Full-hand Electro-Tactile Feedback without Obstructing Palmar Side of Hand

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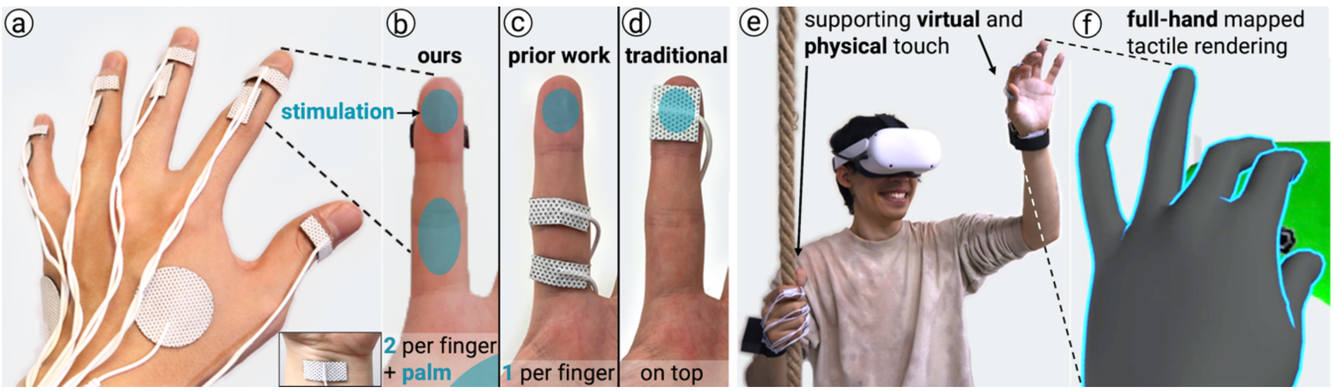

Figure 1: (a, b) We uncover an alternative technique for electro-tactile stimulation that creates touch sensations in 11 distinct locations on the palmar (i.e., front) side of the hand without placing electrodes at the locations where sensations are felt. (c, d) While previous approaches to electro-tactile stimulation showed great promise, they also came with a major limitation as electrodes attached to the palmar side of the hand impair the user's tactile acuity and dexterity; these approaches do not scale to full-hand interactions nor support interactions with physical props. Instead, we explored placing electrodes in strategic locations at the *back of the hand and wrist*, which enables the electrical currents to pass through the median/ulnar nerve, thus providing (e, f) tactile feedback to the palmar side of the hand *while* keeping it free to interact with physical objects.

ABSTRACT

We present a technique to render tactile feedback to the palmar side of the hand while keeping it unobstructed and, thus, preserving manual dexterity during interactions with physical objects. We implement this by applying electro-tactile stimulation only to the back of the hand and to the wrist. In our approach, there are no electrodes on the palmar side, yet that is where tactile sensations are felt. While we place electrodes outside the user's palm, we do so in strategic locations that conduct the electrical currents to the median/ulnar nerves, causing tactile sensations on the palmar side of the hand. In our user studies, we demonstrated that our approach renders tactile sensations to 11 different locations on the palmar side while keeping users' palms free for dexterous manipulations. Our approach enables new applications such as tactile notifications during dexterous activities or VR experiences that rely heavily on physical props.

CCS CONCEPTS

• **Hardware** → Communication hardware, interfaces and storage; Tactile and hand-based interfaces; Haptic devices.

KEYWORDS

Electro-tactile, Haptics, Mixed Reality, Virtual Reality

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1 INTRODUCTION

A driving vision for HCI has been to bring all our senses into interactive experiences—as Sutherland put it "[the interface] should serve as many senses as possible" [65]. This also implies that haptic devices should not be limited to fingerpads but extend to the whole

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hand, which is our primary means of interaction. In fact, a recent study by Maunsbach et al. has shown that even an interaction as mundane as "pressing a button" is improved if the haptic feedback "extends to the whole hand" [46]. To this end, our community has developed many successful haptic devices that can render contact, texture, or force to *many locations of the user's palm* [2, 14, 17, 22, 26, 35, 70]. These devices achieve their spatial fidelity by attaching many actuators *directly* to the part of the user's hand that they are meant to stimulate. For instance, the recent *Meta* glove [30] features tactile actuators placed directly at fifteen locations on the user's palmar side of the hand: fingerpads, finger segments, and palm—this provides realistic hand sensations.

However, **this existing approach to realizing full-hand tactile interfaces comes with a major limitation**. Placing the actuators directly at the user's *palmar side* prevents using these tactile haptic devices beyond purely virtual interactions [52, 67]. In other words, these actuators prevent the user's palms from feeling haptic feedback from the physical object they are grasping, and more dramatically, limit their dexterity to grab or finely manipulate this object—this prevents the usage of these tactile devices in many interactive situations, such as mixed reality.

To circumvent this key issue, researchers have been engineering actuators that minimize the encumberment in three technical ways. The first is to switch to thin haptic actuators that allow the user to *feel-through* physical objects to some degree [25, 71]. However, the user still feels these thin actuators between their fingerpads and the physical world, resulting in a decreased sensation of textured surfaces [52]. A second alternative is to use *foldable* actuators that keep the user's fingerpad or palms free [41, 67]. These devices fold the actuators away from the palm or the fingerpad when the users are not interacting with virtual objects. However, these are still limited in size (i.e., folding is done by mechanical actuators, which still impair dexterity as these occupy much of the sides and back of fingers/hands) and in the application domain (i.e., do not allow for tactile augmentation of real objects). Finally, a third approach, from which we take inspiration, is to place the haptic actuators away from the fingerpad but drive them in a way that causes the sensation to occur at the fingerpad. Researchers have applied this concept to creating sensations only at the fingerpads, by using vibrotactile actuators on the nail [5, 56] / back-of-the-finger [40], or using electro-tactile stimulation via electrodes on the middle and proximal phalanges of the index finger [74, 75]—unfortunately, these electrodes are *still on the palmar side.* Even a single electrode on any part of the palm would exacerbate manual dexterity. This is because manual activities involve the whole hand [60], and its dexterity builds on the sensory image of the entire palmar side synthesizing each part's sensation [33, 63]. Therefore, we strive to keep the palmar side **entirely unobstructed**.

To address this, we propose applying electro-tactile stimulation *only* to the back of the hand and the wrist—*without electrodes on the palmar side*, **yet that is where sensations are felt** (Figure 1b). We discovered that this is possible by strategically placing electrodes, building on a neurological concept called *referred sensations.* To find a suitable electrode arrangement, we tackled the following challenges: (1) finding the anatomically suitable location to place electrodes (we found that the back of the hand is superior to the arm, due to the separation of nerves that conduct sensations to each finger); (2) finding a stimulation intensity that creates sensations primarily on the palmar side, rather than the back side (we leverage the hand's dorsal vs. palmar tactile asymmetry); (3) optimizing the stimulation polarities (anodic or cathodic) to increase the number of stimulated locations. In our first user study, we validated that the resulting electrode arrangement rendered tactile sensations in 11 distinct locations on the palmar side of the hand. To the best of our knowledge, this is an unprecedented number of referred sensations in any related research field including neurology, rehabilitation, and prosthetics.

Finally, enabling haptic feedback to the palm *while keeping the palm free* opens applications where users can feel virtual tactile feedback while *simultaneously* touching and grasping physical objects, which we validated in our second study and demonstrated using three applications: (1) integrating physical props in a VR bouldering experience (Figure 1e), (2) providing tactile notifications while DJing, and (3) feeling both virtual & physical models in mixed reality.

