Parametric Haptics: Versatile Geometry-based Tactile Feedback Devices

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Figure 1: We present customizable and versatile haptic patches that are lightweight, reconfigurable, and can be integrated as wearables or into objects. (a) Users can customize their own haptic patches with a software design tool we provide. (b) One linear pull can actuate many tactors, producing haptic sensations on a large area of the skin. Our approach can, e. g., be integrated (c) into existing worn objects, or (d) designed for VR experiences.

ABSTRACT

Haptic feedback is important for immersive, assistive, or multimodal interfaces, but engineering devices that generalize across applications is notoriously difficult. To address the issue of versatility, we propose Parametric Haptics, geometry-based tactile feedback devices that are customizable to render a variety of tactile sensations. To achieve this, we integrate the actuation mechanism with the tactor geometry into *passive* 3D printable patches, which are then connected to a *generic* wearable actuation interface consisting of micro gear motors. The key benefit of our approach is that the 3D-printed patches are modular, can consist of varying numbers and shapes of tactors, and that the tactors can be grouped and moved by our actuation geometry over large areas of the skin. The patches are soft, thin, conformable, and easy to customize to different use cases, thus potentially enabling a large design space of diverse tactile sensations.

In our user study, we investigate the mapping between geometry parameters of our haptic patches and users' tactile perceptions. Results indicate a good agreement between our parameters and the reported sensations, showing initial evidence that our haptic patches can produce a wide range of sensations for diverse use scenarios. We demonstrate the utility of our approach with wearable prototypes in immersive Virtual Reality (VR) scenarios, embedded into wearable objects such as glasses, and as wearable navigation and notification interfaces. We support designing such patches with a design tool in Rhino.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Metamaterials, Fabrication, Programmable Matter

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1 INTRODUCTION

Haptic feedback is an important perceptual modality in our daily interactions with the world, but is difficult to reproduce artificially. The need for actuation makes careful mechanical design of haptic devices imperative. Many capable devices have been demonstrated that can, e. g., render shapes [5, 19, 24], textures [37], softness [54], impact [45], moving mass [53], and many more features. Such devices that provide active haptic feedback to the user are often presented in rigid form factors, such as hand-held controllers, body-grounded force feedback, wearables, and so on. These devices are usually specially designed for specific applications.

The body is prime real estate for haptic feedback, making wearable haptic feedback devices a research area of great interest. Ideal wearable haptic devices are lightweight, small, and conformable. Vibrotactile actuators have been used extensively due to their small form factor [30, 35, 44, 47]. To go beyond the high-frequency stimuli of vibrotactiles, researchers have investigated other actuation techniques to produce indentation into the skin or stretch the skin laterally. Such tactile displays are driven by, e. g., linear resonant actuators [14], piezoelectric actuators [42, 46], custom magnetic actuators [50], shape memory alloys [22], or hydraulic electrostatic actuator arrays that form raised bumps [41].

However, while the location where current tactile devices provide feedback at can be controlled dynamically, the type of feedback (e. g., vibration, indentation, skin stretch) cannot be adapted to new environments or scenarios. This is because the feedback type is baked into the devices' design. We aim to overcome this by developing a novel parametric device and fabrication approach that enables designers to create versatile and customizable tactile feedback interfaces.

1.1 Parametric Haptics

In this paper, we present a modular haptic interface that is customizable to render different tactile stimuli. Figure 2a shows our device which consists of a (1) passive flexible and *versatile* tactile output geometry that can be connected to a (2) generic wearable actuation interface (here, using micro gear motors).

The key benefit is that the tactors on our passive patches can be *custom-designed* for new experiences and applications, e. g., for different Virtual Reality (VR) environments, assistive devices, or telepresence, while the generic actuation interface remains the same. Figure 2b shows the thin, flexible patches that conform to users' bodies or objects. The custom tactors can be tailored to the specific application to render tactile feedback that is closely aligned with the expected experience. As shown in Figure 2c, multiple tactors are actuated by an integrated pulling geometry and can produce skin stretch, affective stroking, and indentation depending on the tactors' design. These patches are 3D printed and connected to the actuation interface, e. g., the bracelet in Figure 2.

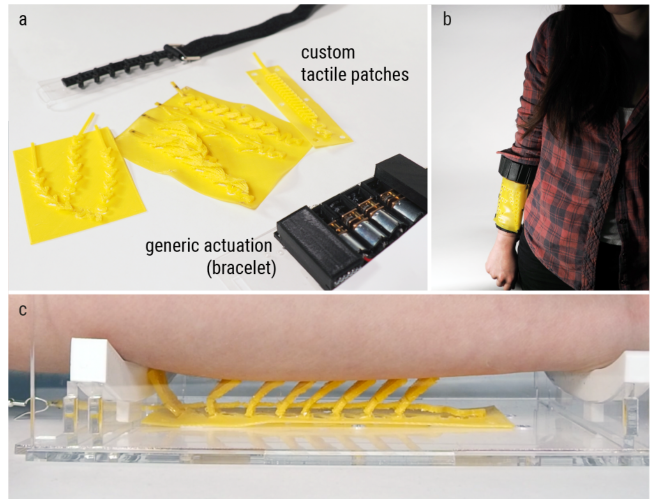

Figure 2: (a) Our tactile feedback device consists of custom tactile patches that can be connected to a generic actuation interface, which (b) is wearable. (c) Multiple tactors are actuated to stroke over the skin, while the tactor design is user-defined.

This decomposition into customizable tactile patches and generic actuation interface allows for tactile experiences to be shared by 3D printing as shared tactile patch geometry. For example, assets for VR environments could be delivered with their tactile experience in addition to their visual representation.

1.2 Contributions

The main contribution of this work is the design of versatile tactile feedback encoded in their geometry. Our novel enabling technology focuses on wearable, selectively actuated, versatile tactors that can be exchanged easily. We support our main contribution with the following specific contributions:

(1) *Actuation geometry.* We develop a parametric geometry that is versatile and can be adapted to mimic custom tactile sensations.
(2) *Tactile perception study.* We investigate the mapping between an initial set of geometric parameters and how they are perceived. We find that participants can distinguish our tested geometric parameters, which supports the customizability of our proposed passive tactile patches.
(3) *Wearable prototypes.* We showcase how the actuation geometry can be used in small wearable forms in varying locations with different sizes.
(4) *Applications & geometric parameter exploration.* We explore an initial set of geometrical parameters, which we use to investigate the applicability of our parametric haptic device by showcasing distinct applications in VR, assistive technology, and notifications.
(5) *Design tool.* We provide a design tool that generates the actuation geometry for user-defined parameters.

Our current paper is focused on the concept of exchangeable tactile patches with parametric tactor design and actuation. While we validate our approach with a user study, the geometric parameters explored in this paper are only a starting point for further investigation into a larger design space for haptic effects using our proposed technology.

2 RELATED WORK

In this section, we discuss literature on tactile perception as a basis for the use of 3D-printed geometric patches to convey varied tactile sensations. Further, we highlight the Human-Computer Interaction (HCI) contributions of passive, 3D-printed mechanisms for delivering haptic feedback. Our work focuses on creating customizable haptic interfaces that leverage geometric parameters, which have promising applications to VR, accessible navigation, and tactile communication (e. g., notifications).

2.1 Tactile Perception

The human sense of touch is encoded through receptors in the skin known as mechanoreceptors. There are four distinct mechanoreceptors found in the hairless skin (i. e., palms, soles of feet). Pacianian Corpuscles (PCs) sense high-frequency vibrations and Ruffini Endings detect skin stretch, Meissner Corpuscles sense the rate of skin deformation, and Merkel Cells detect spatial features. Meissner Corpuscles and Merkel Cells are not present in hairy skin [21, 31].

Hairy skin covers most of the skin's surface and is capable of discriminative touch [48]. While it may have low spatial resolution, it is an effective site to convey both skin stretch and vibratory feedback. Prior work has demonstrated that skin stretch feedback can be used to provide directional cues [4, 10, 34, 36]. Vibratory feedback is salient for texture perception, namely perceived roughness [7, 8]. Surface geometry, which includes the density and shape of textural elements, also has importance for texture perception, namely roughness [36, 39].

The exact tactile cues that impact the perception of compliance (i. e., hardness and softness) are still unresolved [64]. When an object is indented into a stationary finger during passive touch (i. e., stimuli imparted on user by external agent instead of user motion), we are reliant on our tactile, or cutaneous, cues [23, 52, 56, 57]. Recent work by D'Aurizio et al. uses an forearm-worn wearable haptic device for skin-stroking and squeezing. This work demonstrates that users are able to discriminate different levels of compliance successfully [15] and showcases the use of passive tactile feedback to enable the discrimination of relative hardness and softness.

