Haptic Permeability: Adding Holes to Tactile Devices Improves Dexterity

Shan-Yuan Teng
University of Chicago
tengshanyuan@uchicago.edu

Aryan Gupta
University of Chicago
aryan05g@gmail.com

Pedro Lopes
University of Chicago
pedrolopes@uchicago.edu

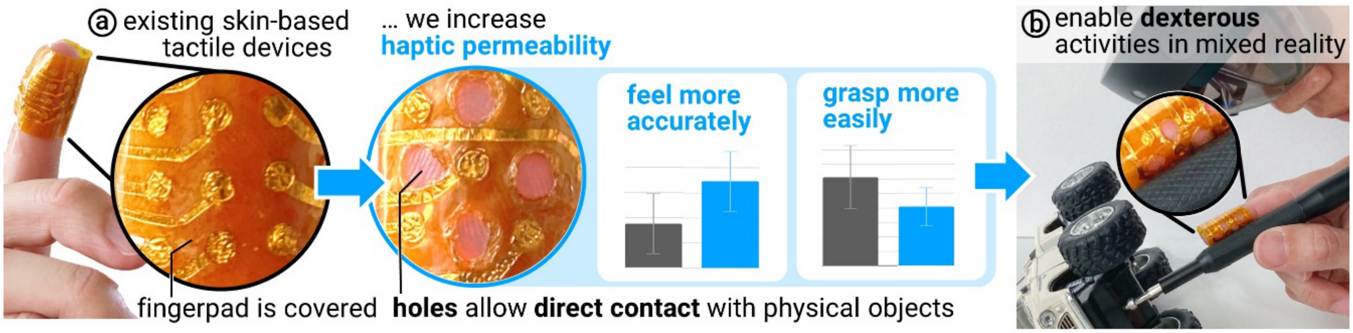

Figure 1: (a) To improve the usability & minimize encumberment of tactile devices for the fingerpads, researchers moved away from thick actuators (e.g., vibration motors) and, instead, focused on thin devices—one successful example is electrotactile stimulation. These can be engineered to be thin, which allows the user to still feel some sensations even though their fingerpads are covered by the electrode film (e.g., compliance or macro features). However, we argue this is not enough and on should also *balance* how much a tactile device *impairs* feeling the real world vs. how *accurately* it delivers virtual sensations. Thus, we propose & evaluate how adding *holes* to electrotactile devices results in: (1) improved perception of tactile features; and (2) improved force control in grasping tasks (b) Our approach significantly improves the haptic users' abilities in dexterous activities, including manipulating tools, in mixed reality.

ABSTRACT

Feeling haptics with our fingerpads is how we achieve manual tasks (e.g., operate a needle or press buttons). Following this, research started adding actuators atop the users' fingerpads to render haptic feedback for interactive virtual environments. Recently, many have moved away from thick actuators (e.g., vibration motors) and turned to electrode-films with electrotactile stimulation—allowing users to still feel *some* sensations through the devices when touching physical objects (e.g., compliance or some macro features). However, we argue & demonstrate that *thin devices are not enough to maximize the user's dexterity.* We evaluate how adding small holes to electrotactile films can allow direct contact and thus increase *haptic permeability,* resulting in: (1) improved perception of tactile features; and (2) improved force control in grasping tasks. Finally, we observed participants in interactive experiences and found that holes can preserve dexterity with physical tasks while still benefiting from haptic feedback.

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CCS CONCEPTS

• **Haptic devices; Mixed / augmented reality**;

KEYWORDS

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1 INTRODUCTION

Feeling haptic cues using our fingerpads is how we achieve precise tasks in the physical world (e.g., pick up a match, press buttons, feel fabrics, and more). Inspired by the crucial role of fingerpad tactile cues, haptic devices have been developed to enable users to also more accurately interact with virtual environments. These devices typically provide precise haptic feedback by attaching mechanical or electrical actuators directly on our fingerpads, which allows the haptic device stimulate the touch on virtual interfaces (e.g., VR [25, 30, 36, 41, 54], AR/MR [11, 45]).

In recent years, to improve the usability & minimize encumberment of these tactile haptic devices for the fingerpads, many researchers have moved away from thick actuators (e.g., vibration motors) and, instead, focused on tactile haptics via thin devices

[11, 51]—one successful example of this is electrotactile stimulation [23, 51].

Electrotactile devices can be engineered to be thin (<100 μm), which allows the user to still feel *some* sensations despite the fact that their fingerpads are covered by the electrode film, e.g., pressure, compliance and even some macro features—unfortunately, researchers also found evidence that even thin films impair haptic perception [33].

We argue that minimizing the thickness of these haptic actuators alone is not enough. Our field needs to be equipped with more approaches to *balance* how much a tactile device *impairs* feeling the real world vs. how *accurate* it can deliver virtual sensations. Thus, we propose & evaluate how adding holes to electrotactile devices enables *haptic permeability*, i.e., allowing one's skin to *directly* make contact with the real-world via the holes.

In our studies, we found that, for the generic case of uniformly distributed holes (Figure 1), haptic permeability resulted in: (1) improved perception of tactile features by 17% (e.g., orientation of tactile gratings, as found in our Study 1); and (2) improved force control in grasping tasks by 34% (e.g., less grasp force needed while grasping, as found in our Study 2). Finally, in our Study 3, we found that even in its most extreme design option (i.e., replacing electrodes with holes, which decreases the device's output resolution), was useful to participants since it was easier to perform dexterous assembly tasks in mixed reality.

Our three studies validate how haptic permeability enables users to retain more dexterity, which ultimately opens the design space for haptic devices—in other words, if users can manipulate small objects & feel fine textures, we can open-up haptics to new interactive domains heavily involving tool-use.

2 RELATED WORK

This paper builds on the field of haptics, with particular emphasis on tactile haptics for the fingerpad. Given our goal of uncovering new ways to feel real-world surfaces, we focus on electrotactile interfaces, which are built from thin films, most suitable for interactions involving feeling virtual & real objects. Thus, we succinctly review the field of electrotactile stimulation (complete review can be found at [28]), and turn our attention to how researchers have decreased the thickness of films to improve the sensation felt through them, despite they cover the fingerpads completely—this is where we take inspiration for proposing *haptic permeability* (via holes).

2.1 The role of touch in our interactions

Texture Discrimination. Texture discrimination at the fingerpad is important for tasks such as recognizing different fabrics, or factory workers detecting defects. Naturally, materials that we touch stimulate many of the receptors [20] (e.g., vibrates, deforms the skin, conducts heat) and, temporally, this forms the sensation of texture [38]. Moreover, spatial acuity in a patch of skin [19] (i.e., how well we perceive tactile sensations in a location) is critical. Fingerpads are one of the most sensitive parts and can detect stimuli within the distance of 1-2 mm [37].

Grip Control. Our ability to grasp objects with our fingers without slipping relies heavily on tactile sensitivity to sense friction [42, 50] (i.e., sense micro-deformation of the skin). The ridges on the fingerpads (which form the fingerprint) and the sweat glands form a dynamic regulated system that can adjust the moisture and maximize the friction of the skin [2, 24, 59]. Altogether, these help us grasp with optimal force (by using the least energy).

2.2 Towards less encumbering tactile interfaces: actuators that conform to skins (e.g., soft, films, etc.)

Most tactile devices were engineered using rigid & thick mechanical actuators—the most popular are vibration-motors. While these offer advantages in low-cost, control simplicity, and haptic capabilities, their inflexibility (mechanical rigidity) limits their applications. As such, in the last decades, much attention has been devoted to engineering devices that conform better to the user's body (e.g., on-skin devices, epidermal devices) [15, 34]. This led to soft and thin actuators [5], including microfluidic actuators [11, 12], magnetic actuators [31, 58], dielectric elastomers [27, 57], piezoelectric actuation [17, 62]. While promising, they are still mechanical devices, thus inheriting their limitations (e.g., a device with moving parts takes more space than one without). Thus, researchers have explored creating tactile sensations without moving parts, by stimulating the mechanoreceptors with electricity—*electrotactile stimulation* [21, 23]. Given that electrodes can be made smaller than a mechanical actuator (which requires physical displacement and that requires empty space), electrotactile devices can be made into arrays suitable for the fingerpad [1, 18, 21, 22, 28]. Thus, electrotactile has been mainly used as a device for fingerpads, to deliver textures [10], shapes [40], softness [55] or touch information in virtual environments [51, 53].

2.3 Improving tactile interfaces by using thinner films (i.e., feel-through)

Recently, researchers argued that it is not only important to render haptics, but also need to *preserve* haptic sensations from the real world [39, 43–45, 51], as they are critical for achieving precise manual tasks (e.g., in MR). Making devices thin and soft is one way that researchers explored preserving cues from the real world. For instance, HydroRing [11] is a ring worn on the fingerpad that uses pumped water for haptics. Its relatively low thickness results in an unobtrusive device that still lets users feel some tactile sensations from the real world. Similarly, Tacttoo [51] is an electrotactile device based on layers of temporary tattoo papers (35 μm) [51]. This can also be taken a step thinner, as shown by Ji, et al. in their 18 μm thick dielectric elastomer [16]. Note that devices with low rigidity can preserve very more tactile sensitivity, but they do so by trading this off with fragility (i.e., prone to breaking when interacting with physical surfaces, such as rough textures) [33].