2 RELATED WORK

Our work is built primarily on (1) electrical stimulation for tactile feedback (known as *electro-tactile*) and (2) haptic devices designed purposefully with the goal of keeping the user's hand unobstructed.

2.1 Electro-tactile Stimulation

While most haptic devices use vibration or pressure via mechanical actuators [11, 12, 14, 42], they do not easily scale down. Thus, researchers keep exploring ways for further miniaturization, and some have turned to electrical stimulation.

By stimulating nerves with electrical currents, an interface can induce tactile sensations, this is referred to as *electro-tactile stimulation.* The application of this technique has historical roots dating back to 1970, when researchers utilized electro-tactile stimulation for blind users [64]. In the late 1990s, Kajimoto et al. proposed a tactile display based on the stimulation [38]. Since then, electro-tactile stimulation rapidly grew as a haptic actuator, and by now, a number of systems build on it for different purposes, e.g., simulating material textures [4, 21, 73], hand skill training [68], or extending mobile surfaces [37]. For providing tactile feedback to the whole hand, Kajimoto et al. proposed a cylindrical handheld device whose surface is an array of stimulation electrodes [38]. Abbass et al. extended this concept further by proposing a haptic glove with a layer of arrayed electrodes for rendering tactile sensations to the whole hand [2]. Pamungkas et al., also explored whole-hand feedback via electro-tactile stimulation, to add realism in VR, by stimulating the user's entire hand, at once, via a conductive glove [53]—this conductive glove is fully closed, as such, it also applies stimulation to the back side of the hand. Unfortunately, all these devices obstruct the hand with electrodes, impeding the user's ability to interact with the physical world.

2.2 Haptic Devices that Preserve the Hand's Tactile Acuity

Most haptic devices are designed to render sensations for touching *virtual* objects. Thus, the traditional way to realize haptics was to place actuators *directly* at the target location where the sensation is meant to be evoked [14]. However, with the rise of AR (and even prop-based VR), users need to move back and forth between VR and the real world, or even interact with augmented physical objects or VR props. Unfortunately, the traditional approach (actuators placed on targets) impedes the user’s ability to feel and dexterously manipulate real objects.

Many researchers have realized this tension and tackled it via different routes. We present these grouped into five categories: (1) foldable actuators; (2) thin actuators; (3) relocated actuators; (4) non-contact actuation; and (5) remote actuation (also known as *referred sensations*)—since our approach falls in this conceptual category, we discuss this approach in further detail in Section 2.3.

Foldable actuators. One approach that keeps the user’s palmar side of the hand free is to leverage an actuator that provides the haptic effect on-demand but then folds away while not in use. For example, *Touch & Fold* [67] allows users to feel their fingerpads touching virtual objects, while also quickly reaching to grab tools (the device responds and tucks away prior to the user grabbing the tool). *Haptic Pivot* [41] takes this approach further and into the whole palmar side, by moving a ball-shaped end-effector from the forearm to the palm. However, these devices display two striking limitations: (1) they are only suited for touching *either* virtual or real objects, but do not allow users to touch both at the same time; and (2) these approaches are *mechanical* in nature, which implies that they require substantial time to activate (340ms for [41] and 92ms for [67]) and end up larger and more encumbering than films or electrodes.

Thin actuators. A strategy is to *balance* tactile feedback on real and virtual objects by placing a thin actuator on the skin. For example, *Tacttoo* [71] is an electro-tactile device built on a thin film of electrodes that stimulates the fingerpad while allowing the user to feel physical objects *through* the film to some extent. Similarly, *HydroRing* [25] is a soft ring that renders pressure, vibration, and temperature in mixed reality, while still being soft enough that users can feel slightly through it. While these approaches are very promising, the user still feels the impairment of the thin actuators every time they touch physical objects, impacting their sensation of textured surfaces [52].

Relocated actuators. Another way to preserve tactile sensations is to move the actuator *completely* from the target area and place it somewhere else—this is often denoted as *relocated haptics* [5, 50]. The idea is to still deliver a sensation but not at the “correct” location. For example, Ando et al. [5] and *Haplets* [56], utilize vibrotactile actuators on the fingernail to render sensations that should, normally, be felt at the fingerpads. Some approaches go further by substituting feedback to fingerpads by applying mechanical pressures to the wrist [55, 58], or the forearm [50, 51]. The resulting haptic devices engineered from this principle, excel in minimizing any encumberment to the target area but sacrifice realism for this—because the tactile sensation occurs in a location where the user might not have expected it.

Non-contact actuation. A conceptually different strategy is to install actuators in the environment, rather than in the user’s skin—thus, rendering tactile feedback in a non-contact manner. One canonical example of this is to cause skin displacement via focused ultrasound [9, 28]. Similarly, researchers also employed air flow to render this type of tactile feedback [24, 61]. However, this requires a line of sight to the user’s skin, which prohibits their application in scenarios where the hands move dexterously in various orientations. Moreover, this approach’s interactive volume is still limited.

2.3 Referred sensations: creating tactile sensations in the target by stimulating a different location

The fifth approach, which we draw inspiration from, is to create sensations in a target skin area, but using actuators attached to another patch of skin. Unlike relocated actuators, this approach stimulates the intended target (not in an unrelated skin patch). This has been achieved in two different ways: (1) using constructive interference of vibrations; and, more important to our approach, (2) via electrical stimulation of the nerves to create sensations “further away”.

Remote tactile sensations via constructive interference of vibrations. Dandu et al. have demonstrated that vibrotactile stimuli directly applied to the fingertip can cause tactile sensations in the middle phalanx, the proximal phalanx (finger base), or the whole finger via constructive interference of the vibrations propagating the finger [15, 16]. While this shows the fundamental insights and the potential of the approach, the device itself covers up the fingerpad.

Referred sensations via electrical stimulation. Referred sensations are defined as “somatosensory feelings that are perceived to emanate from a body part other than, but in association with, the body part being stimulated” [47]. This has been primarily explored in prosthetics to provide tactile feedback to the prosthetic hands or feet of amputees [10, 43, 54] . Recently, neuroscientists started investigating this phenomenon in subjects with intact limbs, and reported tactile sensations were evoked on the palmar side of the hand through electrical stimulation at the forearm [20, 59], elbow [19], and arm [69]. Specifically, Alonzo et al. showed stimulating the lower palm could evoke sensations in the fingers [3]. Moreover, this can also be leveraged for interactive devices. Yoshimoto et al. leverage it by attaching a pair of electrodes to the root of the finger, *on the palmar side*, to cause a tactile sensation at the fingerpad [74, 75]—we depicted this important approach in our Figure 1 (c). While we think this is a step in the right direction and take inspiration from it, we take this further by *removing all the electrodes from the palmar side*, removing the encumberment of this critical tactile area. Finally, while these approaches support *fingerpad* haptics, they have not been shown to scale to more parts of the hand. Our work presents the first actuation technique that scales to many locations of the palmar side of the hand.

3 OVERCOMING THE CHALLENGES TO CREATE TACTILE SENSATIONS AT MULTIPLE POINTS IN THE FRONT OF THE HAND WHILE KEEPING IT ENTIRELY UNOBSTRUCTED

We tackled two, seemingly, incompatible goals: **(1) rendering tactile sensations** on *multiple locations* of the hand’s palmar side, while simultaneously **(2) preserving the tactile acuity** of the *same locations* where we create sensations. We tackled this by electrically stimulating the palmar digital nerves (namely, the median and ulnar) via electrodes attached to the dorsal (i.e., back) side of the hand and the wrist. In this section, we illustrate key challenges that led us to find our final electrode arrangement to realize this back-to-front tactile stimulation.