Touch can be categorized as discriminative, which we described earlier, as well as affective [1, 48]. Recent findings uncovered an additional mechanoreceptor, C-tactile afferents (CTs), which are only present in hairy skin. CTs are selectively responsive to stroking [48]. Research by Hertenstein demonstrates that emotional communication (i. e., love, anger, sadness) can be conveyed through touch. [25]. Furthermore, people are able to differentiate between different emotions through touch alone [25].

2.2 Portable and Wearable Haptic Feedback Devices

A significant amount of prior work exists on haptic feedback devices that are portable enough to be worn or carried [9]. Handheld devices such as [6, 13, 61] are controllers that complement VR scenarios with haptic feedback for touching or grasping virtual surfaces, textures, and shapes. Handheld devices, however, limit haptic feedback to the hand and do not allow free-hand interactions, making them less applicable to be used outside of VR.

Wearable haptic devices can be mounted on the body, freeing users' hands. Such devices could be used to render both force and tactile feedback. Force feedback of interacting with virtual objects can be rendered with an exoskeleton-device arresting forces on users' various body parts [2, 12, 18, 26]. These devices rely on the body part's natural degree of freedom and could sometime limit the freedom of movement, therefore needing much design consideration.

Vibrotactile is commonly used in wearable haptic devices to render tactile feedback due to the small form factor and cheap price of vibratory actuators. Researchers have used vibrotactile wearables to render pleasant social touch [30], provide navigation cues [35, 44], convey textual information [47], and so on. Electrotactile allows wearable haptic devices to be miniaturized to as small as a temporary tattoo [62]. Despite their small form factors, vibrotactile and electrotactile stimuli remain limited: Electrotactile stimuli can not easily stimulate PCs laying in deeper region of the skin [33], and could give an unnatural "electric feeling" [38]. Also, PCs dominates vibrotactile perception, and requires vibrotactile stimuli to be placed far apart due to their large receptive fields [4].

On the other hand, physiology research has shown that skin strain allows mechanoreceptors to respond more quickly and accurately [16, 17, 49]. Leroy et al. proposed using flexible hydraulically amplified electrostatic actuators to produce normal and shear forces to the user's body [41]. Teng et al. suggested providing haptic feedback to mixed reality environments with a device that presses against the user's fingerpad when they touch something [55].

Wearable tactile feedback devices can be used to provide learned tactile vocabularies [32] (e. g., notifications), render virtual textures [59], or to provide directional cues [4, 10, 34, 36]. Research suggests that shear force when delivered to the arm provides superior directional cues compared to that of vibrotactile [4]. Furthermore, skin stretch can also be used to create convincing illusions, such as stiffness perception [51].

2.3 Embedding Functionality within Geometry

Passive haptic feedback mechanisms dissipate applied mechanical energy through interaction with a human [65]. Recent work has demonstrated the significance of embedding functionality within passive mechanisms to provide haptic feedback [43, 65]. Chang et al. introduced simple-to-fabricate Kirigami structures with embedded geometric patterns used to render different types of haptic feedback [11]. Complementary to active feedback mechanisms, researchers also introduced passive haptic feedback devices, e. g., hand-held force feedback controlled by compliant mechanisms [43, 65], or tactile feedback encoded in 3D printed textures [28, 29, 58]. The absence of actuation makes passive haptic feedback devices less complex to build at the expense of dynamic control.

3 DESIGNING PARAMETRIC HAPTICS

We aim to develop a new form of haptic wearable that is highly customizable, lightweight, and requires few electronics. We leverage 3D printing technology to fabricate such wearable patches. A small pull force from a motor can simultaneously actuate many tactors at once, allowing them to produce skin stretch, indentation, and stroking sensations on the users' skin, rendering various complex tactile experiences. The simplicity of our actuation geometry further allows the wearable patches to be customized for different applications, worn on different body parts (e. g., arms, legs, torso), or integrated with existing objects (e. g., glasses, wrapped around water bottles, desktop surface).

In this section, we present the design of our tactile patches. Figure 3 illustrates the main components of our tactile patches. Custom-designed tactors touch the user's skin when actuated. The tactors are connected with an actuation geometry that we detail in the following. When actuated, a stem moves all connected tactors to be approximately perpendicular to the substrate of the patch, such that these tactors touch the user's skin. A passive return spring pulls the tactors back into their flat state.

3.1 Actuation Geometry

The actuation in our tactile patches is inspired by tendon-driven mechanisms. We developed a geometry that can be entirely 3D printed. An example tactor is shown in Figure 3a. Our approach avoids manually assembling and attaching pull strings by replacing them with printable structures.

We design stem-like structures that connect multiple tactors, as shown in Figure 3b. The stem extends beyond the last tactor and acts as a pull string (Figure 3c). When an external pulling force is applied, all connected tactors are actuated at once. They are pulled back into their original flat position by the return spring, when the actuation force is removed. Each tactor is connected to the stem for actuation, and the patch for anchoring, all with compliant hinges, i. e., thin struts that flex easily.

Between tactors, the stem structure forms short thin curved sections, as illustrated in Figure 3c. When the stem is actuated (i. e., pulled), the curved sections straighten out to be orthogonal to their adjacent tactors. The compliant hinge placements transform the linear pulling motion into the rotation of the tactor.

Design recommendations. In the following, we detail the parameterization and recommendations for tactors' connections to the stem and the substrate of the patch, as illustrated in Figure 3a. For each tactor, the position of the stem hinge connected to it, denoted as p_s, is placed at a minimum distance of $\frac{1}{2}l_t$ from its lower edge, with l_t denoting the tactor's length. The gaps g between the tactor and the stem, need to be greater than or equal to 0.2 mm on both sides of the stem. This is both to prevent the stem and tactor from fusing during 3D-printing, and to avoid friction hindering the tactor's actuation. To optimize for low pulling force, the stem's width w_s is best kept around $\frac{1}{3}w_t$ (w_t denoting the tactor's width), and the stem's thickness t_s about $\frac{1}{2}w_s$.

These recommendations were tested on tactor sizes of 5-20 mm wide and for up to 18 connected tactors. These parameters might have to be adjusted for different tactor geometries (e. g., thicker tactors may require a stronger stem structure to actuate).

3.2 Fabrication

The tactile patches are printed with thermoplastic polyurethane (TPU), a common rubber-like filament. We use the filament

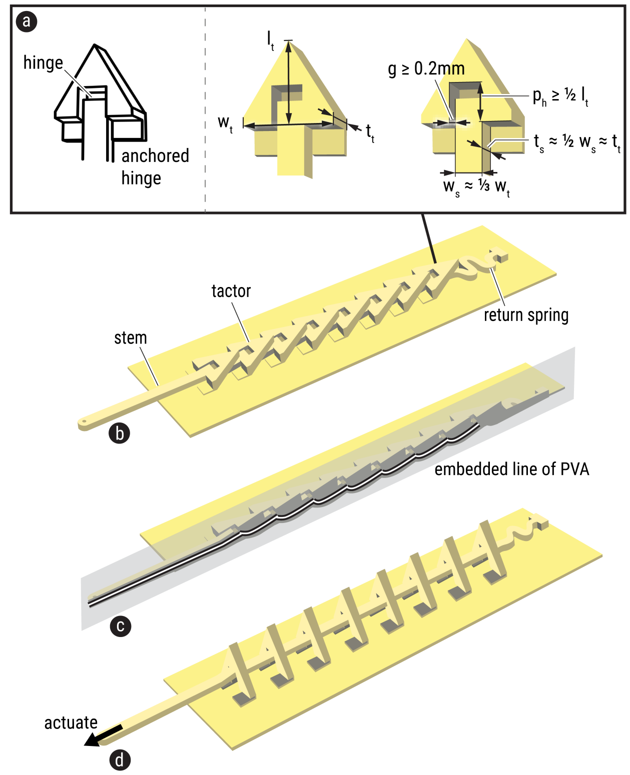

Figure 3: (a) Illustration of a *tactor* and its parameters. (b) Our haptic patches consist of rows of connected tactors. Here, we show one row with 8 tactors, which are connected by a *stem*. A *return spring* at the end of each stem pulls the tactors back after actuation. (c) We embed a line of PVA within the stem for decreased stretch when pulling. (d) The tactors flip up when actuated.

NinjaFlex (Shore 85A). We choose TPU due to its flexibility which allows the patches to easily conform to the body (e. g., wear on forearm), or daily objects (e. g., wrap around a water bottle). TPU can be difficult to print (e. g., it's prone to stringing), but keeping the filament dry greatly improves the print quality. Due to the complexity of our tactile geometry, we need support material, for which we use Polyvinyl alcohol (PVA by Polymaker), which is an off-the-shelf water-soluble support material. We use a consumer-grade dual-extruder printer (Tenlog TL-D3 Pro) to print our patches. After printing, we post-process the patches by dissolving the PVA supports in water overnight. Typically, no additional post-processing is necessary.