2.4 Tactile sensitivity is impaired by covering the fingerpads (e.g., films, gloves, etc.)

Unfortunately, despite the improvement brought the reducing the thickness of a film, researchers confirmed that even thin films impair tactile perception and affect grip control. For instance, wearing thin gloves such as the ones typically used in dental work has been shown to decreased force perception and dampen vibrations [8, 60].

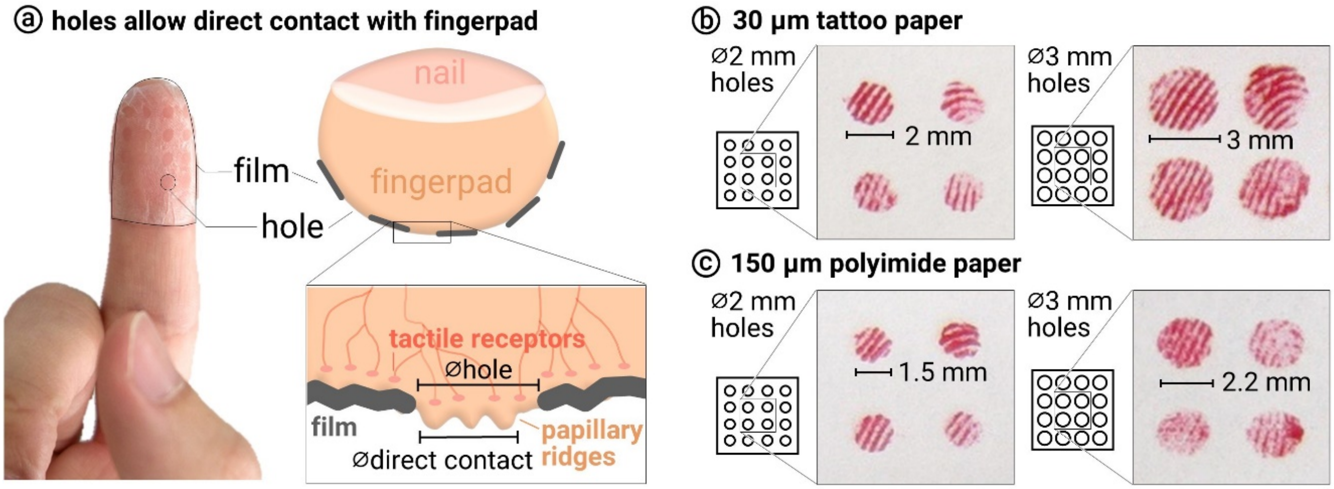

Figure 2: (a) Holes on the film allow direct contact with fingerpad, revealing papillary ridges and can directly transmit tactile signal to receptors. (b) Ink test on tattoo paper with holes. (c) Ink test on polyimide paper with holes.

Similarly, it has also been shown that the required grasping force increases in lifting and holding task while wearing gloves [26]. Specifically, thin films obstruct static tactile perception which is required for optimal grasp efficiency [4]. Most relevant to electrotactile research, Nittala, et al. conducted studies with various thickness of films, ranging from 2.5 μm to 177 μm, and found that *even the thinnest film* covering the fingerpad would increase the detection threshold when discriminating the roughness of a surface (144% compared to bare finger) [33].

As such, we argue that making electrotactile devices thin is not the *only* route to improve tactile sensations. Inspired by this and to advance this research question, we turn our attention to creating actual *haptic permeability*.

3 HOLES: A NEW APPROACH TO PRESERVE DEXTERITY & HAPTICS FROM THE REAL WORLD

We propose & explore a new dimension that designers can incorporate on haptic-devices based on films: *haptic permeability*—adding holes (i.e., any type of cutout of the electrode film) through which the skin can contact the physical environment, instead of *always* being mediated by the film; this is depicted in Figure 2.

Direct skin contact. Figure 2 illustrates the principle behind adding holes. In this ink-test, a finger was coated with red ink. In this case, instead of wearing an existing thin-film device (e.g., [51]) that would cover the entire area of their fingerpad, the user wears a film modified with our approach. The film is the same (same thickness/material as [51]), except we added 2 mm *holes* at equal intervals (4 mm center-to-center) throughout. The ink-test reveals how the skin is able to contact the paper—even the fingerpad ridges are visible in the red ink, which implies that the reverse is also true, i.e., small features that the user is touching are in *direct contact* with the skin.

Tactile receptors. While 2 mm of opening might sound small, it contains ~eight mechanoreceptors [19] and ~five ridges. As humans are sensitive to a stimulus on one single ridge [14], even a proposal as simple as a mm-sized hole might prove powerful at improving tactile perception. The reason is that the exposed receptors can gather more information. This yields our first hypothesis: exposing parts of skin directly via holes would lead to higher haptic sensitivity, which we validated in our Study 1 (i.e., holes increased tactile recognition by 17%).

Grip control. This seemingly simple ink-test reveals a second key benefit of adding holes to haptic devices. Again, we turn the reader’s attention to the fingerpad ridges shown in the ink-test. Ridges contribute to slip control and help us grasp firmly without exerting excessive force [59]. This yields our second hypothesis: exposing parts of skin helps regulate grip and thus decrease the minimal force to grasp an object, which we validated in our Study 2 (i.e., holes decreased grasping force by 34%).

Structural stability of adding holes. The most naïve approach to adding holes would be to turn *all* unused space (i.e., space that is not an electrode or a conductive trace) into a hole. However, cutting out too much space on the film can have structural limitations. First, these films are adhesive (i.e., the larger the surface area the stronger they bond to the skin), thus loosing adhesive risks the device coming off the user’s finger. Second, the less material envelopes electrodes, the more likely is that this electrode will get caught in some material or feature that the user is touching, e.g., as a user operates a tool it can get caught, crinkle, fold or get ripped out. Moreover, while holes can be of different shapes, circular holes minimize aforementioned issues as they (1) are less likely to get caught in materials since there are no sharp angles (as there would be in a square or other polygonal shapes); and, (2) have less impact to the overall bonding force of the adhesive, since circular holes are supported on all sides, thus electrodes are less likely to get dislodged; (3) are shown to be the most stable hole shapes [52], which would make our thin devices more durable for longer use. In our third study, in which participants interacted with objects with high friction (e.g., screwdriver) and small parts (e.g., wires) , no device was caught or dislodged.

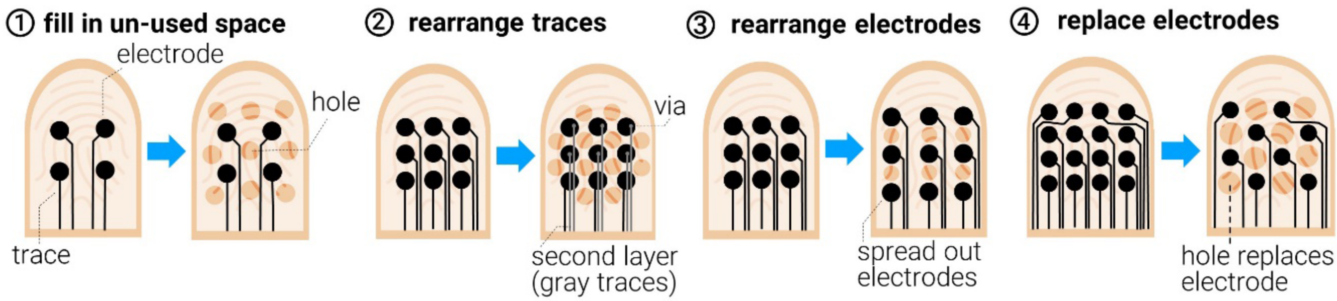

Figure 3: Four design options to implement haptic permeability on an electrotactile device.

Applicability & design options. Figure 3 illustrates how our concept can be applied in a number of ways, depending on both the goal of the haptics application (i.e., how much it requires prioritizing feeling real vs. virtual cues) and engineering constrains (e.g., resolution, unused space, layout of the conductive traces).

We envision four ways a designer can use our approach, presented in ascending order of how much one might expect they would tradeoff the resolution of the target electrotactile device: (1) swapping unused space for holes—no impact to virtual rendering & gains permeability to feel physical cues; (2) rearranging the traces to add holes—low/no impact to virtual rendering & gains permeability to feel physical cues; (3) rearranging the electrodes to add holes—medium impact to virtual rendering & gains permeability to feel physical cues; and (4) replacing electrodes for holes—purposefully trades-off some virtual rendering for more permeability to feel physical cues. Importantly, it is worth noting that we present these design options to illustrate how one might explore holes in electrotactile devices, but our investigation only measured the benefits of swapping unused space for holes (design option 1) and replacing electrodes for holes (design option 4) in the generic case of a uniformly distributed layout.