All the following findings in this section were informed by six months of pilot experiments as well as consultation with an external scholar who is an expert on tactile stimulation in the field of neuroscience (see Acknowledgments).

3.1 Decoupling stimulation points from the palmar side of the hand by evoking *referred sensations*

Our approach builds on the fact that electrical currents can cause sensations in mechanoreceptors, even in those distant from the stimulated point [48]—the aforementioned concept denoted as *referred sensations* [3, 19, 20, 59]. This implies that, in theory, it would be possible to cause sensations on the palmar side of the hand by selectively stimulating nerves anywhere between the hand and the brain (e.g., forearm, elbow, arm). To realize our goal, the first step was to find *suitable stimulation points* that cause sensations at multiple points on the palmar side, including for all individual fingers.

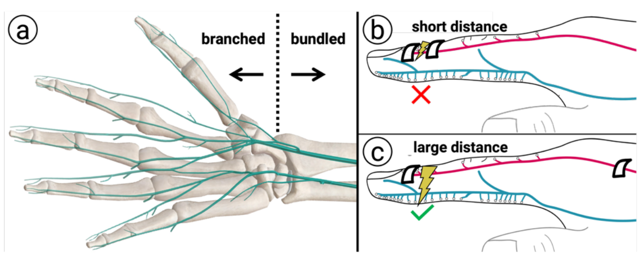

Figure 2: (a) The digital (i.e., finger) nerves branch out for individual fingers after the wrist. (b, c) An inter-electrode distance must be large to stimulate palmar digital nerves; otherwise, the current flow only stimulates the back side (dorsal digital nerves).

3.2 Challenge #1: stimulation from the forearm or wrist does not realize sensations in individual fingers

Figure 2 (a) shows the two main nerves directly connected to the mechanoreceptors on the palmar side of the hand. As illustrated, both nerves go through the forearm and then the wrist. At the wrist, these nerves connect directly to the palm. This allows us to immediately stimulate the whole palm via electrodes at the wrist, as with prior work leveraging referred sensations to create similar sensations. Theoretically, one would expect to stay at the wrist (or even forearm) and be able to create sensations in the individual fingers. Unfortunately, this is where we found **our first technical challenge—this is not possible as the nerves are too close** to each other (bundled) at the wrist. This prevents (non-implanted) stimulation from evoking sensations in individual fingers without *interference across fingers* [59, 69].

However, as shown in Figure 2 (a), the nerves start *branching out* for the fingers *after the wrist*. Thus, we proposed **stimulating the back of the hand**, where the nerves are separated, becoming easier targets for electrical stimulation; to the best of our knowledge, this is the only way to achieve per-finger referred sensations without interference.

3.3 Challenge #2: electrodes applied naïvely to the back of the hand do not stimulate the front of the hand

Now, one could expect a naïve electrode arrangement for the back of the hand: applying two electrodes (positive and negative) directly atop a target location. Applying this to our technique, one can imagine attaching two electrodes next to each other on the dorsal side of a target finger, hoping that they stimulate the palmar-side mechanoreceptors (Figure 2b). Unfortunately, this is where we find our **second technical challenge—the current flow between these electrodes is too shallow** to stimulate palmar digital nerves and it only stimulates the dorsal side. This is because the closer two electrodes are together, the *shallower* the current penetrates into the tissue [36].

However, as prior work in electrical stimulation has demonstrated, increasing the distance between the electrodes allows the current flow to also stimulate deeper regions [36]. Indeed, adopting this, we discovered that the stimulation with a large inter-electrode distance, as depicted in Figure 2 (c), did generate sensations on the palmar side of the hand.

3.4 Challenge #3: stimulation from the back side creates sensations on *both* sides

Now, the mechanism described so far *should not be sufficient* for realizing our goal. As depicted in Figure 2 (c), the current is stimulating both the dorsal side of the finger (undesired) as well as the palmar side of the finger (desired). Applying this idea naïvely would suggest **a mixed sensation on both sides—our third technical challenge**. To make the sensation on the palmar side more dominant, we leverage the asymmetry in tactile sensitivity between the palmar and dorsal side of the hand, which is depicted in Figure 3 (a). In fact, prior work has shown that **the palmar side has ~60 times more mechanoreceptors (≈18000) than the dorsal side (≈300)** [8, 32, 45]—this is understandable since the palmar side plays the most important role in dexterous manipulations.

Now, the density of mechanoreceptors is correlated to the sensory threshold to the electro-tactile stimulation [36, 44]. As such, this asymmetry makes the dorsal side less sensitive to stimulation compared to the palmar side. Using this, we can find a stimulation intensity that surpasses the sensory threshold of the palmar side while staying sub-threshold on the dorsal side. With this, we found it to be feasible to primarily stimulate the palmar side of the hand by adjusting the intensity of electro-tactile stimulation to this range. (Note that we used the range of stimulation intensity capped by 4 mA, which is substantially below the threshold for muscle contraction via the back-of-the-hand stimulation [66].)

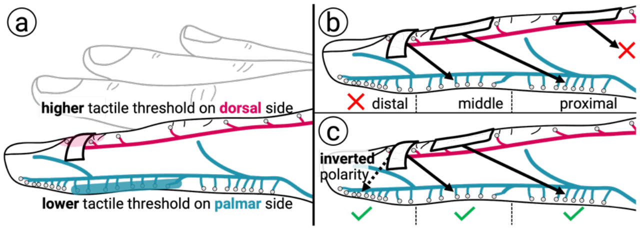

Figure 3: (a) Tactile threshold for electrical stimulation is significantly lower on the palmar side than on the dorsal side. (b, c) Utilizing both polarities (anodic and cathodic) for the electrode attached to the fingertip enables stimulation of the fingerpad.

3.5 Challenge #4: stimulating the back side of the finger results in offset sensations on the front side

Putting all our solutions so far together, we can posit the electrode arrangement depicted in Figure 3 (b) to create sensations in each finger segment, i.e., distal phalanx (i.e., fingerpad), middle phalanx, and proximal phalanx. Note that these electrodes are paired with a ground electrode attached further away on the back of the hand. We found this arrangement did not perform well for two reasons. Firstly, we found that the proximal-phalanx electrode is not able to cause a tactile sensation on the palmar side—this can be explained by the presence of a tendon layer (central slip) under the electrode location [27]. Instead, we found that the middle-phalanx electrode creates sensations on the palmar side of the proximal phalanx, which revealed a more fundamental issue, our **fourth technical challenge—electrodes on the back of the finger create offset sensations** on the palmar side of the finger, as depicted in Figure 3 (b). Importantly, this revealed that none of these electrodes created sensations at the fingerpad, i.e., the distal-phalanx segment.

To tackle this, we resorted to a known practice demonstrated in prior work: cathodic stimulation advances the location of the sensation in the fingertip direction [36, 74]—yet, so far, all our stimulation followed the conventional anodic current flow. As such, we applied this polarity inversion to the distal-phalanx electrode and confirmed that the electrode is able to stimulate the fingerpad from the back of the finger, resulting in the electrode arrangement depicted in Figure 3 (c). Note that our device uses the distal-phalanx electrode for stimulating the fingerpad and the middle-phalanx targets by switching between the cathodic and anodic stimulation (see the Implementation section for details). Finally, the thumb has only one electrode on the distal phalanx as it has one joint less.