The TPU can stretch substantially (up to 660%), which is advantageous for the conformability of our patches, but not for propagating the pulling force through the actuation geometry. When the stem is stretching, due to the material properties of the TPU, less force is propagated to the tactors, meaning that the actuation force decreases with increasing distance between the tactors and the base of the stem. To counteract this behavior, we embed a thin line (0.4 mm width) of rigid material into our actuation geometry, as shown in Figure 3c. We print this line with PVA. Since it is fully enclosed

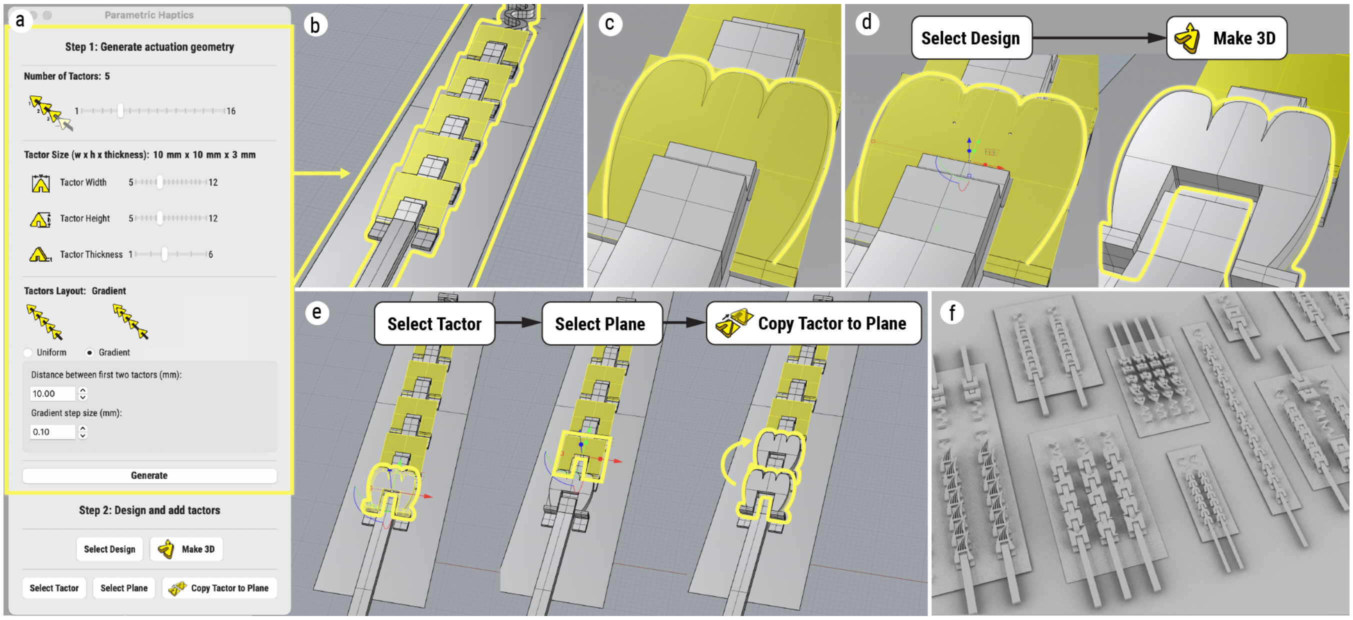

Figure 4: Design tool in Rhino. Users input parameters (a), and our design tool then (b) automatically generates functioning actuation geometries and guidance planes in place of tactors. (c) Then, users can design diverse tactors on generated guidance planes. The design tool provides shortcuts for users to (d) turn their designs into 3D tactors, and (e) copy tactors. (f) Users are able to conveniently create varying haptic patches with the help of the design tool.

within the TPU, it does not dissolve like the support structures, thus providing rigidity to our actuation geometry.

3.3 Design Tool

We provide a design tool that takes user-defined geometrical parameters as input and generates a working actuation geometry.

Figure 4 illustrates a walk-through of designing a haptic patch using our Rhino-based design tool. (a) Using its interface, users first input parameters defining the number of tactors and their layout on a stem. (b) Then, our design tool generates actuation geometries along with guidance planes for users (c) to freely define their 2D tactor shape on, which (d) they can then extrude to 3D. Users can further edit the tactor geometry using standard 3D modeling functions before (e) copying their tactors to other guidance planes.

In general, the tactors are flat or near-flat geometries, allowing them to not contact the skin when they are not actuated. Note that even when tactors are not actuated, they are not laying absolutely flat, but are slightly angled upward along with the front stem structure it is connected to. This allows all tactors to be placed on the same horizontal line, i. e., none is higher or lower than another. The correct angle is a parameter that is calculated by our design tool.

Our design tool is implemented as a plugin for Rhino[1] using the Rhino.Python API[2] in Python 3.6. The front-end is built with Eto.Forms[3]. Our tool calculates the parameters needed for the actuation geometry to work, while giving users the freedom to design the tactors freely. It provides functions for creating single rows of extruded tactors, which users can combine into more complex multi-row patches, shown in Figure 4f, using Rhino's 3D modeling functions. After designing the patch geometry, users can use Rhino's export function to save their model into a 3D printable file (e. g., STL). Our design tool is currently intended to be used by designers familiar with Rhino or other 3D modeling environments.

[1]https://www.rhino3d.com/
[2]https://developer.rhino3d.com/api/RhinoScriptSyntax/
[3]http://pages.picoe.ca/docs/api/html/N_Eto_Forms.htm

3.4 Motorized Actuation Interface

Our motorized actuation interface is a forearm-worn wearable that users can equip with different haptic patches. As shown in Figure 5, (a) the wearable comes with rails of varying heights to fit different tactors. To put a haptic patch onto the wearable, users (b) first insert a pair of rails into slots on the patch and then (c) insert the rails into slots on the wearable. Finally, the tactors are connected to the motors via (c) pull strings (the ends of stems on patches) that are hooked to the motor mounts. Users can then (d) wear the motorized forearm wearable for their intended use scenario.

The motorized actuation interface is a modular design composed of horizontal motor mounts each accommodating a single motor. In Figure 6, we show the components of our wearable bracelet. 8 motors are spaced 13 mm apart (the width of the motor), and placed side-by-side to maximize the number of actuators per surface area. Wearable patches are attached to rails and connected to slots at the base of each motor mount. This modular design allows for the seamless exchange of patches of various sizes and tactor densities, as well as to easily adapt the form factor for placement on different areas of the body (e. g., forearm, back, etc).

We use 12 mm DC gear motors (Ruimou 6V 100 RPM), which are controlled by an Arduino Nano microcontroller through DRV8833

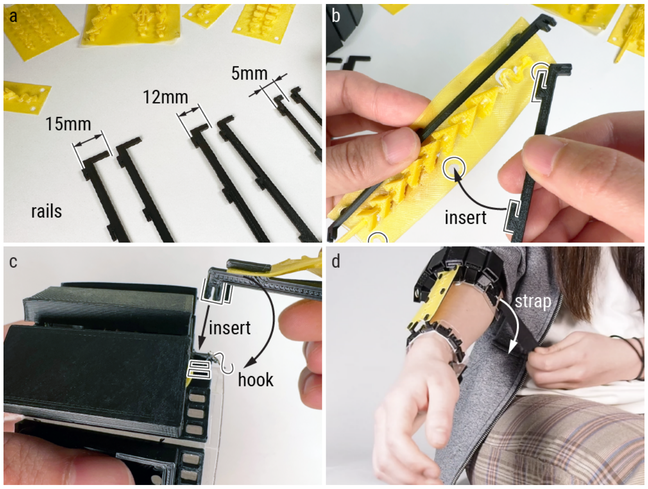

Figure 5: (a) Rails of various heights accompany varying tactors. To put a haptic patch onto the wearable, (b) users would insert a pair of rails into slots on the patch, (c) and insert these rails into slots on the wearable. The tactors are connected to the motors by hooking pull strings (i. e., end of a stem structure) to the motor mounts. (d) users can wear the motor-actuated haptic patch using straps on the wearable.

motor drivers. Wireless versions are attainable with little engineering effort by embedding WiFi-enabled microcontrollers and batteries (e. g., Seeed Studio Xiao and 7.4V LiPo battery as illustrated on the left of Figure 6). Each motor features a pulley system. We use fishing line (Power Pro Spectra Fiber), which is fed through a guidance hole at the base of the motor mount and attaches to a hook on the patch pull string. The stems of the tactile patch are connected to the closest motors on the actuation interface. We highlight in Figure 6 how only 4 of 8 motors are attached to the patch.