1. Swapping unused space for holes: the most straightforward & readily available option is trading holes for unused space on the device. This is useful for electrotactile films with sparse electrode density (e.g., similar to [23]), which leave plenty of space of holes to be added—this is typical of applications that do not require high-resolution.

2. Rearranging the traces to add holes: traces can be rearranged to make space for holes by either rearranging the these to pass through to the back of the film using a *via* [48], or rearranging the traces to optimize empty space. The limitation of using multiple layers is it leads to thicker films, (e.g., 150 μm for double layers [9]).

3. Rearranging the electrodes to add holes: the electrode positions can be altered so that the electrode-to-electrode distance allows for holes—this option might fit applications where densely-packed electrodes are not required, yet their number is important (e.g., rendering information of directions [47, 49]).

4. Replacing electrodes for holes: in our most interesting design option one *trades-off electrodes for holes*, which trades-off some virtual rendering for permeability to feel physical cues, which we validated in our Study 3.

Additional factors. There are several additional factors that might influence haptic permeability when adding holes, including: the size of the hole, the shape of the hole, the layout of the holes, and the material of the film. As the first paper to propose & investigate adding holes to electrotactile devices, we focused only on studying the generic case of *uniformly distributed holes* on a film. While our findings for the case of uniformly distributed holes already provide generalizable insights to other devices (see Section 8), future studies should follow up on our findings to explore how these additional parameters affect tactile performance.

4 STUDY OVERVIEW

We conducted three user studies to inform, measure & understand the impact that adding holes to electrotactile haptic devices has on dexterity & tactile perception. In all our studies we compared thin films applied to the fingerpad against same films with added holes. Study 1: we assessed tactile perception, using a standardized task (orientation of grooves in a material); we found that in the holes condition participants were able to better perceive orientation by 17% than while their fingerpads were covered (no holes). Study 2: we assessed grip control, using a standardized grip-force test (force needed to grasp without slipping); we found that participants were able to grasp 34% less force than while covered. Study 3: participants experienced a mixed reality tutorial involving assembly of a physical toy truck, with virtual instructions accompanied by haptic feedback. We found that participants found it easier to accomplish the task and felt more real-world feedback with the holes condition than when covered.

All our user studies were approved by our Institutional Review Board (IRB23-1225).

5 STUDY #1: HOLES IMPROVE TACTILE PERCEPTION

We aimed to understand whether adding holes to thin-film haptic devices would affect the feel-through perception of physical objects. As the first study to investigate this, we opted for the aforementioned generic case of *uniformly distributed holes* added to the film used in Tacttoo [51]. To evaluate the impact of adding holes, we conducted a **tactile perception** study using the standard grating orientation test [6, 61], in which participants are presented with gratings (grooves on a material) and are asked to guess the orientation of the grating by touch alone.

Hypothesis. Our hypothesis was that adding *holes*, which exposes parts of skin directly in contact with the touch surface, would lead to higher haptic sensitivity (i.e., higher accuracy at determining the orientation of the grating).

5.1 Study Design

Task. Participants were asked to touch (eyes-free) a sample with grooves running in four directions and report which direction was felt—this is a popular test used in psychophysics research to measure tactile perception [6]. As we are interested in fine textures that could be affected by thin film covering, we chose a grating spacing 1.5 mm. Note that at 1.5 mm of spacing, four directions and eyes-free, this is a *fairly challenging* task that requires high sensitivity; thus, we pretested our participants at 70% accuracy.

Grating. We 3D-printed a grating with ridges of 0.65 mm × 0.65 mm (height, width) spaced by 1.5 mm.

Pretest. To qualify for our main experiment, recruited participants performed the task (grating orientation, 20 trials of randomized patterns from four directions) with their bare fingerpad—when scoring equal or above 70%, they would continue to the *holes* vs. *covered* conditions.

Participants. 12 participants qualified (6 females, 6 males; average-age=27.0 years old, SD=4.4; all participants were right-handed). Participants were compensated with $10 USD voucher.

Haptic film. We fabricated a 30 μm thin-film inspired by [51], comprised of stacked layers of tattoo paper and cut using a paper plotter (*Cricut*). The resulting film was attached to the participants' dominant fingerpad.

Interface conditions. Participants performed the grating-recognition task in two interface conditions: *holes* (thin film with holes added to it, 2 mm diameter with 4 mm center-to-center spacing) and *covered* (thin film).

Procedure. Participants performed 20 trials per condition (order was counterbalanced across participants). In total, we collected 480 trials across all participants (i.e., 4 directions × 5 repetitions × 2 conditions × 12 participants).

5.2 Results

Figure 4 depicts our findings regarding tactile discrimination. We found a statistically significant difference between all conditions (paired t-test). Our main finding is that the *holes* condition (M=74.6%; SD=11.6%) improved tactile recognition by ~17% ($p<0.0001$, $F(11)= 10.1637$) compared to the *covered* condition (M=57.5%; SD=12%). As expected, the accuracy of the *bare-finger* result was the highest (M=80%; SD=8.3%), which was unsurprising given that we set the threshold of our pretest above 70%. Taken together, these results confirm our hypothesis that adding holes improved the tactile recognition significantly when compared to a covered film.

6 STUDY #2: HOLES IMPROVE GRIP CONTROL REQUIRED TO GRASP WITHOUT SLIPPING

We set out to understand what the impact of adding holes to a tactile haptic device on the fingerpad might have in terms of **grip control**—a dexterous skill that depends on one's ability to sense friction [50] and control it by adding pressing force. We assessed it using a standardized grip-force test, which measured the grip force

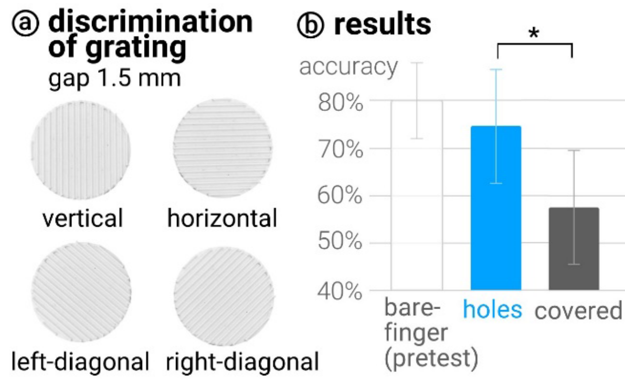

Figure 4: (a) Tactile sensitivity task (grating orientation); (b) Results from tactile sensitivity task.

needed to lift & hold objects without these slipping—a popular task in psychophysics to measure grip control [13, 26].

Hypothesis. We hypothesized that since adding *holes* exposes skin, namely fingerpad ridges which contribute to friction and grip control [59], it would allow participants to enact better grip control when compared to the *covered* condition, resulting in less force required to lift objects without slipping.

6.1 Study Design

Task. (1) Grasp a 300g weight on a rail; (2) lift it 5 cm upwards; and, (3) hold it for 5 seconds.

Apparatus. We fabricated a 30 μm thin-film (same as in Study 1). We used a 1kg (max) load cell, sampled using HX711 and an Arduino board to measure the grasping force. The grasping handle was made from acrylic.

Interface conditions. Participants performed the lift-and-hold task in three interface conditions: *bare-finger*; *holes* (thin film with holes added to it, 2 mm diameter with 4 mm center-to-center spacing) and *covered* (thin film).

Procedure. Participants performed six lifting trials per condition. As the participants may be adjusting their grasping forces in the initial trials, we only measured the force for the last three trials. Force was measured at the middle of the 5-second hold by averaging 10 readings of the load cell. The condition order was counterbalanced across all participants. A total of 108 measurements (3 trials × 3 conditions × 12 participants) were collected.

Participants. 12 right-handed participants (6 females, 6 males; average age was 28.2 years old, SD=7.3 years) were recruited from our neighborhoods. Participants were compensated with $10 USD voucher.

6.2 Results

Figure 5 shows our findings regarding grip control. We tested the data with one-way ANOVA and found a significant difference ($F(2, 105)=75.06$, $p=0$). Tukey's HSD Test for multiple comparisons found significant difference between all condition pairs ($p=0$ for all). Our main finding is that the *holes* condition (M=4.06 N; SD=1.32) improved grip control by reducing the required amount of force by ~34% compared to the *covered* condition (M=6.13 N; SD=2.18). As

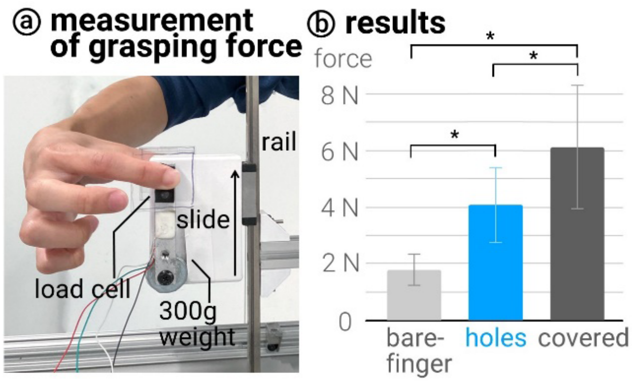

Figure 5: (a) Study apparatus of lift-and-hold task. (b) Force results for the grip task.

expected, the force required with the *bare-finger* condition was the lowest (M=1.79 N; SD=0.55), which was unsurprising given that participants use the whole fingerpad for optimal grip control.