3.6 Challenge #5: stimulating the back side with one ground electrode creates inter-finger interference

Finally, we observed that the resulting electrode configuration so far not only caused sensations in the target finger, but also unwanted tactile feedback in other fingers. This is our **fifth technical challenge—fingers do not individually code tactile sensations.** For instance, while stimulating a segment of the middle finger, it could also create referred sensations in a segment of the ring or even the pinky finger, which is entirely undesired.

The reason behind this interference is anatomical; Figure 4 (a) depicts how the median and ulnar nerves divide the left and right regions of the hand, i.e., the thumb, index, and middle fingers sense via the median nerve whereas the ring and pinky fingers sense via the ulnar nerve. If an electrical current traverse the two nerves, it can cause sensations to be felt across multiple fingers. To prevent this interference, we implemented two ground electrodes that respectively serve the median and ulnar nerves. By using one of the two grounds at a time depending on which nerve the target finger belongs to, we found that the currents primarily stimulated the correct finger.

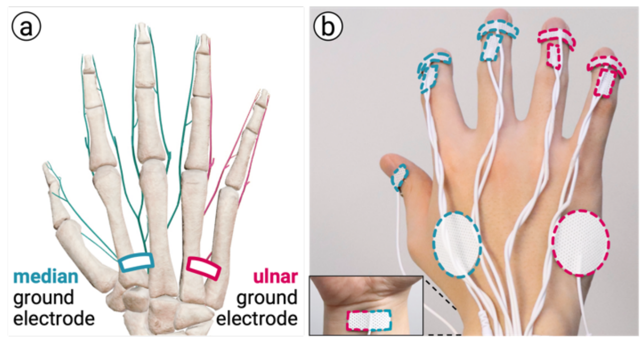

Figure 4: We implemented (a) two ground electrodes to avoid median/ulnar interference. (b) Our final electrode arrangement.

Combining our five solutions, described in this section, we established our final electrode arrangement, shown in Figure 4 (b), which can create tactile sensations at up to 15 locations (one on the palm, two on the thumb, three on each of the index, middle, ring, and pinky fingers). Tying this up with our *Study 1*'s results, we discourage the use of the middle segments, which we found to exhibit more spatial variance (blurred sensations). Choosing locations where we found lesser spatial variance (focused sensations), our approach totals 11 locations of the user's palmar side, without placing a single electrode on the palm.

4 CONTRIBUTION, BENEFITS, AND LIMITATIONS

Our key contribution is a method to render electro-tactile feedback to the palmar side of the hand while keeping it unobstructed. The benefits of our approach include: **(1) Renders tactile sensations on the palmar side of the hand**, while maximizing the hand's dexterity during interactions with physical objects; **(2) Scales well to full-hand interactions**—in fact, we know of very few wearable techniques that are capable of 11 distinct tactile stimulation points on the palmar side of the hand, and none that realize this without physically attaching actuators to the palmar side; and, **(3) Applicable in a range of domains**, from VR experiences that rely heavily on prop manipulation, AR experiences that use physical tools, or mobile applications that render tactile feedback during dexterous activities.

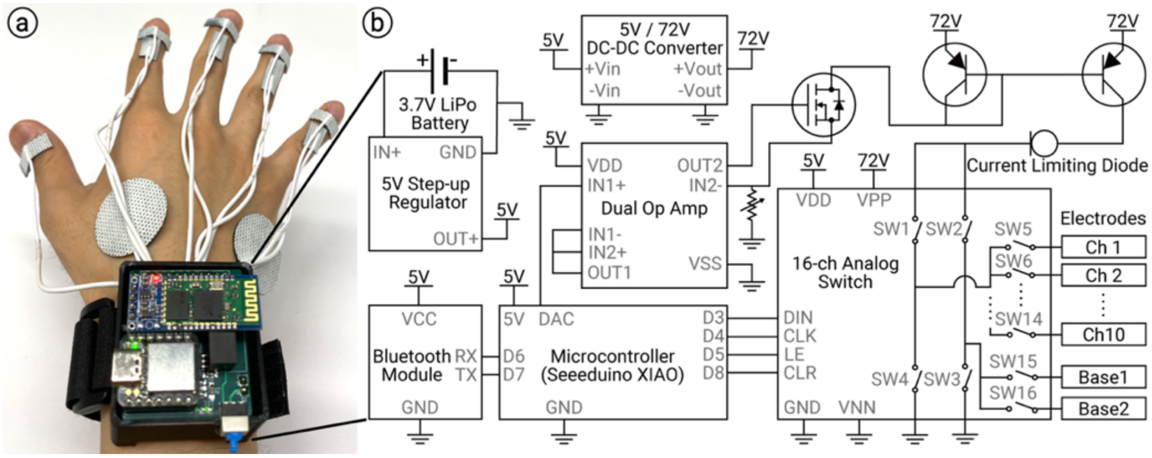

Figure 5: (a) Out wrist-worn electro-tactile stimulator. (b) Electronics schematics of our custom electrical stimulator.

Our approach is not without limitations. First, as with most electrical-stimulation techniques, it requires per-participant calibration of intensity and electrode orientation within finger segments. Second, while we found that most of the primary sensations were felt on the palmar side of the hand (93.3%), some primary sensations could still be felt on the back of the hand (6.7%). Third, while our approach keeps the palmar side free and preserves some tactile acuity, it still uses electrodes on the dorsal side, which might restrict some of the user's movements. Fourth, to make our technique readily available for any stimulator and existing electro-tactile implementations, we used the traditional square waveform for stimulation, hence there is ample space for increasing the quality of perceived sensation by exploring custom waveforms [6]. Fifth, our study population was limited to adults between 20 and 28 years old. Finally, as with existing electro-tactile stimulation, ours is unable to render continuous pressure, which would have been beneficial for increased realism in our VR bouldering application. Others have also argued for the importance of rendering pressure [13]—we agree and acknowledge that this remains an open challenge in electro-tactile stimulation.

5 IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details. Furthermore, to accelerate replication, we provide all the source code, firmware, and schematics of our implementation[1].

5.1 Electronics: custom 10-channel electrical stimulator

As shown in Figure 5 (a), we implemented a wrist-worn electro-tactile stimulator that can output currents to 10 polarity-switchable channels (i.e., cathodic/anodic stimulation). It measures 3.4 cm × 4.6 cm × 4.2 cm and weighs 34 g.

Circuit design. As depicted in Figure 5 (b), we power our stimulator using a 3.7 V LiPo battery, converted to 5 V by a step-up regulator (U1V11F5). This 5V powers the microcontroller (Seeeduino XIAO) and the Bluetooth module (HC-06). To generate the 72V voltage supply for electrical stimulation we added a 5V/72V DC-DC converter (NMT0572SC).

Generating electro-tactile impulses. When our microcontroller receives a serial message from an application via Bluetooth, it responds by generating an analog signal using its DAC; this 0-3.3V signal controls the stimulation intensity. Using a 10-bit resolution DAC allows our system to perform precise increments to fine-tune the tactile thresholds, which is a key requirement for back-of-hand tactile stimulation. We feed this DAC output into a dual op-amp (LMV358) and a FET (BSS87) to output a load-independent current. Then, two transistors (FCX705) duplicate the current source, outputting it to an analog-switch IC (HV2701). We use it to direct the stimulation to a target pair of electrodes with a specific polarity: SW1-4 forms an h-bridge that dictates the stimulation polarity, while the states of SW5-16 decide which pair of electrodes output the stimuli. For instance, when stimulating the fingerpad of the index finger, the IC configures SW1,3,6,15 to ON and all other switches to OFF—a cathodic stimulation between *channel-2* and *base-1* electrodes.

