. This process was repeated for all assigned textures. After each texture, participants answered two questions assessing their confidence and fatigue levels. This helped identify when focus might wane and diagnose the validity of the collected data.

5.2 UI Action to Gesture Mapping Task

This segment of the user study informed potential applications of microtextures in executing UI actions for electronic devices.

Action Generation. A UI action is an action a user imagines an interface could perform. The UI actions used for the user study were decided and generated by providing a set of prompts to ChatGPT, following the same procedure conducted for the previous parts of the experiment. To guarantee that the prompts generated by the AI were appropriate, we once again checked the list for and removed duplicates both within and between clusters.

Protocol. Users were asked to perform an action on the silicone textures that would demonstrate how a specific UI action could be performed. As these answers could vary among participants, it was conducted as a think-aloud exercise.

Initially, we encountered a challenge: when prompted, users often struggled to articulate descriptors for their experiences. To mitigate this issue, we devised seven broad categories of UI actions: Orientation Controls, Cursor Controls, Audio Controls, Video Controls, Display Controls, History Controls, and Text Controls which were subdivided into more detailed actions displayed on the reverse side of our cards. In the duration of the task, users referenced these given actions and categories.

6 RESULTS

We analyze the textures utilized in the user study based on the ratings they received on the 5-point scale of the Texture Wheel. As noted in Fig. 5b, the most common texture words used across all textures were bumpy, soft, and coarse.

6.1 Gesture Analysis

The results from Fig. 5b show the four highest-rated texture descriptors per texture for each gesture - tap, lateral swipe, vertical swipe, and circular motion. Interesting differences are highlighted