6.3 Study interpretation & limitations

We denote that there were two possible factors at play. First, holes expose skin, which might lead to more tactile cues felt at the fingerpad, resulting in more precise grip control. Second, the friction of the film's material may contribute to the results, since a low coefficient of friction between film and skin could require more force to prevent slipping. Thus, to explore which of these is likely the main factor, we measured the friction of the film with and without holes.

Measuring friction of the materials. We conducted a technical evaluation, in which we created an artificial fingerpad (*Smooth-On KX Flex 40*, a material known to simulate a fingerpad [7]), and measured its static coefficient of friction on an acrylic plate using a mass-pulley tribometer [46]. We measured the coefficient of static friction for three conditions: *artificial fingerpad* (simulating bare finger), artificial fingerpad covered with the *holes film*, and artificial fingerpad completely *covered with a film*—we conducted five measurements per condition. For the condition in which the artificial finger was covered with the *holes* film, we ensured that the artificial finger was contacting with the acrylic through the holes by using the ink test shown in Figure 2. We found the following coefficients of static friction for: *artificial fingerpad* at 1.77 (SD=0.13); *holes* at 0.86 (SD=0.08); and, *covered* at 0.84 (SD=0.08).

Interpretation. The coefficient of friction for the *artificial fingerpad* (M=1.77) was 2.1 times larger than that of the *covered* condition (M=0.84), indicating that adding a film to the artificial fingerpad decreased friction. So naturally, one expects to see a higher force when grasping via the films, which we indeed observed in Study 2. However, the coefficient of friction of the artificial finger covered with *holes* film (M=0.86) is **remarkably similar** to that of the completely *covered* film (M=0.84), with a difference smaller than 3%. That being said, the forces we observed in these conditions differed by a much larger margin than 3%; in fact, participants' grasping forces for *holes* (M=4.06N) were 34% less than *covered* (M=6.13N). This suggests the major factor that is likely to explain the grip improvement is not the 3% of increased friction of the added holes, but likely the advantage given by the holes exposing more skin and, thus, providing more tactile information to the fingerpads.

Limitations. We acknowledge that our results are specific to the case where the electrotactile films are of lower friction than the fingerpad's skin. While this seems to be the case for most electrotactile devices (i.e., including [51] which we used as a material for this study), films with a larger coefficient of friction, require further investigation.

7 STUDY #3: HOLES IMPROVE DEXTERITY DURING MIXED REALITY ASSEMBLY TASKS

Finally, we aimed at understanding how holes added to tactile devices affect actual interactions in Mixed Reality (MR), where the users interact not only with virtual interfaces but also with physical objects. Specifically, we focus on our extreme design option, shown in Figure 3(4), *where holes even replace some electrodes.* Following this, we created an MR task that required manual dexterity to complete: assemble a toy truck following an interactive MR assembly guide. Since our objective was to focus on participants' observed dexterity, we video-taped the study (with their prior consent) and conducted interviews to assess their experience.

7.1 Study Design

Conditions. Participants experienced our MR application in two conditions: *covered* and *holes*. The order was counterbalanced across all participants.

Tactile devices. As the study requires robust devices that can handle dexterous manipulations with lots of friction, pulling & pushing, we opted for polyimide films, a common material used in electrotactile devices [18, 47]; in contrast to tattoo paper which is known to be easily scrubbed off during interactions (as reported by [33]; we also confirmed in our early pilots that when using the screwdriver, the tattoo paper rubbed off on the thumb and/or index). Our device was thus comprised of flexible polyimide with copper traces (cut with a Cricut). The final device measured 150 μm in thickness. In the *covered* condition it consisted of 16 electrodes (2 mm diameter) with 4 mm spacing. In the *holes* condition, we used the same layout except holes replaced the electrodes alternatively, for a total of 8 holes and 8 electrodes. According to our ink test, see Figure 2 (c), in order to provide a similar contact area as with our previous studies (2 mm diameter of skin contact) we chose to cut out holes in 3 mm diameter.

Active & passive devices. Achieving electrotactile actuation in all ten fingers is challenging (and not done in almost any prior work). Thus, for the sake of setup-simplicity (and to avoid wiring that might contribute to decreased dexterity), we only asked participants to wear one active device on their dominant index finger, and wear nine passive devices on all other digits (i.e., same material, but not wired to our multiplexer & stimulator).

Stimulation design. In our MR experience, users encountered three different haptic sensations on their dominant index finger: (1) feeling the shape of large buttons; (2) feeling the shape of small buttons; (3) feeling the truck vibrating if its motor was running. The electrodes actuated for each of these haptic effects are depicted in Figure 6. Note that, since our *holes* condition traded-off some electrodes for holes, the haptic stimulation becomes distorted in

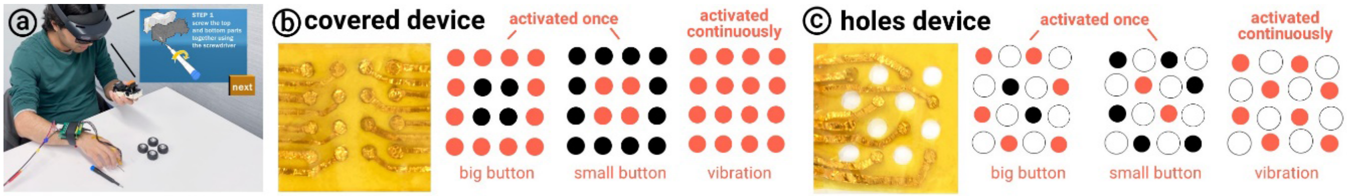

Figure 6: (a) Study setup. (b) Covered device and their stimulation patterns (c) holes device and their stimulation patterns.

this condition—a purposeful trade-off we wanted to explore in this study. For example, when touching the outline of a large square button, the electrodes are actuated in a hexagonal pattern, due to the missing electrodes swapped for holes. As for stimulation intensity, we kept it equalized (per-participant) for both conditions.

Haptic apparatus. We utilize a medical-compliant stimulator to generate electrotactile (Rehamove 3). To multiplex all 16 electrodes, we utilize a custom-made multiplexer (similar to [47]). For every electrode, we employ a half-bridge circuit with two photorelays (TLP176), allowing us to route this target electrode to either negative or positive side of the medical-stimulator. We control the photorelays via shift registers (SN74HC595) using an ESP32 microcontroller. This setup requires ~1 ms to cycle through all stimulation channels. The final circuit was worn on the participants' wrist.

MR apparatus. An MR headset (Microsoft HoloLens 2) was used to render virtual graphics and track fingers. Our custom-made MR application displayed a series of assembly instructions on how to build a truck from a real toy model. This included buttons to touch that advanced to the next instruction, adjusting buttons for virtual truck cover, and feeling the car vibrate as its virtual motor started running. Once any of these interactions was detected, an Open Sound Control (OSC) packet was sent wirelessly to the PC which controlled the haptic stimulation.

Props. Participants assembled a toy truck (51 mm in width without the wheels, 120 mm in length, modeled after a 1955 Chevy Stepside Pick-up). The top half of this truck was made from metal, and the bottom part was plastic. Wheels were 38 mm in diameter (ϕ), 18 mm thickness, and connected via a metal axle (ϕ 2 mm). All screws were 30 mm long hex-screws (ϕ 3 mm). The truck featured an antenna (ϕ 0.8 mm wire, length 28 mm). Participants were also handed a screwdriver (model F145-419-1, aluminum-construction, ϕ 12 mm at grasping handle, length 150 mm).

Task. Participants were asked to "assemble the toy truck following the MR instructions". These were comprised of step-by-step guides, depicted in Figure 7. To navigate the instructions, participants tapped on mid-air buttons. Every virtual interaction was accompanied by haptic feedback. The task involved **five phases**: **(1) operate the screwdriver**: pick up the screw and use the screwdriver to assemble the top & bottom parts of the truck; **(2) assemble the wheels**: push the four wheels onto the truck's axle; **(3) assemble the antenna:** pick up the thin antenna and insert it onto the truck; **(4) adjust the virtual truck cover**: tap on MR buttons to adjust the size of the virtual cover to match the truck's volume accordingly; and **(5) start the truck's engine**: touch the top of the finished truck to start a simulation of virtual roads accompanying by an engine vibration (and sound).

Participants. Eight participants were recruited (four females, four males; two left-handed), with average age 24.3 years old (SD=2.3). A voucher of $10 USD was given to each participant as compensation.

Procedure. After the truck was assembled, participants were asked to rate realism (1: not realistic; 7: very realistic); "how difficult was the whole task wearing the devices" (1: easy; 7: difficult), and "how much texture/material can you feel" (1: nothing; 7 fully). We also collected comments at the end of the study and conducted a short brainstorming & discussion with each participant. The whole study took ~40 minutes.