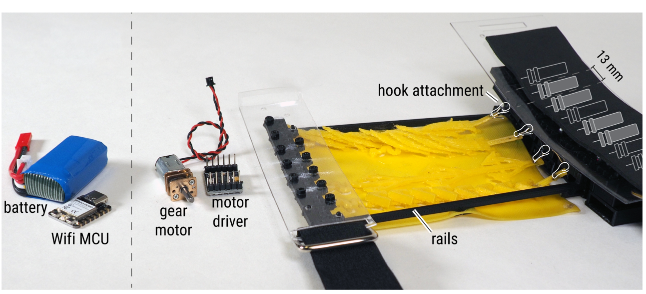

Figure 6: Modular wearable interface. Users can exchange patches of different sizes for various use scenarios with the same wearable interface.

For our demonstration, we implement a simple open-loop control strategy. We linearly actuate the motors by varying the direction of the rotation, and the duration and frequency of the pulse width modulation (PWM). This allows us to control the displacement of the tactors and the actuation velocity for achieving a diverse set of tactile sensations. Control strategies can be adapted to elicit desired tactile feedback and incorporate refined control with appropriate hardware considerations (e. g., encoder for refined position or velocity control, etc).

4 GEOMETRIC PARAMETER EXPLORATION

Our tactile patches can be designed and fabricated with a large number of geometry parameter variations. We showcase our explored parameters in Figure 7 and structure them into the dimensions detailed below. Our tactile geometry spans a larger design space, the exploration of which is outside the scope of this current paper, but our dimensions can inform future exploration.

Tactor geometry. Tactors are what contacts the skin and create skin stretch and stroking when actuated. They can take nearly arbitrary forms to render various sensations. We show only 4 examples of different tactor shapes in Figure 7, but designers can create arbitrary tactors.

Tactor parameters. The tactor geometry can be further parameterized. To keep the overall sensation, but alter, e. g., its intensity, designers can change the tactors size, particularly their length and thickness. Thicker tactors typically render a harder stimulus, longer tactors may render softer, more stroke-like sensations.

Density. Our tactile patches are designed to render feedback on larger areas of the skin. To do so, multiple tactors and tactor rows can be combined within one patch. The designer may vary their density to render, e. g., individual stimuli with sparse tactors or area sensations using dense tactor layouts. The density can be varied non-uniformly as well.

Heterogeneity. Different tactor geometries may be combined within one patch, either column-wise, row-wise (in terms of tactors' layout on a patch, not a row of tactors connected by one stem), or entirely freely.

Direction. The direction in which the tactors are actuated can be designed as well. All tactors might be actuated in the same direction. Designers might actuate tactor rows in opposite directions by using two actuation interface bracelets, for example. The tactors may also be arranged in curved paths on the patches to vary the direction of the stimuli within the patch.

5 USER STUDY: PERCEPTION OF GEOMETRIC PARAMETERS

We conducted a lab-based user study to validate the core idea behind Parametric Haptics, i. e., that our tactor shapes can be designed to align with desired haptic properties. Our study represents a validation of our novel tactile actuators and a first exploration of a possibly much larger design space, which we plan to investigate thoroughly in the future. To investigate whether the geometry parameters of our approach match the corresponding perceptual sensation, we test three different parameters (*tactor, stiffness, layout*), with a total of 18 differently parameterized tactile patches. Participants experienced the individual patches, and rated them for different sensations such as softness, coarseness, or sharpness. Results indicate a good agreement between our parameters and the reported sensations.

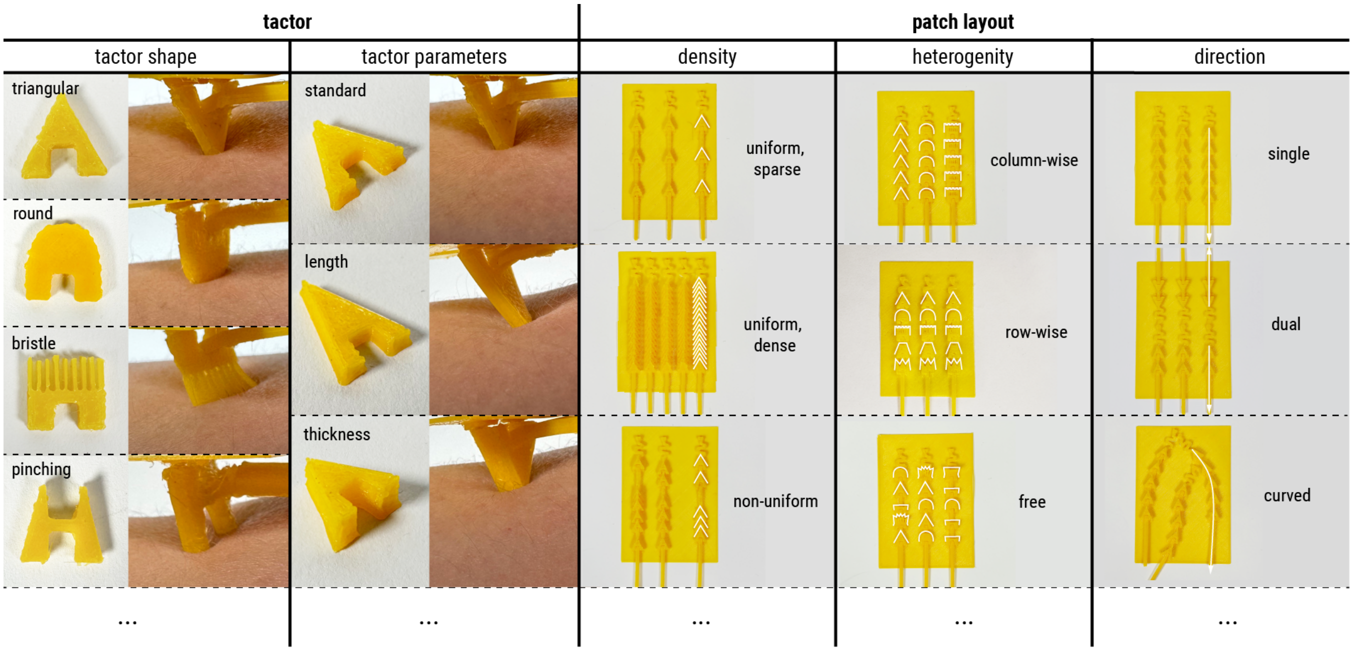

Figure 7: We explore a set of geometrical parameters that can be varied when designing and fabricating our haptic patches. This investigation presents a starting point for future in-depth explorations into their design space.

5.1 Study Design

We focused on evaluating whether fundamental properties can be altered by changing the tactors' geometry. We leaned on common tactile material properties (i. e., compliance, friction, roughness, and coldness [36, 55]). We omitted thermal properties to match our parametric space, which led us to investigate the properties of compliance, friction, and roughness. We hypothesized that these subjective properties would be influenced by the geometry, stiffness, and density of the tactors.

5.1.1 Design of tactile patches. The independent variables are reflected in the design of the tactile patches *tactor, stiffness, layout*, all shown in Figure 8. We sampled our geometry space to cover a range of conditions. We chose the triangle, round, and bristles as *tactor* shapes since they are distinct yet simple. The parameterization of *stiffness* for each tactor varies. For triangle and round tactors, stiffness is controlled through the thickness of the tactor. For the bristles, stiffness is controlled by the length of the bristles, with shorter bristles being stiffer. The *layout* is controlled by varying the spacing between individual tips over the length of each patch (total length 70 mm; sparse: 4 tips, medium: 8 tips, dense: 16 tips, gradient: 8 tips with the distance between tips increasing by 0.7 mm each tip). We chose the overall length of the patch to be about 70% of an average arm's length and empirically determined the stiffness parameters for each tactor.

5.1.2 Data collection. We collected data on participants' perceived tactile sensations. As mentioned previously, we build on the common tactile properties of compliance, friction, and roughness. After experiencing each patch, we asked participants to rate the sensation on four different seven-point scales from 1 (low) to 7 (high) of soft to hard (modeling compliance), over-the-skin to into-the-skin (modeling friction), blunt to sharp, and single contacts to many contacts (both modeling roughness). Additionally, we elicited qualitative feedback using semi-structured interviews.

5.2 Participants and Apparatus

We recruited 12 paid participants (6 male, 6 female), aged $M = 25.92$ years ($SD = 2.50$), all students and staff from a local University through convenience sampling. We compensated them with $15 for their participation. All participants felt the patches with their dominant arm, except for one participant wearing braces on their dominant arm. The study was conducted in an experimental space, shown in Figure 9. Each tactile patch was embedded into a laser-cut box. The distance between participants' arms and the patches could be adjusted with modular spacers to ensure proper contact, described below. All patches were mounted onto a wooden table, and covered with a visual barrier so that participants could not see the individual tactors.