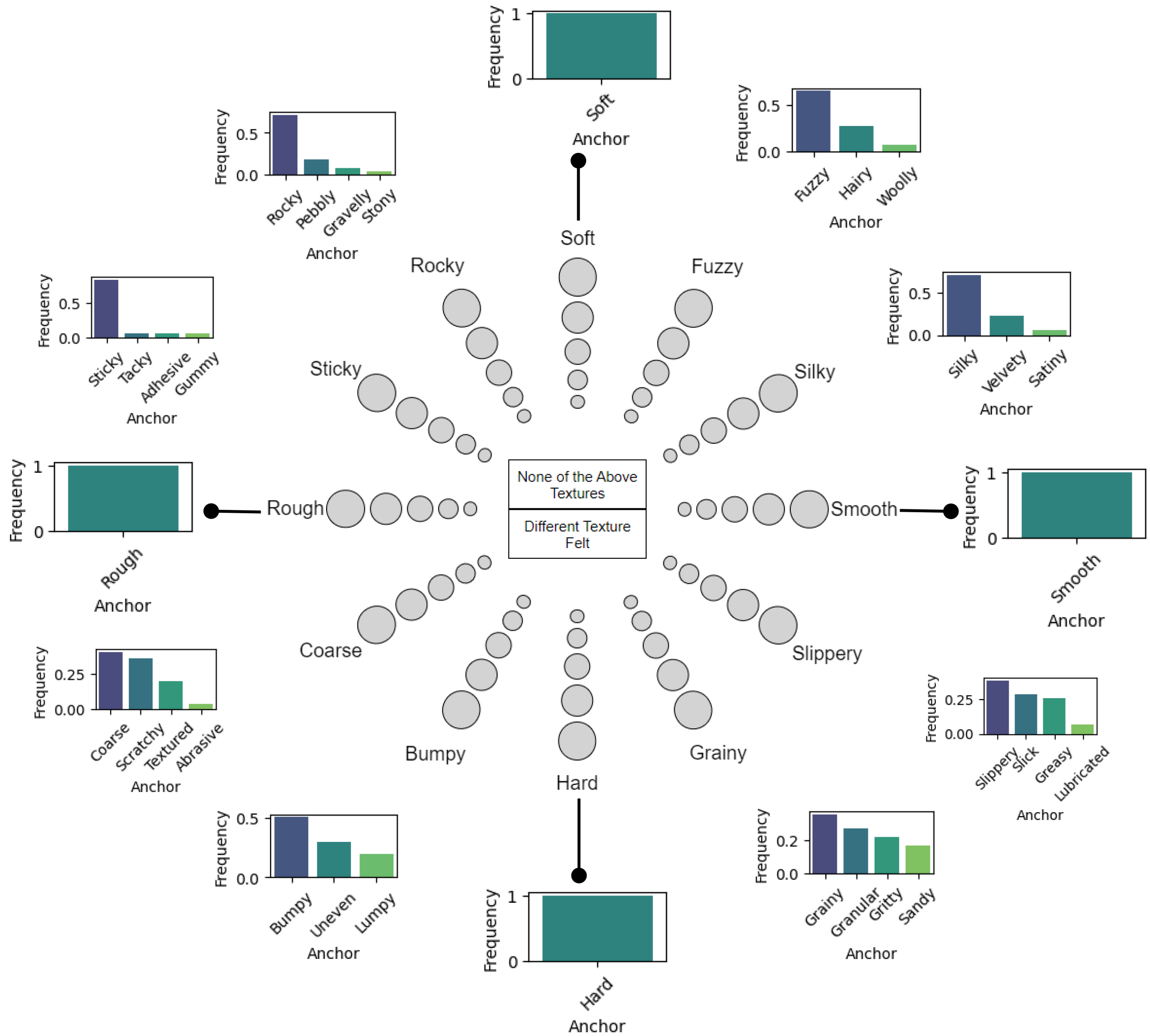


Figure 3: Texture Wheel. The Texture Wheel is adapted from the Geneva Emotion Wheel with 12 texture anchors. The graph placed beside each anchor displays the texture word that was chosen most often from each word group during the Texture Perception Characterization Task of the user study.

in the table in **bold**. When comparing circular motion with lateral swipe, vertical swipe, and tap, we see that swipe is significantly different. These differences could imply that dragging the finger clock-wise or counter-clockwise can change the perception of the texture when compared to tapping, laterally swiping, and vertically swiping.

Looking at the textures individually, when users tapped bristly textures such as Brush rather than swiping or swirling, the feeling of softness was enhanced. More ridged textures such as Macro-Directional similarly see an increase in bumpiness when they are swiped or swirled. Interestingly, for textures such as Shark and Pentagonal Pits, despite Lateral Swipe and Vertical Swipe being gliding motions, the direction of the motion changed the perception of softness and roughness for the textures.

6.2 UI Action Mapping

6.2.1 Theme 1 – Driving Sliding Gestures. The distinction between macro and micro textures serves as a critical factor in how participants perceived and interacted with a texture. Macro textures in this study were Brush, Hairy, and Macro-Directional Grid. They can often physically steer the user's finger movements, enhancing the sense of control in navigating through interfaces. However, this guiding effect can also become a hindrance in scenarios requiring precision. The very features that provide direction can restrict free

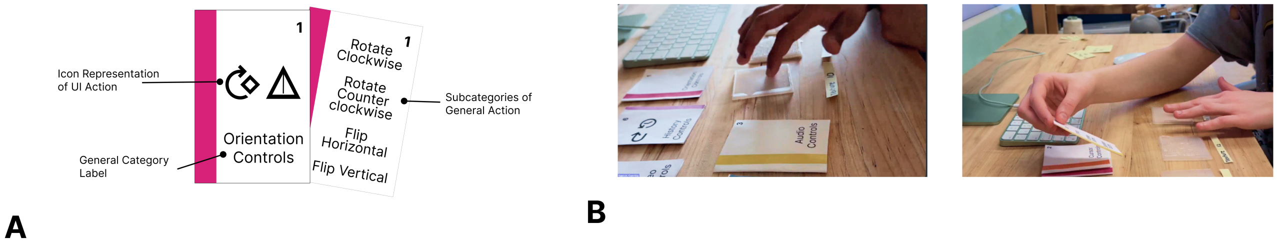
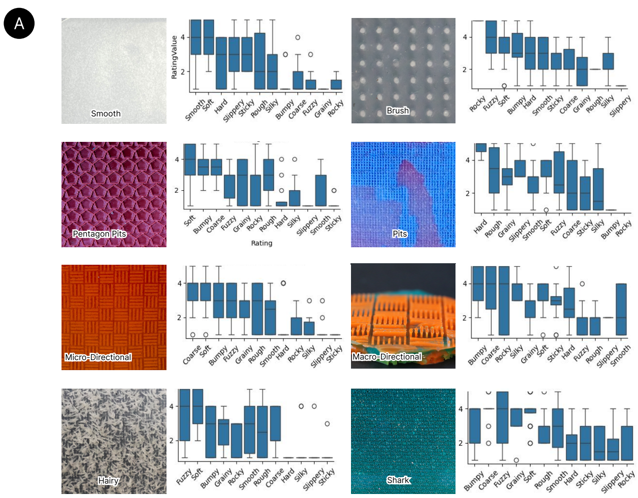


Figure 4: A. One of the cards used in the UI Action task. The front contains an icon as well as a brief description of the general UI Category it represents. The back of the card elaborates on more specific actions or subcategories within this category. B. Users perform the UI Acton to Gesture Mapping Task.