Hypothesis. We hypothesized that holes would allow participants: **(H1)** to perform tasks easier (i.e., lower perceived task difficulty); **(H2)** to feel more of the materials & textures under their fingerpads (i.e., higher perceived feel-through); **(H3)** feel less realistic virtual interactions, due to the trade-off between holes and usable electrodes for electrotactile output (i.e., lower realism scores).

7.2 Results

All participants were able to assemble their own trucks, in both conditions. We present participants feedback organized by (1) assembly (2) virtual sensations. Finally, we present the overall comments about the experiences.

Figure 7: Steps of the MR assembly.

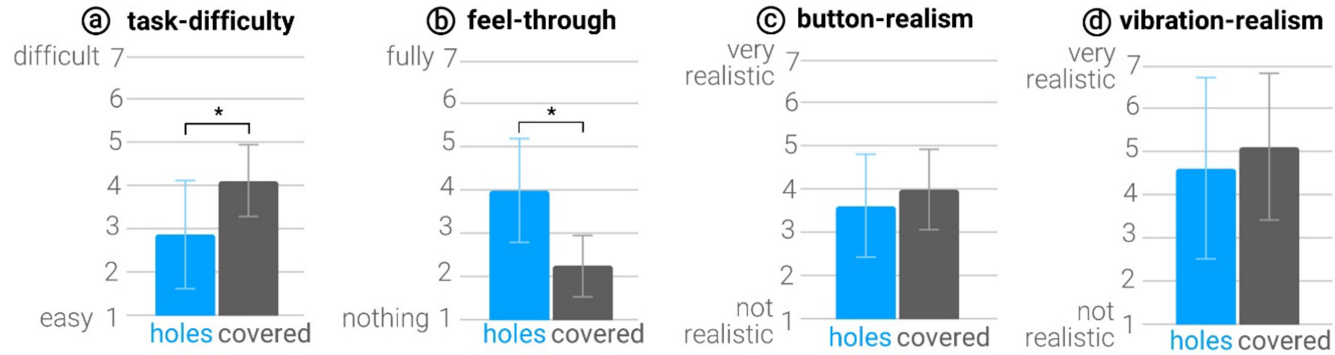

Figure 8: Results of participants' ratings.

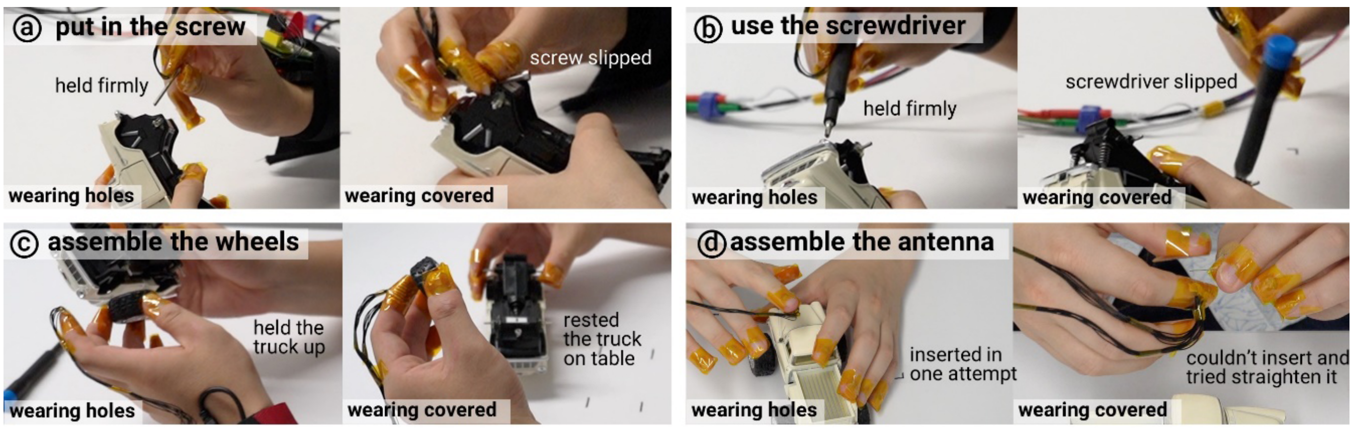

Figure 9: Some exemplary interactions from participants observed in this study.

Reported dexterity & realism. Figure 8 depicts perceived task-difficulty, feel-through, and realism of virtual interactions. We found a statistically significant difference between perceived task-difficulty (paired t-test; p<0.01; F(7)=3.99) across conditions. This suggests that participants found it easier to perform manipulations with the *holes* condition (M=2.9; SD=1.2) than with the *covered* (M=4.1; SD=0.8)—which supports our **H1**. Moreover, we found a statistically significant difference between perceived feel-through (paired t-test; p<0.01; F(7)=4.78) across conditions. This suggests that participants felt more textures/materials with the *holes* condition (M=4.0; SD=1.2) than with the *covered* (M=2.3; SD=0.7)—which supports our **H2**. However, we did not find statistically significant difference between realism of buttons (paired t-test; p=0.1970; F(7)=1.43) or perceived realism of vibrations (paired t-test; p=0.2753; F(7)=1.18) across conditions—which did not support our **H3**.

Observed dexterity. With this study being focused on observing participants, we annotated videos and depicted, in Figure 9, some illustrative examples where the same participant experienced visible differences between manipulating a tool across conditions. For instance, Figure 9 (a) shows P7 successfully manipulating a screw with the *holes* device, but letting it slip with *covered*. Similarly, Figure 9 (b) shows P5 successfully using the screwdriver with *holes*, but letting it slip with *covered* (they even dropped a second time after picking it up). Moreover, Figure 9 (c) shows P4 assembling the wheels while holding the truck with *holes* device but needing to rest the truck on the table for extra stability when doing this with the *covered* (later confirmed during interview). Finally, Figure 9 (d) shows P1 inserting the antenna onto the truck in the first try with the *holes* device, which they could not do with the *covered* device, causing the antenna to be bent (and later needing to straighten it, which also was difficult).

Difficulties grasping with cover. Six (out of eight) participants reported it felt easier to use the screwdriver with *holes* device: 6 (P1, P3, P4, P5, P6, P7) than with the *covered*. In fact, of these six, three dropped the screwdriver while wearing the *covered* device (P5, P6, P7)—none dropped it with *holes*. Indeed, these observed grip difficulties seem to be correlated with the size of the tool, since four dropped screws several times while wearing the *covered* device (P2, P3, P4, P5)—none with *holes*. Two (out of eight) participants commented specifically on why they think it was easier to use the *holes*, quoting "the holder felt slippery with [*covered*]" (P1, and similarly P3). Conversely, larger objects seem to be easier to manipulate in either condition. For instance, all participants found it straightforward to assemble the wheels. That being said, with these larger objects, some participants voiced their preferences. For instance, P4 stated that "[with *holes*] I can feel the truck when grabbing it and it's easier to orient the truck [to insert the wheel, proceeds to visually demonstrate it]". P2, P4 & P10 reported that the truck itself was also hard to grasp with the *covered* device, but with holes device "I had a better grip." (P2, similarly P4 & P10).

Limits of both devices. Again, the smaller the feature, the most problems arose. For the assembly of the antenna, six (out of eight) participants found it difficult to do with either device (P1, P2, P4, P5, P6, P8). Still, participants commented on differences between both. For instance, P1 stated "I couldn't pick it up the antenna [with *covered* device] and it fell off the table onto my pants (. . .) I could do it with the [*holes*]" and P4 stated "hard to pinch, can't feel [the] antenna, need another hand (. . .) but with [*holes* device] it's so easy to pick up, I don't need two hands".

Tactile sensitivity: Seven (out of eight) participants reported they felt more through the *holes* device, especially feeling the texture of the tires (only P8 stated these felt similar for both conditions). To this end, P1 stated "[with *covered*] I couldn't even feel any texture. It feels like my fingers bashing into things", P3 stated "[with *covered*] I could only feel I was holding something". In fact, two participants compared the devices directly in their own words: P4 stated that the devices provide "totally different feelings, with [*holes*] is easier to feel texture and grasp stuff". Finally, P8 stated "for [*covered*] I feel I have tapes on the fingers, for [*holes*], it feels like wearing thinner gloves".

Feel-through. When it came to the different feel-through afforded by each device, only one participant (out of eight) denoted they could still feel specific sensations through the *covered*, while all eight participants stated they could feel specific sensations through the *holes*. Namely, regarding feel-through the *covered* device, P7 stated "[I] can still feel rubbery [texture] but hard to feel the patterns (. . .) I can barely tell there's a pattern (. . .) I can tell only pressing down very hard". Conversely, with the *holes* participants accounts suggested they were able to feel more. For instance, P2 (similarly P5) stated "[with *holes*] I could feel a lot more (. . .) I can really feel the rubber and it passes [the] little things on the tires (. . .) I am able to feel texture easier", or P7 who stated "[with *holes*] I can feel (. . .) rubbery (. . .) doesn't feel as sticky". Moreover, two participants stated they perceived the truck's surface through the *holes*, P1 stated "[with *holes*] I could feel it's cold like metal (. . .) with [*covered*] I couldn't feel as much" and P6 "[with *holes*] I could feel it's not completely smooth material, I could feel slight friction, like the paint on the metal".