Electrodes. We utilized off-the-shelf pre-gelled electrodes from *Omron*, sized as follows: 1.1cm^2 rectangular electrodes for the fingers; 2.5cm^2 rectangular electrodes for the wrist; and 5cm^2 electrodes for the bases.

Stimuli. For the fingerpads, we deliver cathodic currents to the electrodes at the distal phalanges. For the proximal phalanges and the palm, the device outputs anodic currents to the middle-phalanx and the wrist electrodes respectively.

Application-specific haptic effects. Based on the literature [21, 36, 39, 75] and our initial pilots, we used the following parameters for haptic effects shown in the Application section: (1) for pressing MR buttons, we output a single 50-ms pulse; (2) for other touching or grasping interactions (e.g., touching a teddy bear or DJing), we used 100 Hz pulses with 400-μs pulse width; and (3) for rendering the roughness of the bouldering pegs, we used 40 Hz pulses with 800-μs.

[1]https://lab.plopes.org/#boh-electro-tactile

Temporal Multiplexing. To mitigate interference across multiple channels, our switching IC only opens a current path for one target at a time. Still, as this IC can toggle between channels in 10 μs [29], our device completes a cycle of sequentially single-pulse to all 11 targets within 10ms. Since the temporal discrimination threshold of tactile stimuli is about 50ms [57], this means our device can stimulate multiple targets *concurrently* in the user's perception, up to 100 Hz.

Safety Measures. To ensure a safe operation, the variable resistor is adjusted to set the maximum current to 4 mA. As a fail-safe, we also added a current limiting diode (E-452) that shuts off currents over 4.5 mA.

5.2 Tracking, display & application-specific implementations

Our MR/VR applications run via a Quest 2 headset and Unity3D. Moreover, the headset also tracks the user's hands. For the VR bouldering simulator, we used a *VR hand physics simulator* [34] to make the virtual hands compliant when touching virtual objects. For the MR clay modeling application, we adopted Quest's PassThrough API [49] (we also explored the Hololens 2, but found that it could not provide robust hand tracking while touching physical objects).

For our DJ application, we implemented its backend using Max/MSP and the front-end uses MIXXX (DJ application that supports Digital Vinyl System, allowing DJs to play digital audio via turntables). To decode the timecode information stored on the digital vinyl record we utilized *xwax*, a decoder to extract the current speed and position of a record. Our implementation compares these to the metadata saved for the records (which DJs save using MIXXX, including the original BPM, cue points, and so forth). We use this to determine when to render an electro-tactile cue, for example, when the current record position matches any saved cue point.

6 USER STUDY #1: LOCALIZING THE PERCEIVED TACTILE SENSATION

In our first study, we measured *where* the participants perceived tactile feedback on their hands. We stimulated all 15 possible locations via electrodes on the back of the hand. In each trial, we stimulated one location, then we asked participants to denote the skin area where they felt the stimulation and its strongest point—this study design is based on traditional psychophysics methods employed also by prior work to investigate perceived locations of electro-tactile stimuli [59, 69, 74, 75]. Our study was approved by our Institutional Review Board (IRB21-1229).

Participants. We recruited ten participants from our institution (7 identified as male, 3 as female, average age = 23.9 years, SD = 2.5). All participants were right-handed. The participants were compensated with $30 USD.

Apparatus. Participants sat at a desk with their non-dominant hands resting on a cushioned arm stand with our stimulator and electrodes connected. To ensure good conductivity, we applied conductive gel on electrodes. We provided an iPad and Apple pencil so that they could draw (with their dominant hand) to indicate the perceived sensation area on our GUI, which depicted both a palmar side and dorsal side of a hand model.

Stimulus. We used the traditional square wave stimulation with the current polarities described in *Implementation* (i.e., cathodic for the distal-phalanges and anodic for all others).

Ensuring no bias from calibration. The calibration process typical of electrical stimulation (i.e., attach electrodes, stimulate, ask perceived touch location, move/rotate electrodes, and repeat until the sensation is on the expected location) would *bias* participants' responses during actual trials as they would expect the sensation to be at the location they reported during calibration. Thus, instead of running calibration before trials, we conducted trials with multiple electrode adjustments and, per participant, used the data from the best (i.e., calibrated) electrode adjustment.

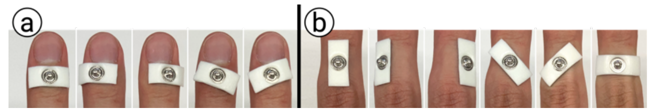

Figure 6: To not bias participants' responses in locating the perceived sensation, we included all these electrode adjustments as trials.

Electrode adjustment (only within a finger segment). As described in our pilot experiments (see Section 3), we found that our technique worked with fixed locations, i.e., electrodes are placed within the finger segments. However, while coarse location calibration is not needed, as with most electrical-stimulation techniques, it requires minor adjustment of the electrode position and orientation within the finger segments. Thus, we used the following electrode adjustments, depicted in Figure 6, determined from pilot experiments: (a) five adjustments for the distal phalanges and (b) six adjustments for the middle phalanges. We found the wrist and the ground electrodes do not need adjustment.

Study procedure. Each participant performed 75 trials in a randomized order: all 15 targets in all aforementioned electrode adjustments. At the beginning of each trial, we calibrated the intensity by increasing the current amount by 0.1 mA steps while ensuring it was pain-free (the maximum current limit was set to 4mA). We stopped at the intensity where participants noticed *any* tactile sensation, i.e., we did not ask where the sensation was felt. We used this intensity + 0.1mA to ensure participants could clearly perceive the stimulation, yet still operated pain-free (after calibrating all participants, we found an average intensity of 1.85 mA, SD=0.8). Then, after a random waiting period, our device output ten 50-ms pulses spaced by one second. During stimulation, our interface reminded participants to move their hand between two poses: resting on the desk and staying in mid-air; this allowed participants to feel stimuli in both *skin-contact* and *non-contact* conditions. Finally, the participant indicated the point where the sensation was the *strongest* and the *area* where the sensation occurred on our GUI. At the end of the trials for each target, we arranged the responses by the distance from the strongest point to the center of the target area. Then, to analyze data based on *calibrated* electrode adjustments, we selected the response with the smallest distance.