5.3 Procedure

After completing the consent form and background questionnaire, participants were briefed on the purpose of the study. We then performed a height calibration. Participants were asked to place their dominant arm onto a transparent box, shown in Figure 9. The experimenter selected a 3D-printed spacer so that the tactors of the test patch indented participants' skin between 1 – 2 mm. The spacer was then used for all other patches throughout the experiment.

The presentation order of the 18 patches was randomized. For each patch, the experimenter triggered the tactile sensation multiple times by pulling a string at a constant velocity to a distance of

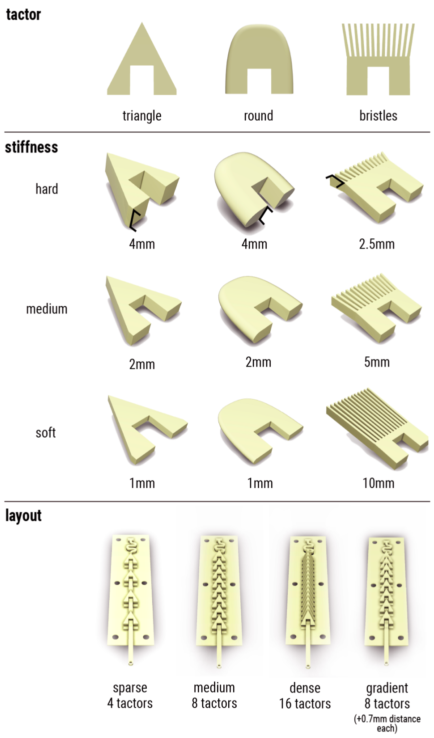

Figure 8: The tested parameters (i. e., the independent variables in the study) are reflected in the tactors and their layouts. We tested 18 patches in total.

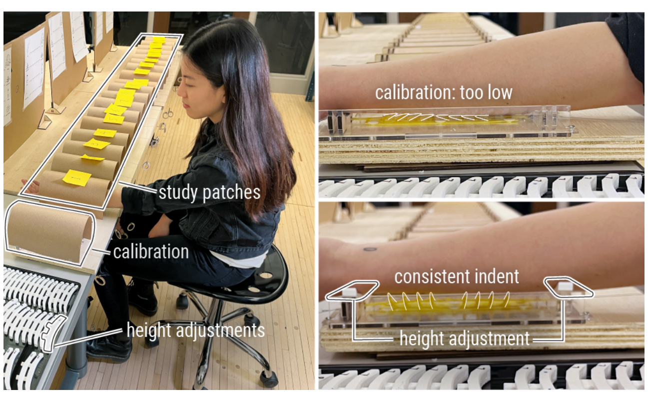

Figure 9: Study setup. Before conducting the study, each participant's arm is first calibrated for consistent indentation of the tactors into the skin.

about 15 mm. We set up all 18 passive patches and utilized manual actuation, rather than changing patches in and out of a motorized interface, to keep the study session focused and within a reasonable duration. Participants were then asked to rate the experience on the aforementioned scales and briefly describe the sensation. After experiencing all patches, participants were asked to reflect on the sensations and provide examples of what the experience reminded them of, either in real life or digital experiences such as games or VR. The experiment took approximately 45 minutes per participant.

6 RESULTS

In summary, subjective ratings indicate that triangle tactors were perceived as harder and sharper, and as more protruding into the skin. Bristles and round tactors led to a softer, surface-oriented sensation. The parameterized stiffness of the tactors successfully changed participants' perception towards soft, blunt and unified sensations. Dense layouts move participants' reported perception into a similar direction. This is also reflected in participants' qualitative comments.

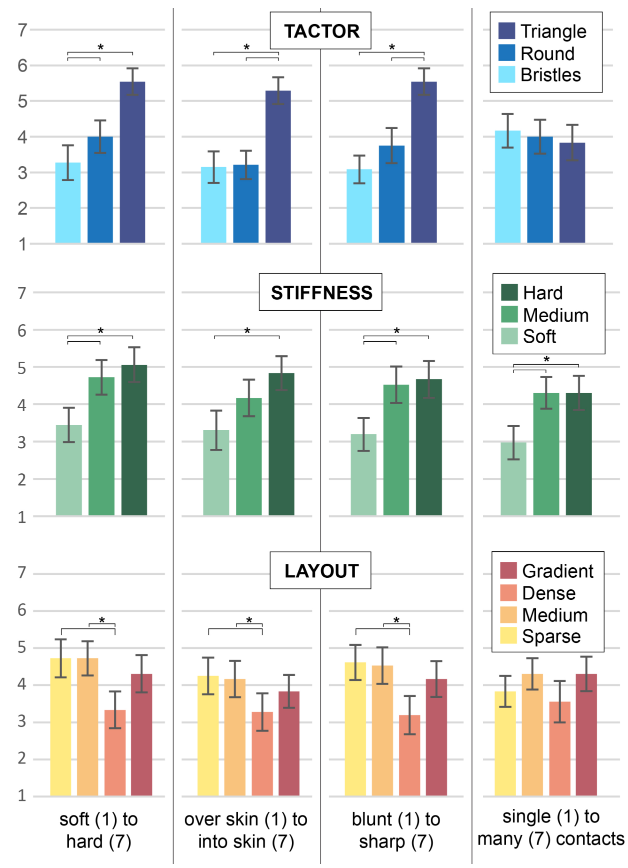

Figure 10: Mean subjective ratings from the experimental questionnaires. Error bars indicate standard errors, (*) indicates statistically significant differences.

6.1 Quantitative Rating of Stimuli

We analyzed the subjective ratings on the perception of soft to hard, over skin to into skin, blunt to sharp, and single to many contacts, all on scales from 1 to 7 (e. g., one scale ranged from 1 - soft to 7 - hard). Results are shown in Figure 10.

We performed an Aligned Rank Transform (ART) [63] on the ranking using the Windows tool of ARTool. The transformed data was analyzed using a series of repeated measures ANOVAs, performed in SPSS 29 [27]. Since the data was unbalanced between the three independent variables, we performed individual RM-ANOVAs on tactor and stiffness; and tactor and layout. For clarity of exposure, we only report on significant main effects ($\alpha = 0.05$). Posthoc tests of significant main effects were performed including Bonferroni adjustment for multiple comparisons.

For *soft to hard ratings*, we found significant main effects for tactor ($F_{2,22} = 11.323,\ p < 0.001$), stiffness ($F_{2,22} = 15.727,\ p < 0.001$) and layout ($F_{3,33} = 9.796,\ p < 0.001$). Bristle and round tactors were perceived as significantly softer than triangle tactors (all $p < 0.05$). Soft tactors (i. e., tactors with thin tips or long bristles) were perceived as significantly softer than medium or hard tactors (all $p < 0.01$), and dense layouts were perceived as softer than medium and sparse layouts (all $p = 0.001$).

For *over-skin to into-skin ratings*, we found significant main effects for tactor ($F_{2,22} = 12.371,\ p < 0.001$), stiffness ($F_{2,22} = 7.763,\ p = 0.003$), and layout ($F_{3,33} = 4.558, p = 0.009$). Triangle tactors were perceived as delivering more of an into-skin sensation compared to bristles ($p = 0.007$) and round tactors ($p = 0.010$), similar to hard tactors compared to soft ones ($p = 0.008$). Dense layouts were perceived more as over-skin sensations compared to medium and sparse layouts (all $p < 0.05$).

For *blunt to sharp ratings*, we found significant main effects for tactor ($F_{2,22} = 36.343,\ p < 0.001$), stiffness ($F_{2,22} = 14.762,\ p < 0.001$) and layout ($F_{3,33} = 10.354,\ p < 0.001$). Triangle tactors were perceived as sharper compared to bristles and round tactors (both $p < 0.001$). Soft tactors were perceived as more blunt than medium ($p = 0.001$) or hard tactors ($p = 0.005$). Dense layouts were perceived as more blunt sensations compared to medium and sparse layouts (all $p < 0.01$).

For *single vs multiple sensations ratings*, results indicate a main effect for stiffness ($F_{2,22} = 10.412,\ p < 0.001$), but no main effect for tactors ($p = 0.924$) or layout ($p = 0.144$). Soft tactors were perceived to yield sensations closer to a single surface compared to medium ($p = 0.004$) or hard ($p = 0.016$).

6.2 Qualitative feedback

In general, participants' qualitative feedback indicates that our tactile patches can render a wide range of sensations for various usage scenarios.