Sweating. Two participants commented on sweat generated under the cover. P1 noted that "it's sweatier wearing the fully covered one" and P4 was surprised at noticeable sweat when taking off *covered* devices.

Virtual realism. When asked about the haptics from the buttons (e.g., the larger big "plus" vs. small "minus" buttons when scaling the virtual cover to fit the truck's real size), all participants reported to feel difference between them in both conditions. However, differences started to emerge when asked if they could distinguish the intensity of the stimulation between both buttons (i.e., smaller button provided a weaker stimulus) or the shape of the buttons. Here, we observed the *covered* device providing superior benefits, for instance, five participants (P1, P5, P6, P7, P8) found it easier to distinguish intensities, and two (P1, P2) found it easier to distinguish shapes. Exemplary comments included, P1 stating "minus button ['s intensity] was less as strong and more localized" (P1) or, P2 stating "I could feel the two buttons stimulate different parts of the fingers". While participants were still able to do this as well with the holes device, they commented this required more attention, for instance, P4 stated "I had to pay attention to feel the difference". Moreover, while we did not see a statistically significant difference in reported realism, their comments suggest otherwise. With three participants (P1, P3, P6) specifically stating they found the virtual feedback more realistic with the *covered*, as expected per our H3. For instance, P1 stated "[with *covered*] really felt like the engine rolling", "way stronger" (P3), "even more vibration" (P6). Conversely, the holes device had a range of mixed options regarding realism, with P7 stating "decently realistic", while P8 stated that "[vibration] is weaker and irregular". Finally, P4 found haptics via *holes* as more realistic, stating "felt like it's coming from the object".

Envisioned use-cases. Finally, we asked participants what they would see themselves using our holes-based device for. The majority of participants provided examples that blended real-world with virtual assistance, some of the most unique included: "education, in chemistry labs, feel objects that you cannot touch, like mercury" (P7); "feel my pet's fur despite wearing haptics" (P4); "feedback for when you hold the badminton racket too tight" (P8, and similarly P6 for Ping-Pong); "indoor design, like set up virtual furniture in my real room" (P3); and, "typing in VR and then grabbing my coffee, having the friction to do so" (P5, also P1 & P2 had similar uses for VR/MR typing).

Study Limitations: While we were not able to statistically validate our third hypothesis (i.e., trading off holes for electrodes results in decreased realism), we observed participants' accounts that might support it. We believe this was in part due to two limitations of our study. First, like any study of this nature, participants were not experienced with electrotactile and will need long-term acquaintance to develop an ability to recognize high-resolution sensations (e.g., 12 points of stimulation with covered vs. six with holes, when feeling the large button). Secondly, since our goal was to focus on physical manipulation, our MR task did not feature a lot of virtual interactions with the full array—these might explain why we did not quantitatively measure the realism trade-off. Finally, we only tested polyimide, commonly used in electrotactile devices—leaving other variants (e.g., materials with higher friction) for future investigation.

8 DISCUSSION OF HOW RESEARCHERS/DESIGNERS CAN APPLY OUR FINDINGS TO THEIR DEVICES

8.1 How our approach can improve haptic permeability of *existing* electrotactile devices

While we only explored the generic case of uniformly distributed holes (leaving other parameters, such as hole size, for future investigations), our findings can already be immediately applied to state-of-the-art devices, namely *Tacttoo* [51]. This device consists of eight electrodes, leaving enough space in between to place (2 mm) holes once its traces are rerouted, which we depict in Figure 10 (a). Further, we expect that many more electrotactile devices

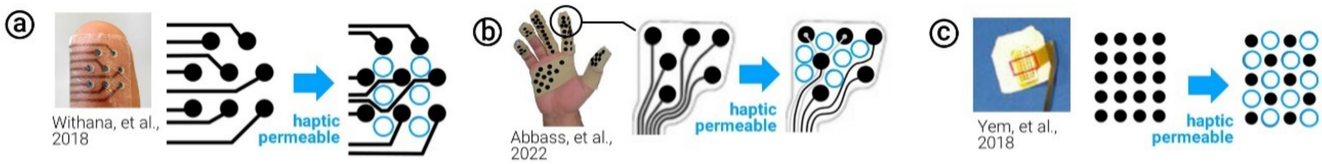

Figure 10: Simulating the addition of holes (blue circles) to existing electrotactile devices. (a) [51]; (b) [1]; (c) [55].

can be improved by utilizing our design options. For example, the routing of [1] can be changed to the backside, allowing spaces for holes, as depicted in Figure 10 (b). Our approach is likely to be beneficial beyond the fingerpad, for instance it should extend to the whole hand. For electrotactile arrays with high resolution [55], researchers can explore how trading-off electrodes with holes might improve tactile sensitivity, as depicted in Figure 10 (c).

8.2 How our approach can improve haptic permeability of *future* electrotactile devices

Future devices can be designed with haptic permeability in mind from the start. According to the expected usage scenario, designers can assess how much tactile sensations should be preserved, and how much resolution of virtual haptic should be needed, and weight in technical limitations (e.g., material thickness, traces thickness). In the study, we uniformly laid out the holes on the film. However, the layout of the holes can be tailored for specific applications (e.g., holes that allow for better grip on a tool with a specific shape). Following this, researchers can determine a suitable hole size for the desired application (here, they can utilize our ink test to see fingerprint ridges revealed by holes, see Figure 2). We hope that variations on these parameters might lead to new designs that can best balance the virtual haptics without obstructing many sensations from the real world.

8.3 Haptic permeability beyond electrotactile

While our exploration was centered around the haptic permeability of electrotactile interfaces, we envision that our approach can be applied to other film-based devices that do not use electrical stimulation, including actuators or sensors. While these are exciting new opportunities for haptic permeability, we warrant caution when extrapolating our findings beyond electrotactile as these might first require further studies.

Film-based mechanical actuators: Other on-skin actuators might benefit from our approach of adding holes. For instance, dielectric-elastomer actuators [27]; yet, note that holes should not interfere with the mounting points for moving parts. Second, miniature piezo actuators [17] could potentially be improved with holes; however, when adding holes one should pay attention to possible changes in resonance frequency. Finally, adding holes to fabric-based actuators [3] might provide some benefits but might impact parameters such as fabric stretchability.

Film-based sensors. Conversely, our approach might even be beneficial in the case of on-skin sensors [34]. For instance, EMG based devices [32], might benefit from adding holes between/in electrodes; however, it is worth noting that holes might impact the sensitivity of the electrode. Similarly, on-skin capacitive touch sensing [35] might also take advantage of holes, but may require (in some cases) altering the sensing layout.

8.4 Exploring haptic permeability beyond holes

Finally, because we focused on improving tactile aspects of interaction (e.g., tactile sensitivity or grip friction), we implemented our haptic permeability by adding holes. Yet, it is entirely possible that other forms of permeability exist. For instance, our design with holes also can achieve *air permeability*, similar to [29, 56], allowing the user to feel the wind and also let sweat evaporate (as we observed in the user study, noticeable sweat accumulates with covered devices). Similarly, if a tactile device will be used in a context where it is paramount that users can feel liquids on surfaces (e.g., cooking, repairs, etc.), one might engineer a device for *liquid permeability*—e.g., purposefully engineering the device from a porous material that allow fluids to passthrough. Likewise, if a tactile interface will be used in an interactive context where it is paramount that users feel the temperature of surfaces (e.g., cooking, factories, etc.), one might engineer a device for *thermal permeability*—e.g., purposefully engineering the device from a highly conductive thermal material that rapidly transmits thermal energy to the user's skin.

These examples illustrate how our notion of haptic design can change once we embrace the idea of *haptic permeability*, which we humbly hope will inspire researchers to follow this direction.

9 CONCLUSION

To improve the usability & minimize encumberment of tactile haptic devices for the fingerpads, many researchers have moved away from thick actuators (e.g., arrays of vibration motors) and, instead, focused on thin devices—e.g., electrotactile. While these can be engineered to be thin, not all of the important haptic cues can pass through the device's film, which our three studies confirmed. To improve the feel-through of electrotactile devices, we proposed & evaluated *adding holes*. By means of this, we argue that *haptic permeability*—the amount to which a haptic interface lets the user feel real-world sensations—is a understudied aspect that needs to be brough to the foreground. We argue that the next generation of haptics interfaces will need to consider not only how accurately they deliver virtual sensations but also how they *balance* this with allowing to feel the real world.

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We would like to acknowledge that the ACM CHI 2024 conference has decided to take place in Hawaii, offering extremely limited options for remote participation. While some authors have chosen to present their work in person or bring its physical prototype to the CHI community, they have done so with compassion towards Native Hawaiians and with a heavy heart. We urge that the ACM's process for conference selection should more carefully consider the impact our conferences have on local communities. We especially want to acknowledge Prof. Josiah Hester, a Känaka Maoli Professor in Computing, who organized comprehensive resources that educated us about the negative impacts of over-tourism and climate degradation in Hawaii[1]. Finally, the decision of some authors to participate in this conference does not represent the views of other members of our lab, who have chosen not to engage with this edition of the CHI conference due to its impact on Native Hawaiians.