B

Texture ID	Lateral Swipe	Vertical Swipe	Tap	Swirl
Smooth	Smooth (3.4) Soft (3.0) Sticky (1.67) Slippery (1.2)	Soft (3.75) Smooth (3.45) Hard (1.6) Sticky (1.15)	Sticky (3.08) Soft (2.31) Smooth (1.77) Silky (0.62)	Smooth (2.23) Sticky (2.15) Soft (1.85) Rough (1.15)
Brush	Soft (3.14) Fuzzy (3.0) Smooth (1.29) Silky (1.0)	Soft (3.57) Fuzzy (3.14) Smooth (1.14) Bumpy (1.0)	**Soft (2.29)** Fuzzy (2.0) Bumpy (1.86) Hard (0.86)	Soft (3.5) Fuzzy (3.12) Bumpy (1.62) Smooth (1.62)
Macro-Directional	Bumpy (3.25) Grainy (1.5) Soft (1.5) Coarse (1.0)	Bumpy (3.25) Soft (2.62) Sticky (1.5) Coarse (0.88)	Sticky (3.0) **Bumpy (2.62)** Soft (2.25) Hard (0.62)	Bumpy (3.75) Soft (2.5) Sticky (2.0) Rough (0.88)
Pits	Soft (1.62) Sticky (1.38) Coarse (1.25) Rough (1.25)	Smooth (2.25) Soft (2.25) Rough (1.38) Sticky (1.25)	Smooth (1.88) Soft (1.88) Silky (1.25) Fuzzy (1.12)	**Rough (2.12)** Soft (1.5) Coarse (1.38) Sticky (1.38)
Shark	**Soft (3.14)** Fuzzy (2.71) Smooth (1.86) Coarse (1.71)	**Rough (2.25)** Coarse (2.12) Soft (2.0) Fuzzy (1.62)	Soft (3.33) Fuzzy (2.5) Coarse (2.0) Smooth (1.33)	Fuzzy (2.71) Bumpy (2.29) Soft (2.14) Rough (2.0)
Pentagonal Pits	**Rough (3.0)** Soft (3.0) Bumpy (2.57) Coarse (2.57)	**Soft (3.29)** Bumpy (2.29) Rough (2.29) Coarse (1.86)	Soft (2.5) Bumpy (2.0) Coarse (1.67) Rough (1.67)	Soft (3.43) Coarse (3.29) Bumpy (2.29) Rough (1.86)
Micro-Directional	Soft (3.71) Rough (2.57) Bumpy (1.86) Fuzzy (1.86)	Soft (3.43) Bumpy (2.0) Coarse (2.0) Fuzzy (2.0)	Soft (3.86) Coarse (2.57) Fuzzy (2.29) Grainy (1.57)	Coarse (2.71) **Soft (2.43)** Bumpy (2.0) Rough (2.0)
Hairy	Soft (3.71) Fuzzy (3.43) Smooth (2.0) Grainy (1.71)	Fuzzy (3.43) Soft (3.43) Rough (1.57) Grainy (1.43)	Soft (4.14) Fuzzy (3.14) Coarse (1.57) Rough (1.0)	Fuzzy (3.43) Soft (3.43) Rough (2.57) Coarse (2.14)

Figure 5: A. Haptic Evaluation Each texture and the percentage amount by which they fit the description words from the Texture Wheel are shown. B. Texture Ratings The top four texture ratings for each texture and gesture combination are shown.

movement, imposing a physical constraint that may lead to inaccuracies or unintended inputs. Conversely, micro textures, with their subtler surface characteristics, tend to support a more nuanced form of user control. These textures enhance grip and tactile response without significantly altering the path of finger movement. Micro textures used in this study were Pits, Shark, Pentagon Pits, and Micro-Directional Grid. The consensus was that participants felt more confident and secure when making motions on micro textures.

These results show that Macro textures might be more suitable for applications where user guidance is necessary and actions should be constrained. Examples include navigational tasks in physical spaces or applications where sensory feedback can enhance the immersive experience. On the other hand, micro textures are preferred in precision-oriented tasks, such as drawing or detailed data entry where greater user agency is preferred.