6.2.1 Influence of tactor. Triangle tactors were connected to scratching or stroking from people, animals, or hard objects. *"Like finger nails scratching"* (P1 - sparse triangle); *"dog paw or cat paw scratching"* (P8 - sparse triangle). Stiff triangle tactors were related to unpleasant scratching that could be used for urgent notifications: *"...pine needles...that hurts"* (P2 - hard triangle); *"try to alert the user... or bring back their attention..."* (P6 - medium triangle). Participants related coarse and soft triangle tactors to more pleasant sensations ($n = 5$) such as a comfortable scratch of the itch ($n = 3$) and a feeling in-between scratch and touch from a human or a pet ($n = 2$).

Round tactors were associated with scratching or stroking, but pleasant and blunt: *"between finger and nails... between touch and scratch"* (P2 - medium round); *"more like a brush in a narrow area"* (P10 - medium round); *"...a VR scenario where I'm a pet being groomed"* (P12 - sparse round). Further comments suggest that round tactors can render versatile sensations, such as big velcro (P1 - sparse round), rub against wood surface (p6 - hard round), water wave (P7 - hard round), or gentle grabbing (P2 - soft round).

Bristle tactors produced the widest range of haptic sensations, ranging from neutral to pleasant. Participants compared the sensations with social and affectionate touch ($n = 3$), and with different bristle structures such as a comb (P18), toothbrush (P9, P11), and shoe brush (P8). Bristle tactors produced the sensations of friction: *"it's like when you have a light comfortable wearable, and when you are like running, it rubs against your skin"* (P6 - short bristles); Long bristles triggered sensations such as *"a soft object hitting you fast"* (P6); a bubble wrap surface (P11), and a blunt tapping sensation from an eraser (P12).

6.2.2 Influence of stiffness. Softer tactors and sparse layouts were suggested for subtle notifications ($n = 5$), haptic feedback for button press (P7 - sparse triangles), a replacement for vibration (P7, P12), or augmenting digital media with pleasant sensations ($n = 3$). Harder patches were suggested for rendering unpleasant sensations such as cuts ($n = 3$).

6.2.3 Influence of layout. Gradient layouts were often associated with motion: *"Yeah I can feel a single thing that is moving, it's kind of like a point"* (P3 - gradient triangle); *"soft fine sand... sliding off"* (P2 - gradient bristles); *"Wind. Like spring wind. When I sleep, when I was young, I was sleeping during the spring and then I open the window."* (P7 - gradient bristles); *"running something along your arm"* (P12 - gradient round). Dense layouts decreased the perception of motion, and participants' comments were focused on the texture or material qualities: *"it's like a shower loofah"* (P1 - dense bristles); *"someone's dry skin... or maybe plywood"* (P2 - dense round); *"like, you know how you feel when it's dry and your skin is scratched off"* (P6 - dense triangle); *"a pool of tiny stones"* (P7 - dense triangles); *"needles in a square or a circle"* (P10 - dense triangles).

7 APPLICATION EXAMPLES

We showcase the versatility of our haptic patches with several application scenarios, including haptic feedback for VR, integration with existing objects to communicate information through haptics, and a wearable notification device that can send users different kinds of notifications. The implementation of the applications are shown in Figure 11 (haptic feedback for VR), Figure 12 (glasses augmented with haptics), and Figure 13 (wearable notification device).

7.1 Haptic feedback in Virtual Reality

With our modular design, haptic sensations that accompany VR environments can be shared as assets. Creators can upload them to e. g., Thingiverse, and users can download and print them.

We showcase the example of a haptic patch created for a jungle expedition game in Figure 11. The patch includes three kinds of tactors: a stiff triangular tactor laid out densely to render a sharp cut, a dual-triangular tactor with a thin connector in the middle that pinches the user when actuated, and a soft feather-like tactor to render stroking from relatively soft objects.

During the VR jungle expedition game, the user is taking a walk through the jungle. When they sweep their arm against a bush on the side of the path, the stroking tactors are actuated to produce the

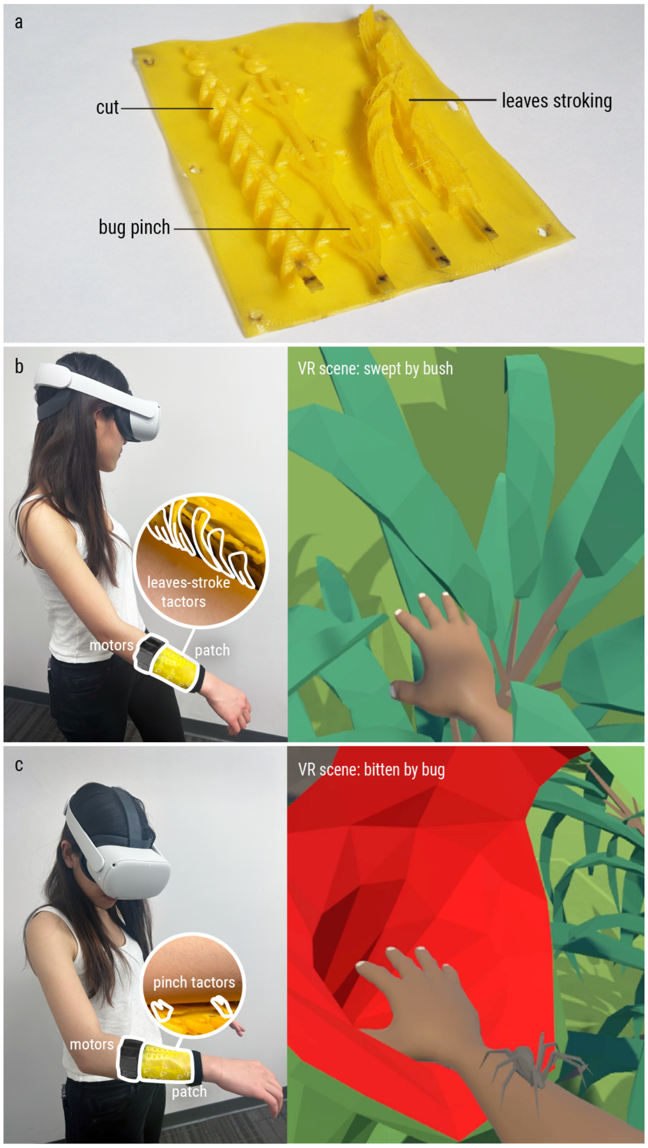

Figure 11: (a) A haptic patch for a VR jungle expedition game (b) a user touching leaves in the VR game, feeling the sensation on their forearm (c) a user being bitten by spiders in the VR game, with the haptic patch rendering a pinching sensation.

corresponding haptic feedback. Then, out of the spirit of exploration, the user places their arm into a hole. Spiders climb out of the hole and onto the user's arm, biting their skin. The pinching tactors are now actuated to give this encounter more realism. Afterward, the user accidentally gets a thin cut from a sharp plant. The stiff triangular tactors are actuated to render this cut.

Despite this example only showing one scenario for each kind of tactor's usage, tactors can be reused for multiple scenarios. This goes in line with the findings of our study, where participants associated different sensations with the same tactor. Multi-modal perception studies indicate that the visual sense is much stronger among different kinds of perception [20, 40, 60], but benefits from a combination with stimuli from other modalities such as haptics.

7.2 Augmenting objects

Parametric Haptic interfaces are small and flexible, and can be integrated with existing objects. In Figure 12, we show a simple 3-tactor patch that is integrated into a pair of glasses, without having to compromise the form factor. If connected with smart devices or sensing systems, this small haptic interface could quickly and effectively deliver notifications or low-level information to the user, while being unobtrusive.

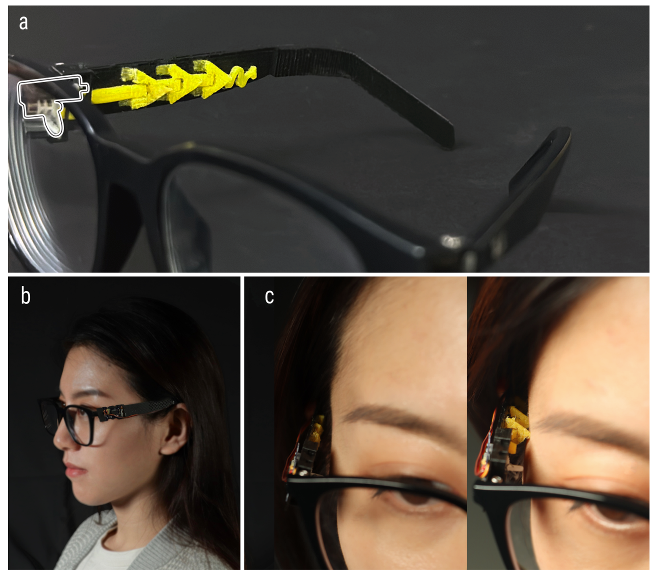

Figure 12: (a) A row of 3 tactors integrated into an existing pair of glasses (b) a user wearing a pair of Parametric Haptic-integrated glasses in daily life, (c) the glasses can unobtrusively deliver notifications.