REFERENCES

[1] Abbass, Y., Dosen, S., Seminara, L. and Valle, M. 2022. Full-hand electrotactile feedback using electronic skin and matrix electrodes for high-bandwidth human–machine interfacing. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.* 380, 2228 (Jun. 2022), 20210017. https://doi.org/10.1098/rsta.2021.0017.

[2] André, T., Lefèvre, P. and Thonnard, J.-L. 2010. Fingertip moisture is optimally modulated during object manipulation. *Journal of Neurophysiology.* 103, 1 (Jan. 2010), 402–408. https://doi.org/10.1152/jn.00901.2009.

[3] Bianchi, M. 2016. A Fabric-Based Approach for Wearable Haptics. *Electronics.* 5, 3 (Sep. 2016), 44. https://doi.org/10.3390/electronics5030044.

[4] Bilaloglu, S., Lu, Y., Geller, D., Rizzo, J.R., Aluru, V., Gardner, E.P. and Raghavan, P. 2016. Effect of blocking tactile information from the fingertips on adaptation and execution of grip forces to friction at the grasping surface. *Journal of Neurophysiology.* 115, 3 (Mar. 2016), 1122–1131. https://doi.org/10.1152/jn.00639.2015.

[5] Biswas, S. and Visell, Y. 2019. Emerging Material Technologies for Haptics. *Advanced Materials Technologies.* 4, 4 (2019), 1900042. https://doi.org/10.1002/admt.201900042.

[6] Craig, J.C. 2009. Grating orientation as a measure of tactile spatial acuity. *Somatosensory & Motor Research.* (Jul. 2009). https://doi.org/10.1080/08990229970456.

[7] Dąbrowska, A.K., Rotaru, G.-M., Derler, S., Spano, F., Camenzind, M., Annaheim, S., Stämpfli, R., Schmid, M. and Rossi, R.M. 2016. Materials used to simulate physical properties of human skin. *Skin Research and Technology.* 22, 1 (2016), 3–14. https://doi.org/10.1111/srt.12235.

[8] Dianat, I., Haslegrave, C.M. and Stedmon, A.W. 2012. Methodology for evaluating gloves in relation to the effects on hand performance capabilities: a literature review. *Ergonomics.* 55, 11 (Nov. 2012), 1429–1451. https://doi.org/10.1080/00140139.2012.708058.

[9] Flexible Printed Circuit Board (Flex Circuit Board) Manufacturer: https://www.rigiflex.com/products-services/flexible-pcb. Accessed: 2023-11-21.

[10] Germani, M., Mengoni, M. and Peruzzini, M. 2013. Electro-tactile device for material texture simulation. *The International Journal of Advanced Manufacturing Technology.* 68, 9 (Oct. 2013), 2185–2203. https://doi.org/10.1007/s00170-013-4832-1.

[11] Han, T., Anderson, F., Irani, P. and Grossman, T. 2018. HydroRing: Supporting Mixed Reality Haptics Using Liquid Flow. *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2018), 913–925. https://doi.org/10.1145/3242587.3242667.

[12] Han, T., Bansal, S., Shi, X., Chen, Y., Quan, B., Tian, F., Wang, H. and Subramanian, S. 2020. HapBead: On-Skin Microfluidic Haptic Interface using Tunable Bead. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu HI USA, Apr. 2020), 1–10. https://doi.org/10.1145/3313831.3376190.

[13] Hiramatsu, Y., Kimura, D., Kadota, K., Ito, T. and Kinoshita, H. 2015. Control of Precision Grip Force in Lifting and Holding of Low-Mass Objects. *PLOS ONE.* 10, 9 (Sep. 2015), e0138506. https://doi.org/10.1371/journal.pone.0138506.

[1] "https://www.chiinhawaii.info/

[14] Jarocka, E., Pruszynski, J.A. and Johansson, R.S. 2021. Human Touch Receptors Are Sensitive to Spatial Details on the Scale of Single Fingerprint Ridges. *The Journal of Neuroscience.* 41, 16 (Apr. 2021), 3622–3634. https://doi.org/10.1523/JNEUROSCI.1716-20.2021.

[15] Jeong, J.-W. *et al.* 2013. Materials and Optimized Designs for Human-Machine Interfaces Via Epidermal Electronics. *Advanced Materials.* 25, 47 (2013), 6839–6846. https://doi.org/10.1002/adma.201301921.

[16] Ji, X., Liu, X., Cacucciolo, V., Civet, Y., El Haitami, A., Cantin, S., Perriard, Y. and Shea, H. 2021. Untethered Feel-Through Haptics Using 18-μm Thick Dielectric Elastomer Actuators. *Advanced Functional Materials.* 31, 39 (2021), 2006639. https://doi.org/10.1002/adfm.202006639.

[17] Jin, H., Kim, Y., Youm, W., Min, Y., Seo, S., Lim, C., Hong, C.-H., Kwon, S., Park, G., Park, S. and Kim, H.J. 2022. Highly pixelated, untethered tactile interfaces for an ultra-flexible on-skin telehaptic system. *npj Flexible Electronics.* 6, 1 (Sep. 2022), 1–11. https://doi.org/10.1038/s41528-022-00216-1.

[18] Jingu, A., Withana, A. and Steimle, J. 2023. Double-Sided Tactile Interactions for Grasping in Virtual Reality. *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2023), 1–11. https://doi.org/10.1145/3586183.3606798.

[19] Johansson, R.S. and Vallbo, A.B. 1979. Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin. *The Journal of Physiology.* 286, (Jan. 1979), 283. https://doi.org/10.1113/jphysiol.1979.sp012619.

[20] Jones, L.A. and Smith, A.M. 2014. Tactile sensory system: encoding from the periphery to the cortex. *WIREs Systems Biology and Medicine.* 6, 3 (2014), 279–287. https://doi.org/10.1002/wsbm.1267.

[21] Kaczmarek, K.A., Tyler, M.E. and Bach-Y-Rita, P. 1994. Electrotactile haptic display on the fingertips: preliminary results. *Proceedings of 16th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Nov. 1994), 940–941 vol.2. https://doi.org/10.1109/IEMBS.1994.415223.

[22] Kajimoto, H. 2021. Electro-Tactile Display Kit for Fingertip. *2021 IEEE World Haptics Conference (WHC)* (Jul. 2021), 587–587. https://doi.org/10.1109/WHC49131.2021.9517192.

[23] Kato, K., Ishizuka, H., Kajimoto, H. and Miyashita, H. 2018. Double-sided Printed Tactile Display with Electro Stimuli and Electrostatic Forces and its Assessment. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2018), 1–12. https://doi.org/10.1145/3173574.3174024.

[24] Kim, D., Yang, J. and Yun, D. 2023. Anthropomorphic robot hand using the principle of sweat and fingerprints of human hands. *2023 IEEE International Conference on Robotics and Automation (ICRA)* (May 2023), 10289–10295. https://doi.org/10.1109/ICRA48891.2023.10161390.

[25] Kim, H., Kim, M. and Lee, W. 2016. HapThimble: A Wearable Haptic Device Towards Usable Virtual Touch Screen. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2016), 3694–3705. https://doi.org/10.1145/2858036.2858196.

[26] Kinoshita, H. 1999. Effect of gloves on prehensile forces during lifting and holding tasks. *Ergonomics.* 42, 10 (Oct. 1999), 1372–1385. https://doi.org/10.1080/001401399185018.

[27] Koo, I.M., Jung, K., Koo, J.C., Nam, J.-D., Lee, Y.K. and Choi, H.R. 2008. Development of Soft-Actuator-Based Wearable Tactile Display. *IEEE Transactions on Robotics.* 24, 3 (Jun. 2008), 549–558. https://doi.org/10.1109/TRO.2008.921561.

[28] Kourtesis, P., Argelaguet, F., Vizcay, S., Marchal, M. and Pacchierotti, C. 2022. Electrotactile Feedback Applications for Hand and Arm Interactions: A Systematic Review, Meta-Analysis, and Future Directions. *IEEE Transactions on Haptics.* 15, 3 (Jul. 2022), 479–496. https://doi.org/10.1109/TOH.2022.3189866.

[29] Li, Z., Ma, Y., Zhang, K., Wan, J., Zhao, D., Pi, Y., Chen, G., Zhang, J., Tang, W., Lin, L. and Zhong, J. 2023. Air Permeable Vibrotactile Actuators for Wearable Wireless Haptics. *Advanced Functional Materials.* 33, 8 (2023), 2211146. https://doi.org/10.1002/adfm.202211146.

[30] Lim, B., Kim, K., Oh, S.-R. and Hwang, D. 2019. HaptiCube: a Compact 5-DoF Finger-wearable Tactile Interface. *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (Nov. 2019), 5094–5100. https://doi.org/10.1109/IROS40897.2019.8967773.