6.1 Results

Palmar vs. dorsal side. Figure 7 depicts our key findings. We found that, in aggregate, **93.3% of points where the strongest**

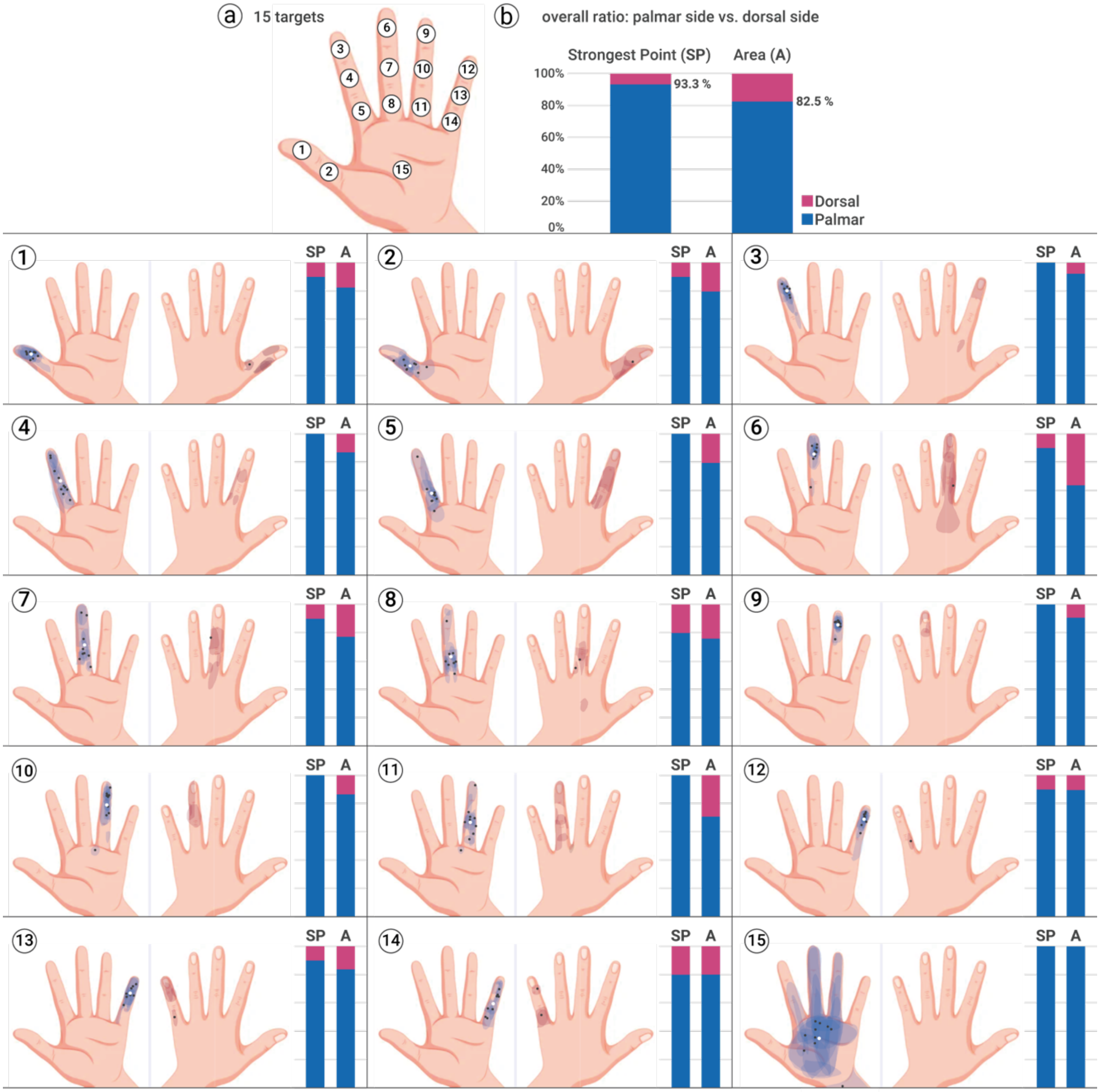

Figure 7: (a) The 15 target locations on the palmar side of the hand to elicit tactile sensation via our back-of-hand electro-tactile stimulation. (b) The overall ratio of the tactile sensation elicited on the palmar vs. dorsal side. (1-15) Overlayed raw data for all participants; black points correspond to strongest points; white points are averages; colored shades depict the area indication.

sensation was felt occurred on the palmar side, despite the electrodes being attached to the dorsal side and the wrist. Moreover, we found that the stimulated area was 82.5% on the palmar side (SD=13.41 %). In fact, the majority of unwanted (dorsal) sensation was reported only for the middle and pinky fingers. Conversely, for all participants, the strongest points for the index, middle, and palm were always on the palmar side. On average participants felt strongest points on the palmar side for 14 out of 15 targets (SD = 1.63; minimum = 11; maximum = 15).

Location accuracy. Figure 7 (1-15) also depicts the average location (white dot), per target, where sensations were felt. To further analyze these in detail, we depict in Figure 8 (a), all 15 locations: each ellipse depicts the center of the average location and the horizontal/vertical standard deviations of all strongest points on the palmar side for each target. Overall, the distal-phalanx (fingerpad) targets had smaller deviations than the others. Moreover, as depicted in Figure 8 (b), we found a clear spatial separation (i.e., the standard deviations did not overlap with each other) between finger segments when we exclude the middle-phalanx ones which tended to overlap primarily with the proximal phalanges (Figure 8a).

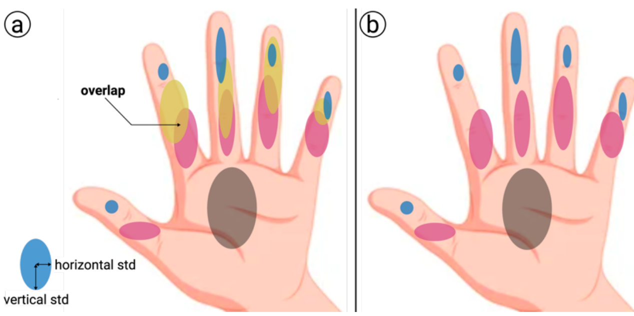

Figure 8: The aggregated plots of the means and the standard deviations of the strongest points across all participants. For each ellipse, the center point depicts the mean, and the horizontal radius and the vertical radius represent the horizontal and vertical standard deviations respectively. (a) The version with all 15 targets. We found that sensations at the *middle* phalanges overlap with those at the proximal phalanges. Therefore, (b) we concluded that 11 individual targets are robust with our approach.

Study interpretation. Overall, we found out that our approach creates tactile sensations mostly on the user's palmar side of the hand, not the dorsal side. Moreover, even if we discard the middle phalanges where sensations were more blurred (higher spatial variance than other regions), we still found that our approach can render an unprecedented number of distinctive points—the 11 tactile locations depicted in Figure 8 (b). Yet, we do acknowledge that: (1) in rare individual cases (10 out of 150 trials, 6.7% of total trials), participants felt the strongest tactile sensation on the dorsal side; (2) in 11 trials, participants felt the sensation on the palmar side but off from the target finger segment.

7 APPLICATIONS: KEEPING THE PALMAR SIDE FREE ENABLES NEW INTERACTIVE EXPERIENCES

Our unencumbering tactile feedback enables a variety of applications, including some not possible before, for instance: (1) VR climbing with haptic props; (2) DJ'ing with tactile notifications; and (3) modeling clay in mixed reality.

7.1 Adding Physical Props to VR Bouldering Simulator

Using physical props that stand in for virtual objects is a popular technique to yield higher haptic realism in virtual environments [7, 31]. However, typically, this approach is employed when users are not wearing any haptic wearable devices, such as vibration gloves, because most haptic devices would impair the user's ability to manipulate and feel the rich tactile feedback from the props. We demonstrate how our technique can alleviate this as it allows users to feel *both* physical props as well virtual feedback. As shown in Figure 9 (a), the user is in a VR bouldering simulator and before climbing the wall, they put chalk onto their hands. Our device does not encumber the user's palms while rubbing the real chalk, which acts as a physical prop to enhance immersion.

While climbing, they feel electro-tactile stimulation at the locations where their hands touch the bouldering pegs—in fact, Figure 9 (b) shows how the user's thumb and pinky are not touching the peg and thus do not experience feedback; this depicts how our approach is selective at the level of individual finger segments. Note that our device only presents the tactile aspect of the virtual bouldering pegs, unable to render force feedback (e.g., continuous pressure) as this is a limitation of contemporary electro-tactile stimulation (see *Limitations*).