7.3 Wearable notification device

Parametric Haptic patches can be used for various wearable devices. In Figure 13, we showcase a wearable that is worn on the user's back to render different kinds of tactile notifications. Tactors in this example patch are larger and placed further apart, taking advantage of the large area of the back and the fact that the mechanoreceptors on the back have larger receptive fields and are of low density [3, 36]. The patch shown in Figure 13c has four curved rows of round tactors of medium stiffness to deliver navigation instructions [32]. The ability of our actuation geometry to redirect tactors allows motors to be placed only on two sides of the haptic patch, while allowing the patch to render four directions to help users navigate. This example application can be leveraged for accessibility purposes (e. g., aiding low-vision users with navigational cues).

Besides directional information, this haptic patch also delivers various notifications. Informed by our study and previous works [4, 10, 34, 36], a stroking sensation from a soft tactor is perceived as affective and comforting [25, 48]. Here, a row of soft bristle tactors are placed on the right side of the patch (Figure 13b). They can be actuated when the user receives a text notification from friends and family—one of many scenarios that is suitable for affective touch. For more urgent notifications, such as a phone call from the user's social circle, a shorter row of elliptical tactors are used to render a poking sensation (insight from participants in our study). Another short row with softer tactors is used for other subtle notifications. The row of triangular tactors on the left side of the patch (Figure 13c), on the other hand, renders more urgent notifications that need users' immediate attention (e. g., a fraudulent charge on credit card). We note that in our research prototype, we only placed the motors needed for the actuation of the tactile patch across the user's back as highlighted in Figure 13a. A generic and densely motorized actuation device for the torso can be built with little engineering effort based on our bracelet design.

Figure 13: (a) This back wearable patch delivers various notifications and information to the user's lower back. (b) The user gets a gentle notification for a text message from their family. (c) We show the various tactors and directions we can render on this larger area.

8 CONCLUSION

We presented Parametric Haptics, a versatile and customizable tactile feedback device. The versatility of the device stems from its decomposition into (1) passive 3D-printed tactile feedback patches with custom tactors designs and (2) a generic actuation platform that the tactile patches can be connected to. Our design has several tangible benefits. The 3D-printed customizable geometry allows tactors to be designed for versatile applications. Since the patches are thin and soft, they conform easily to the user's body or objects. Additionally, the tactile patches are designed to provide tactile feedback over a larger area while offsetting the actuation away from the area of feedback.

Conceptually, the biggest benefit is that the tactors can be designed to match the represented stimuli closely and are easily exchangeable. Since the stimuli are encoded in the geometry, this allows the tactile experience to be shared with and replicated by others—a longstanding challenge in the field of haptics.

The scope of this paper includes designing, developing, and validating our novel enabling technology for haptic feedback. In the future, we are interested in investigating the broader possibilities of this technology. Interesting directions include psychophysical studies to investigate how the geometrical parameters impact tactile perception, establishing a broader design space and more compound parameters, and exposing such higher-level parameters to the design tool interface for novice users to use directly. Additionally, the distance between the tactor and the skin will influence the perception of different subjective parameters. While we maintained a consistent distance in our user study, we have not investigated the influence of different distances on the tactile perception of our actuators. Our user study shows differences in the perception of lateral skin stretch and indentation normal to the skin, and we believe that we further enhance this and produce more distinct differences by, e. g., building a Sarrus linkage[4] as a tactor mechanism to produce true indentation.

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REFERENCES

[1] Rochelle Ackerley, Karin Saar, Francis McGlone, and Helena Backlund Wasling. 2014. Quantifying the sensory and emotional perception of touch: differences between glabrous and hairy skin. *Frontiers in Behavioral Neuroscience* 8 (2014). https://doi.org/10.3389/fnbeh.2014.00034

[2] Ahmed Al Maimani and Anne Roudaut. 2017. Frozen Suit: Designing a Changeable Stiffness Suit and Its Application to Haptic Games. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 2440–2448. https://doi.org/10.1145/3025453.3025655

[3] Paul Bach-y Rita. 2004. Tactile sensory substitution studies. *Annals of the New York Academy of Sciences* 1013, 1 (2004), 83–91.

[4] Karlin Bark, Jason W Wheeler, Sunthar Premakumar, and Mark R Cutkosky. 2008. Comparison of skin stretch and vibrotactile stimulation for feedback of proprioceptive information. In *2008 Symposium on haptic interfaces for virtual environment and teleoperator systems*. IEEE, 71–78.

[4] https://en.wikipedia.org/wiki/Sarrus_linkage

[5] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-Fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 717–728. https://doi.org/10.1145/2984511.2984526

[6] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. NormalTouch and TextureTouch: High-Fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 717–728. https://doi.org/10.1145/2984511.2984526

[7] Sliman Bensmaïa and Mark Hollins. 2005. Pacinian representations of fine surface texture. *Perception & psychophysics* 67 (2005), 842–854.

[8] Sliman J Bensmaïa and Mark Hollins. 2003. The vibrations of texture. *Somatosensory & motor research* 20, 1 (2003), 33–43.

[9] Carlos Bermejo and Pan Hui. 2021. A Survey on Haptic Technologies for Mobile Augmented Reality. *ACM Comput. Surv.* 54, 9, Article 184 (oct 2021), 35 pages. https://doi.org/10.1145/3465396

[10] Nathaniel A Caswell, Ryan T Yardley, Markus N Montandon, and William R Provancher. 2012. Design of a forearm-mounted directional skin stretch device. In *2012 IEEE Haptics Symposium (HAPTICS)*. IEEE, 365–370.

[11] Zekun Chang, Tung D Ta, Koya Narumi, Heeju Kim, Fuminori Okuya, Dongchi Li, Kunihiro Kato, Jie Qi, Yoshinobu Miyamoto, Kazuya Saito, et al. 2020. Kirigami haptic swatches: Design methods for cut-and-fold haptic feedback mechanisms. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–12.

[12] Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 119–130. https://doi.org/10.1145/3126594.3126599

[13] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3173574.3174228

[14] Artem Dementyev, Alex Olwal, and Richard F. Lyon. 2020. Haptics with Input: Back-EMF in Linear Resonant Actuators to Enable Touch, Pressure and Environmental Awareness. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 420–429. https://doi.org/10.1145/3379337.3415823

[15] N. D'Aurizio, T. Lisini Baldi, A. Villani, K. Minamizawa, Y. Tanaka, and Domenico Prattichizzo. 2021. Wearable Haptics for Object Compliance Discrimination Through Passive Touch. In *2021 IEEE World Haptics Conference (WHC)*. 894–899. https://doi.org/10.1109/WHC49131.2021.9517143

[16] Benoni B Edin. 2004. Quantitative analyses of dynamic strain sensitivity in human skin mechanoreceptors. *Journal of neurophysiology* 92, 6 (2004), 3233–3243.

[17] Benoni B Edin and Niclas Johansson. 1995. Skin strain patterns provide kinaesthetic information to the human central nervous system. *The Journal of physiology* 487, 1 (1995), 243–251.

[18] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling Complex Tangible Geometries in Virtual Reality with Worn Multi-String Haptics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3313831.3376470

[19] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation.. In *Uist*, Vol. 13. Citeseer, 2501–988.

[20] Steve Guest and Charles Spence. 2003. Tactile dominance in speeded discrimination of textures. *Experimental brain research* 150 (2003), 201–207.

[21] K.S. Hale and K.M. Stanney. 2004. Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations. *IEEE Computer Graphics and Applications* 24, 2 (2004), 33–39. https://doi.org/10.1109/MCG.2004.1274059

[22] Nur Al-huda Hamdan, Adrian Wagner, Simon Voelker, Jan Borchers, and Jürgen Steimle. 2019. Demonstration of Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–4.

[23] Roland Harper and SS Stevens. 1964. Subjective hardness of compliant materials. *Quarterly Journal of Experimental Psychology* 16, 3 (1964), 204–215.

[24] Chris Harrison and Scott E. Hudson. 2009. Texture Displays: A Passive Approach to Tactile Presentation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 2261–2264. https://doi.org/10.1145/1518701.1519047

[25] Matthew J Hertenstein, Rachel Holmes, Margaret McCullough, and Dacher Keltner. 2009. The communication of emotion via touch. *Emotion* 9, 4 (2009), 566.