6.2.2 *Theme 2 – Sensation Reinforces Emotion.*

In several instances, tactile sensations play a significant role in eliciting and associating with specific emotions. Pits, with its simplistic design, emerged as a favorite for tapping actions. This can be attributed to its straightforwardness and immediate tactile response. This preference underscores the intuitive appeal of less complex textures for basic interactions. One user, for example, mentioned that the distinct feel of the texture lends itself to situations of urgency.

Additionally, the ratings of the pleasantness of each texture were aggregated, with Pentagon Pits hitting a "sweet spot" for distinguishing regions, and Macro-Directional having the lowest rating. The users' responses indicate that certain micro-textures can be applied to elicit different emotions and provide better feedback to the users when making an action.

6.2.3 *Theme 3 – Even subtle textures offer textural diversity.*

Many of the macro textures were found to cause a form of sensory overload in users. During the study, numerous participants reported feeling fatigued by these textures. Consequently, users preferred using less complex textures for more common interactions on a device, while reserving more intricate textures for less frequent actions.

The perception and utility of textures in user interfaces heavily depend on the context of their application and the baseline sensory environment. Complex textures hold value in situations that benefit from or require greater textural diversity. However, microtextures demonstrate more promise within the current landscape of smooth user interface surfaces.

7 DISCUSSION

Based on the findings from our user study, microtextures may have promising applications within the wearable haptics space. One advantage of the *Castura* method is its ability to integrate specially-designed microtextures either into its own artifact or onto existing surfaces, such as porous fabric. *Tactile Sleeve for Social Touch* (TaSST) [11], for example, provides vibration feedback in response to mediated touch as a way of expressing certain emotions to the user. Silicone microtextures can expand the scope of possible gestures, allowing more nuanced ways of haptically expressing emotions.

Due to the versatile properties of silicone [15] and the advancements microtextures provide the material, silicone can be adapted to develop unique and interesting haptic interfaces. Systems such as *Stretchis*, a stretchable silicone-based interface [18], and *Silicone Devices*, "a Do-It-Yourself (DIY) fabrication workflow" [12], can utilize *Castura* with their processes to make the surfaces more intuitive. For instance, *HapBead* is a vibration-based haptic interface that uses microfluidics to run the system [8], while *Parametric Haptics* are "geometry-based tactile feedback devices" that can be customized to emit specific haptic sensations within users [9]. The use of textures such as Shark and Pentagonal Pits that influence the perception of roughness and smoothness can both increase the perception of tactile input or indicate how to interact with a surface. For example, when the user performs the intended gesture, it could be perceived as smooth, and when they perform the wrong gesture, it could become rough.

Through our analysis of the emotional responses collected during the user study, it has also become evident that certain surface textures provoke strong emotional responses. These findings have implications for *affective haptics* [3], an area of research aiming to heighten user's sense of emotions through touch, and for wearable systems that specifically aim to emulate human touch [17]. This indicates that microtextures could be used to represent or elicit certain emotions, ranging from joy to anger, or even work to indicate how users should use an interface. Examples include using unpleasant textures such as Pits to discourage the user from interacting with a certain element, or using pleasant textures for elements intended to be used more frequently.

7.1 Limitations

One limitation in our study is that we only considered participants without a sensitivity to silicone and those without autoimmune disorders. This means that our results are currently only applicable to individuals without sensory issues. Further work should be done to explore how microtextures are perceived by individuals with disabilities or those with a sensitivity towards microtextures.

In addition, during the study, some participants expressed confusion towards one of our questions regarding fatigue. While it was intended to gauge fatigue experienced during the task, it might have been interpreted to mean general fatigue levels at the current moment. So, if users answered that they had a high level of fatigue, but it was not related to the task, or the question was misinterpreted in some other way, then their data might have been wrongfully interpreted.

Finally, there was the possibility of uncured silicone being present in our textures due to the quick curing time, which might have enhanced the perception of stickiness. A way to resolve this in future studies is to apply corn starch on the textures for better usability, or to allow more time for the textures to cure.

8 CONCLUSION

Microtextures have the potential to change our approach to haptic design and improve user experience. As our user study has shown, the choice of texture characteristics and of gestures can influence user's emotions and interactions with devices. Based on whether users desire more or less autonomy over an interface, intend to convey positive or negative emotions to an interface, or manage their fatigue while using an interface, certain microtextures can be chosen. We can use these micro-geometries to guide nuanced gestures and invoke a range of emotions leading to applications in wearables, gaming controllers, and other innovative haptic devices.

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