Moreover, this VR climbing experience is furnished with another prop, a climbing rope attached to a pulley in the ceiling. As depicted in Figure 9 (d), the user can grab the rope and feel its texture, or even apply force on it, without any encumbrance from our electrodes.

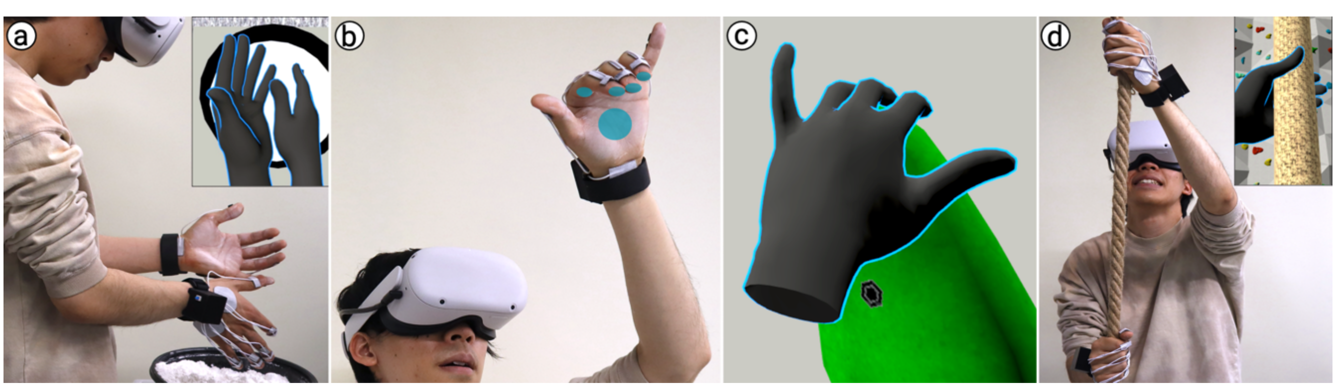

Figure 9: Our VR bouldering includes grabbing virtual pegs to climb but also manipulating real props (e.g., chalk and a rope).

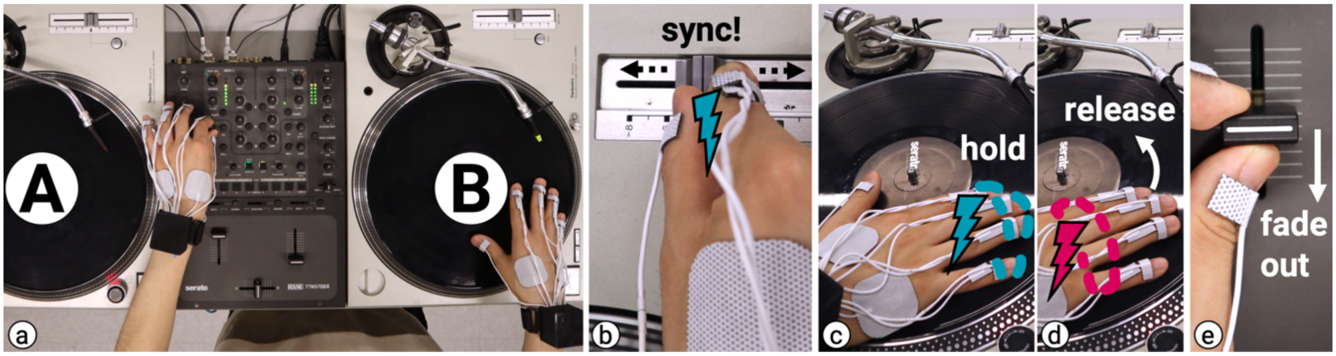

Figure 10: Our electro-tactile feedback allows this DJ to receive tactile notifications while still using their fingerpads to mix.

7.2 Tactile Notification in Dexterous Activities (e.g., DJing)

In our DJ application, our tactile feedback approach supports a DJ's performance without encumbering their hands' dexterity, i.e., placing the vinyl onto the turntable, manipulating the mixer, "scratching" the record, etc. As depicted in Figure 10 (a), the user is DJ'ing, attempting to mix the two turntable decks (**A** and **B**) together, by matching their tempo. DJs that use Digital Vinyl Systems (e.g., the popular *Serato* [1], which allows playing digital audio using traditional turntables) rely on visual information in their laptops for mixing. Instead, our DJ uses electro-tactile notifications.

First, the DJ adjusts the tempo of deck **B** by moving the turntable's pitch slider. When the tempo is in sync with that of deck **A**, the tactile feedback to the fingers holding the slider notifies the user, as depicted in Figure 10 (b). Now that deck **B** is at the correct tempo, they need to find the cue point to fade deck **B** into the main mix. Again, DJs that use Digital Vinyl Systems must look at their laptop screen and move the record until it hits the desired cue point. Instead, our DJ can focus on the turntables, relying on electro-tactile notifications. As depicted in Figure 10 (c), the user moves deck **B**'s record back and forth, searching for the cue point, which our system renders as an electro-tactile sensation under the fingerpads that hold the record—this indicates the physical cue point. Finally, DJs need to release the record at the cue point, *on time*. As shown in Figure 10 (d), our DJ waits for electro-tactile feedback to the proximal phalanges (close to palm) that indicates to release deck **B**. Now both tunes are being played in sync and the DJ fades deck **A** using the mixer's fader, as depicted in Figure 10 (e). Note they can perform this without encumberment from our electrodes.

7.3 Interactively Guided Clay Modeling in Mixed Reality

We demonstrate the usage of our system for guiding the user as they model physical shapes in mixed reality (MR) using real clay. This is inspired by prior work on interactive painting [18] and sculpting [76], but takes these ideas further by allowing users to physically model directly with their hands, rather than through handheld tools. Figure 11 (a) depicts the user pushing MR buttons to browse through 3D models to choose which model they want the system to assist them with—as they press buttons, they feel electro-tactile feedback to confirm the actions and add realism to the interactions.

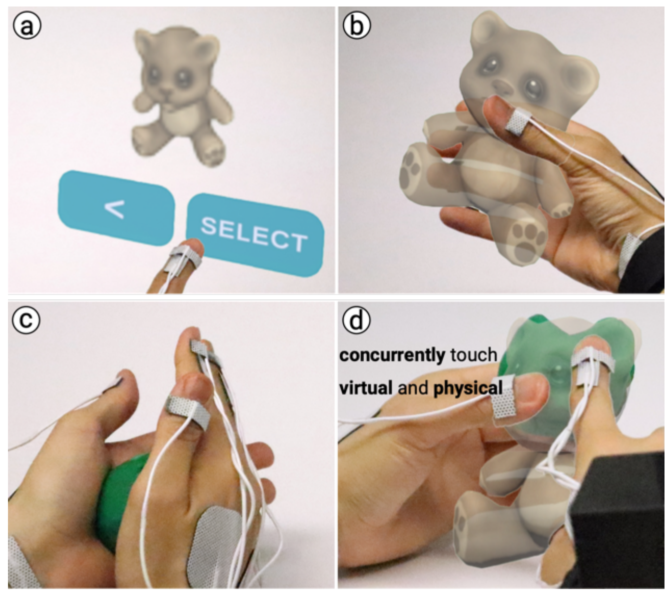

Figure 11: MR clay application alongside virtual 3D models (superimposed the virtual content for the sake of visual clarity).