[31] Mazursky, A., Teng, S.-Y., Nith, R. and Lopes, P. 2021. MagnetIO: Passive yet Interactive Soft Haptic Patches Anywhere. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), 1–15. https://doi.org/10.1145/3411764.3445543.

[32] Nittala, A.S., Khan, A., Kruttwig, K., Kraus, T. and Steimle, J. 2020. PhysioSkin: Rapid Fabrication of Skin-Conformal Physiological Interfaces. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2020), 1–10. https://doi.org/10.1145/3313831.3376366.

[33] Nittala, A.S., Kruttwig, K., Lee, J., Bennewitz, R., Arzt, E. and Steimle, J. 2019. Like A Second Skin: Understanding How Epidermal Devices Affect Human Tactile Perception. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19* (Glasgow, Scotland Uk, 2019), 1–16. https://doi.org/10.1145/3290605.3300610.

[34] Nittala, A.S. and Steimle, J. 2022. Next Steps in Epidermal Computing: Opportunities and Challenges for Soft On-Skin Devices. *Proceedings of the 2022 CHI*

Conference on Human Factors in Computing Systems (New York, NY, USA, Apr. 2022), 1–22. https://doi.org/10.1145/3491102.3517668.

[35] Nittala, A.S., Withana, A., Pourjafarian, N. and Steimle, J. 2018. Multi-Touch Skin: A Thin and Flexible Multi-Touch Sensor for On-Skin Input. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2018), 33:1-33:12. https://doi.org/10.1145/3173574.3173607.

[36] Pacchierotti, C., Sinclair, S., Solazzi, M., Frisoli, A., Hayward, V. and Prattichizzo, D. 2017. Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives. *IEEE Transactions on Haptics*. 10, 4 (Oct. 2017), 580–600. https://doi.org/10.1109/TOH.2017.2689006.

[37] Purves, D., Augustine, G.J., Fitzpatrick, D., Katz, L.C., LaMantia, A.-S., McNamara, J.O. and Williams, S.M. 2001. Differences in Mechanosensory Discrimination Across the Body Surface. *Neuroscience. 2nd edition*. Sinauer Associates.

[38] Saal, H.P. and Bensmaia, S.J. 2014. Touch is a team effort: interplay of submodalities in cutaneous sensibility. *Trends in Neurosciences*. 37, 12 (Dec. 2014), 689–697. https://doi.org/10.1016/j.tins.2014.08.012.

[39] Sarac, M., Okamura, A.M. and Di Luca, M. 2019. Effects of Haptic Feedback on the Wrist during Virtual Manipulation. *arXiv:1911.02104 [cs]*. (Nov. 2019).

[40] Sato, K. and Tachi, S. 2010. Design of electrotactile stimulation to represent distribution of force vectors. *2010 IEEE Haptics Symposium* (Mar. 2010), 121–128. https://doi.org/10.1109/HAPTIC.2010.5444666.

[41] Schorr, S.B. and Okamura, A.M. 2017. Fingertip Tactile Devices for Virtual Object Manipulation and Exploration. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2017), 3115–3119. https://doi.org/10.1145/3025453.3025744.

[42] Sobinov, A.R. and Bensmaia, S.J. 2021. The neural mechanisms of manual dexterity. *Nature Reviews Neuroscience*. 22, 12 (Dec. 2021), 741–757. https://doi.org/10.1038/s41583-021-00528-7.

[43] Tanaka, Y., Shen, A., Kong, A. and Lopes, P. 2023. Full-hand Electro-Tactile Feedback without Obstructing Palmar Side of Hand. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2023), 1–15. https://doi.org/10.1145/3544548.3581382.

[44] Tao, Y., Teng, S.-Y. and Lopes, P. 2021. Altering Perceived Softness of Real Rigid Objects by Restricting Fingerpad Deformation. *The 34th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2021), 985–996. https://doi.org/10.1145/3472749.3474800.

[45] Teng, S.-Y., Li, P., Nith, R., Fonseca, J. and Lopes, P. 2021. Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), 1–14. https://doi.org/10.1145/3411764.3445099.

[46] Tribometer: 2022. https://en.wikipedia.org/w/index.php?title$=$Tribometer&oldid$=$1119668403. Accessed: 2023-11-21.

[47] Ushiyama, K. and Lopes, P. 2023. FeetThrough: Electrotactile Foot Interface that Preserves Real-World Sensations. *The 36th Annual ACM Symposium on User Interface Software and Technology* (2023). https://doi.org/10.1145/3586183.3606808.

[48] Via (electronics): 2023. https://en.wikipedia.org/w/index.php?title$=$Via_(electronics)&oldid$=$1160189171. Accessed: 2023-09-15.

[49] Vizcay, S., Kourtesis, P., Argelaguet, F., Pacchierotti, C. and Marchal, M. 2022. Design and Evaluation of Electrotactile Rendering Effects for Finger-Based Interactions in Virtual Reality. *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology* (New York, NY, USA, Nov. 2022), 1–11. https://doi.org/10.1145/3562939.3565634.

[50] Westling, G. and Johansson, R.S. 1984. Factors influencing the force control during precision grip. *Experimental Brain Research*. 53, 2 (Jan. 1984), 277–284. https://doi.org/10.1007/BF00238156.

[51] Withana, A., Groeger, D. and Steimle, J. 2018. Tacttoo: A Thin and Feel-Through Tattoo for On-Skin Tactile Output. *The 31st Annual ACM Symposium on User Interface Software and Technology - UIST '18* (Berlin, Germany, 2018), 365–378. https://doi.org/10.1145/3242587.3242645.

[52] Wu, H., Zhao, G. and Liang, W. 2020. Mechanical properties and fracture characteristics of pre-holed rocks subjected to uniaxial loading: A comparative analysis of five hole shapes. *Theoretical and Applied Fracture Mechanics*. 105, (Feb. 2020), 102433. https://doi.org/10.1016/j.tafmec.2019.102433.

[53] Yem, V. and Kajimoto, H. 2017. Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world. *2017 IEEE Virtual Reality (VR)* (Mar. 2017), 99–104. https://doi.org/10.1109/VR.2017.7892236.

[54] Yem, V., Okazaki, R. and Kajimoto, H. 2016. FinGAR: combination of electrical and mechanical stimulation for high-fidelity tactile presentation. *ACM SIGGRAPH 2016 Emerging Technologies* (New York, NY, USA, 24 2016), 1–2. https://doi.org/10.1145/2929464.2929474.

[55] Yem, V., Vu, K., Kon, Y. and Kajimoto, H. 2018. Softness-Hardness and Stickiness Feedback Using Electrical Stimulation While Touching a Virtual Object. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (Mar. 2018), 787–788. https://doi.org/10.1109/VR.2018.8446516.

[56] Yeon, H. *et al.* 2021. Long-term reliable physical health monitoring by sweat pore–inspired perforated electronic skins. *Science Advances*. 7, 27 (Jun. 2021), eabg8459. https://doi.org/10.1126/sciadv.abg8459.

[57] Yoon, S.H., Ma, S., Lee, W.S., Thakurdesai, S., Sun, D., Ribeiro, F.P. and Holbery, J.D. 2019. HapSense: A Soft Haptic I/O Device with Uninterrupted Dual Functionalities of Force Sensing and Vibrotactile Actuation. *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2019), 949–961. https://doi.org/10.1145/3332165.3347888.

[58] Yu, X. *et al.* 2019. Skin-integrated wireless haptic interfaces for virtual and augmented reality. *Nature*. 575, 7783 (Nov. 2019), 473–479. https://doi.org/10.1038/s41586-019-1687-0.

[59] Yum, S.-M., Baek, I.-K., Hong, D., Kim, J., Jung, K., Kim, S., Eom, K., Jang, J., Kim, S., Sattorov, M., Lee, M.-G., Kim, S., Adams, M.J. and Park, G.-S. 2020. Fingerprint ridges allow primates to regulate grip. *Proceedings of the National Academy of Sciences*. 117, 50 (Dec. 2020), 31665–31673. https://doi.org/10.1073/pnas.2001055117.

[60] Zamani, N. and Culbertson, H. 2019. Effects of Dental Glove Thickness on Tactile Perception Through a Tool. *2019 IEEE World Haptics Conference (WHC)* (Jul. 2019), 187–192. https://doi.org/10.1109/WHC.2019.8816166.

[61] Zhang, M., Mariola, E., Stilla, R., Stoesz, M., Mao, H., Hu, X. and Sathian, K. 2005. Tactile discrimination of grating orientation: fMRI activation patterns. *Human Brain Mapping*. 25, 4 (Apr. 2005), 370–377. https://doi.org/10.1002/hbm.20107.

[62] Zhong, J., Ma, Y., Song, Y., Zhong, Q., Chu, Y., Karakurt, I., Bogy, D.B. and Lin, L. 2019. A Flexible Piezoelectret Actuator/Sensor Patch for Mechanical Human–Machine Interfaces. *ACS Nano*. 13, 6 (Jun. 2019), 7107–7116. https://doi.org/10.1021/acsnano.9b02437.