[26] Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges. 2018. DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 901–912. https://doi.org/10.1145/3242587.3242657

[27] IBM Corp. [n. d.]. *IBM SPSS Statistics for Windows.* Armonk, NY: IBM Corp. https://hadoop.apache.org

[28] Alexandra Ion, Robert Kovacs, Oliver S Schneider, Pedro Lopes, and Patrick Baudisch. 2018. A Demonstration of Metamaterial Textures. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–4.

[29] Alexandra Ion, Robert Kovacs, Oliver S Schneider, Pedro Lopes, and Patrick Baudisch. 2018. Metamaterial textures. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–12.

[30] Ali Israr and Freddy Abnousi. 2018. Towards Pleasant Touch: Vibrotactile Grids for Social Touch Interactions. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3170427.3188546

[31] Kenneth O Johnson. 2001. The roles and functions of cutaneous mechanoreceptors. *Current Opinion in Neurobiology* 11, 4 (2001), 455–461. https://doi.org/10.1016/S0959-4388(00)00234-8

[32] Lynette A Jones, Jacquelyn Kunkel, and Erin Piateski. 2009. Vibrotactile pattern recognition on the arm and back. *Perception* 38, 1 (2009), 52–68.

[33] Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2003. Psychophysical evaluation of receptor selectivity in electro-tactile display. In *Proc. of 13th International Symposium on Measurement and Control in Robotics (ISMCR)*, Vol. 13. 83–86.

[34] Smita Kanjanapas, Cara M Nunez, Sophia R Williams, Allison M Okamura, and Ming Luo. 2019. Design and analysis of pneumatic 2-DoF soft haptic devices for shear display. *IEEE Robotics and Automation Letters* 4, 2 (2019), 1365–1371.

[35] Francisco Kiss, Robin Boldt, Bastian Pfleging, and Stefan Schneegass. 2018. Navigation Systems for Motorcyclists: Exploring Wearable Tactile Feedback for Route Guidance in the Real World. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3173574.3174191

[36] Roberta L. Klatzky, Dianne Pawluk, and Angelika Peer. 2013. Haptic Perception of Material Properties and Implications for Applications. *Proc. IEEE* 101, 9 (2013), 2081–2092. https://doi.org/10.1109/JPROC.2013.2248691

[37] Katherine J Kuchenbecker, Joseph Romano, and William McMahan. 2011. Haptography: Capturing and recreating the rich feel of real surfaces. In *Robotics Research: The 14th International Symposium ISRR*. Springer, 245–260.

[38] Shinobu Kuroki, Hiroyuki Kajimoto, Hideaki Nii, Naoki Kawakami, and Susumu Tachi. 2007. Proposal for tactile sense presentation that combines electrical and mechanical stimulus. In *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*. IEEE, 121–126.

[39] Susan J Lederman. 1974. Tactile roughness of grooved surfaces: The touching process and effects of macro-and microsurface structure. *Perception & Psychophysics* 16, 2 (1974), 385–395.

[40] Susan J Lederman and Roberta L Klatzky. 2004. Multisensory texture perception. (2004).

[41] Edouard Leroy, Ronan Hinchet, and Herbert Shea. 2020. Multimode hydraulically amplified electrostatic actuators for wearable haptics. *Advanced Materials* 32, 36 (2020), 2002564.

[42] Vincent Lévesque, Jérôme Pasquero, Vincent Hayward, and Maryse Legault. 2005. Display of Virtual Braille Dots by Lateral Skin Deformation: Feasibility Study. *ACM Trans. Appl. Percept.* 2, 2 (apr 2005), 132–149. https://doi.org/10.1145/1060581.1060587

[43] Hongnan Lin, Liang He, Fangli Song, Yifan Li, Tingyu Cheng, Clement Zheng, Wei Wang, and HyunJoo Oh. 2022. FlexHaptics: A Design Method for Passive Haptic Inputs Using Planar Compliant Structures. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–13.

[44] Robert W Lindeman, Yasuyuki Yanagida, Haruo Noma, and Kenichi Hosaka. 2006. Wearable vibrotactile systems for virtual contact and information display. *Virtual Reality* 9 (2006), 203–213.

[45] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 11–19. https://doi.org/10.1145/2807442.2807443

[46] Joseph Luk, Jerome Pasquero, Shannon Little, Karon MacLean, Vincent Levesque, and Vincent Hayward. 2006. A Role for Haptics in Mobile Interaction: Initial Design Using a Handheld Tactile Display Prototype. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Montréal, Québec, Canada) *(CHI '06)*. Association for Computing Machinery, New York, NY, USA, 171–180. https://doi.org/10.1145/1124772.1124800

[47] Granit Luzhnica and Eduardo Veas. 2018. Investigating Interactions for Text Recognition Using a Vibrotactile Wearable Display *(IUI '18)*. Association for Computing Machinery, New York, NY, USA, 453–465. https://doi.org/10.1145/3172944.3172951

[48] Francis McGlone, Johan Wessberg, and Håkan Olausson. 2014. Discriminative and affective touch: sensing and feeling. *Neuron* 82, 4 (2014), 737–755.

[49] Michel Paré, Heather Carnahan, and Allan M Smith. 2002. Magnitude estimation of tangential force applied to the fingerpad. *Experimental Brain Research* 142 (2002), 342–348.

[50] Fabrizio Pece, Juan Jose Zarate, Velko Vechev, Nadine Besse, Olexandr Gudozhnik, Herbert Shea, and Otmar Hilliges. 2017. Magtics: Flexible and thin form factor magnetic actuators for dynamic and wearable haptic feedback. In *Proceedings of the 30th annual ACM symposium on User interface software and technology*. 143–154.

[51] Domenico Prattichizzo, Claudio Pacchierotti, Stefano Cenci, Kouta Minamizawa, and Giulio Rosati. 2010. Using a fingertip tactile device to substitute kinesthetic feedback in haptic interaction. In *Haptics: Generating and Perceiving Tangible Sensations: International Conference, EuroHaptics 2010, Amsterdam, July 8-10, 2010. Proceedings, Part I*. Springer, 125–130.

[52] Mandayam A Srinivasan and Robert H LaMotte. 1995. Tactual discrimination of softness. *Journal of neurophysiology* 73, 1 (1995), 88–101.

[53] Evan Strasnick, Christian Holz, Eyal Ofek, Mike Sinclair, and Hrvoje Benko. 2018. Haptic Links: Bimanual Haptics for Virtual Reality Using Variable Stiffness Actuation. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174218

[54] Yujie Tao, Shan-Yuan Teng, and Pedro Lopes. 2021. Altering Perceived Softness of Real Rigid Objects by Restricting Fingerpad Deformation. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 985–996. https://doi.org/10.1145/3472749.3474800

[55] Shan-Yuan Teng, Pengyu Li, Romain Nith, Joshua Fonseca, and Pedro Lopes. 2021. Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 736, 14 pages. https://doi.org/10.1145/3411764.3445099

[56] Wouter M Bergmann Tiest. 2010. Tactual perception of material properties. *Vision research* 50, 24 (2010), 2775–2782.

[57] Wouter M Bergmann Tiest and Astrid ML Kappers. 2009. Cues for haptic perception of compliance. *IEEE transactions on haptics* 2, 4 (2009), 189–199.

[58] Cesar Torres, Tim Campbell, Neil Kumar, and Eric Paulos. 2015. HapticPrint: Designing feel aesthetics for digital fabrication. In *Proceedings of the 28th annual ACM symposium on user interface software & technology*. 583–591.

[59] Velko Vechev, Juan Zarate, David Lindlbauer, Ronan Hinchet, Herbert Shea, and Otmar Hilliges. 2019. TacTiles: Dual-mode Low-power Electromagnetic Actuators for Rendering Continuous Contact and Spatial Haptic Patterns in VR. (Mar 2019). https://doi.org/10.1109/VR.2019.8797921

[60] T Aisling Whitaker, Cristina Simões-Franklin, and Fiona N Newell. 2008. Vision and touch: Independent or integrated systems for the perception of texture? *Brain research* 1242 (2008), 59–72.

[61] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173660

[62] Anusha Withana, Daniel Groeger, and Jürgen Steimle. 2018. Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 365–378. https://doi.org/10.1145/3242587.3242645

[63] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 143–146. https://doi.org/10.1145/1978942.1978963

[64] Chang Xu, Yuxiang Wang, Steven C Hauser, and Gregory J Gerling. 2018. In the tactile discrimination of compliance, perceptual cues in addition to contact area are required. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 62. SAGE Publications Sage CA: Los Angeles, CA, 1535–1539.

[65] Clement Zheng, Zhen Zhou Yong, Hongnan Lin, HyunJoo Oh, and Ching Chiuan Yen. 2022. Shape-Haptics: Planar & Passive Force Feedback Mechanisms for Physical Interfaces. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. 1–15.