The user now chooses the bear model and attempts to clay a copy of it. To understand the model's geometry, the user can touch, grasp, move, and rotate the virtual bear with their whole hand. As they do so, our system renders each of the 11 possible palm segments that are in contact with the 3D model, e.g., feeling on the whole hand as they grab the model as shown in Figure 11 (b). Then, as depicted in Figure 11 (c), the user molds clay, putting force on their palm and fingerpads—since our electrodes are attached to the back of the hand and the wrist, they provide minimal encumberment. Finally, to give the finishing touches to the clay bear's head, the user aligns the physical and real model and uses our electro-tactile stimulation to feel the places where the VR model differs from the clay model, as depicted in Figure 11 (d).

8 USER STUDY #2: USER'S EXPERIENCE IN APPLICATIONS INVOLVING OBJECT MANIPULATION

While in Study #1, we validated that our approach was able to cause sensations at 11 different points on the palmar side of the hand, now we turned to understanding how much our device preserved dexterity and tactile acuity while rendering electro-tactile feedback. The motivation of the study was inspired by prior work that also investigated how wearable devices affected the user's tactile acuity [25, 67, 71]. Following the study design employed by [67], we asked participants to interact with real-world objects while using our device and interviewed them regarding whether our device preserved or encumbered their interactions with these real-world objects. The study was approved by our Institutional Review Board (IRB21-1229).

8.1 Study Design

Participants. We recruited eight participants (three identified as male, five as female, average age = 22.3 years, SD = 2.1) from our institution; four had partaken in our first user study; one was left-handed. Moreover, with the participants' consent, we videotaped and transcribed the study. Participants received $30 USD as compensation.

Tasks. The participants experienced our MR clay modeling and VR bouldering simulator. We modified our MR clay modeling to fit the study format by removing the browsing feature and, instead, adding two buttons that could respectively reset the 3D model's position to its origin; and fix the 3D model in place. When participants were satisfied with their clay model, they proceeded by choosing a textured surface to place their "clay bear" on (Velcro, sandpaper, and silk, which acted as props for the floor of an MR forest, desert, and snowfield). We also added a 5-inch virtual button at the top of the VR bouldering wall to conclude the experience.

Interactions. We designed these tasks to require the participants to touch, grab, rub, and knead physical objects while enjoying tactile feedback from our system. To elaborate: (1) both tasks required the participant to put on/off the Quest headset *by themselves*, which involves rotating a mechanical knob to adjust the tightness; (2) VR bouldering application demanded that the participant rubbed the chalk onto both hands prior to the first wall; (3) it also required them to grab the rope and apply force to pull it down; (4) the clay modeling involved kneading, molding, and grabbing the clay; (5) it also demanded the participant to feel the different textured samples (e.g., sandpaper).

Apparatus. The participants wore a Quest headset and a USB tethered version of our stimulator device with the electrodes and the cables. While, in the MR task, participants wore the full set of twelve electrodes on their dominant hand, in the VR bouldering task, we evenly distributed these electrodes so that they could feel tactile feedback on both hands (five tactile points per hand: fingerpads of the thumb/index/middle fingers, the thumb's proximal phalanx, and the palm). We also provided participants with physical props, including *play-doh*, with three texture samples (i.e., Velcro, sandpaper, and silk), a bowl with bouldering chalk, and a one-inch-thick rope.

Procedure. The participants performed the two tasks in a counterbalanced order. Prior to each task, we calibrated the stimulation intensity and adjusted the attachment for all electrodes. Unlike our first study, we verbally asked the participants which part of the hand they felt tactile stimuli to adjust the electrode's position. We set the intensity one step above the minimum intensity required to evoke the sensation (see *User Study 1* procedure for details). During the trials, we encouraged the participants to "think out loud" and voice any of their own thoughts about the experience.

Interview. We followed each task with a semi-structured interview where we asked the participants about their experiences with virtual widgets and manipulating physical props. We started with two questions, common to both tasks: (1) "Could you describe how you felt tactile feedback while interacting with virtual props?"; (2) "Could you describe how much our device, including its electrodes and cables, encumbered putting on/off the headset?". For the first question, after a response, we also asked about their experience with individual props (i.e., the virtual bear and the buttons for the mixed-reality task, the bouldering holds, and the finish button for the VR task). Then, we asked two additional questions that were unique to each task. For the MR task: (3) "Could you describe how much our device encumbered touching, molding, and moving the clay?", and (4) "Could you describe how much our device encumbered feeling different textures?". For the VR task: (5) "Could you describe how much our device encumbered chalking your hands?"; (6) "Could you describe how much our device encumbered grabbing the rope?". Finally, after both tasks, we concluded the study by asking (7) "Is there any other aspect of your experience that you would like to share with us?".

8.2 Qualitative Feedback

Discrete tactile feedback when touching MR buttons. Six participants directly described that they enjoyed the tactile feedback when pressing the MR buttons, e.g., "like a nice detent" (P2), "like physical resistance that I was supposed to feel when pushing the button" (P3), or "I liked the button, felt more like pressing something than touching " (P6).

Continuous tactile feedback when touching VR/MR objects. Seven participants directly mentioned that tactile feedback to the 3D "bear" model was helpful during the interaction; the comments included, "it reinforced my understanding of the shape" (P1), or "I felt the size of the bear, when I was putting my fingers around the head, I could tell how large it was" (P6). P5 described how tactile feedback to the proximal phalanges positively shaped their experience: "I was pretty amazed that I felt on these areas [pointing the proximal-phalanx segments] because that's the part where the most points of contact occur when I'm actually grabbing." For the "finish" button in the bouldering simulator, four participants commented that it contributed to their experience; the comments included "I felt the sensation all over my palm, which made me think that I was actually touching something physical" (P2), and "I felt exactly what I expected to feel" (P7). Moreover, six participants stated that tactile feedback to the bouldering pegs shaped their experience; the comments included "I enjoyed the continuous feeling on my palm and fingers (…) it felt like (…) holding something tangible" (P1), "[while grabbing the pegs] I felt exact locations where I was

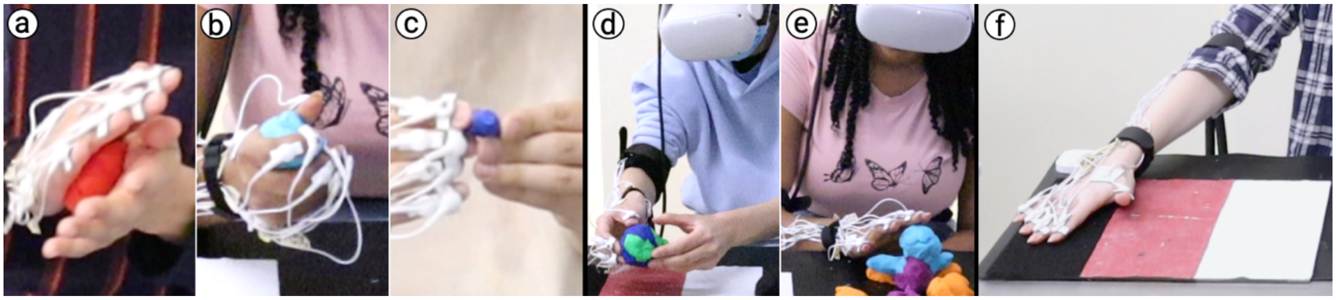

Figure 12: (a) Shaping the clay mold by rolling, (b) squeezing, or (c) pinching (d) Overlaying clay on the virtual model, feeling the haptics of the physical and virtual models concurrently. (e) Touching and feeling the alignment of the entire model in the same way.

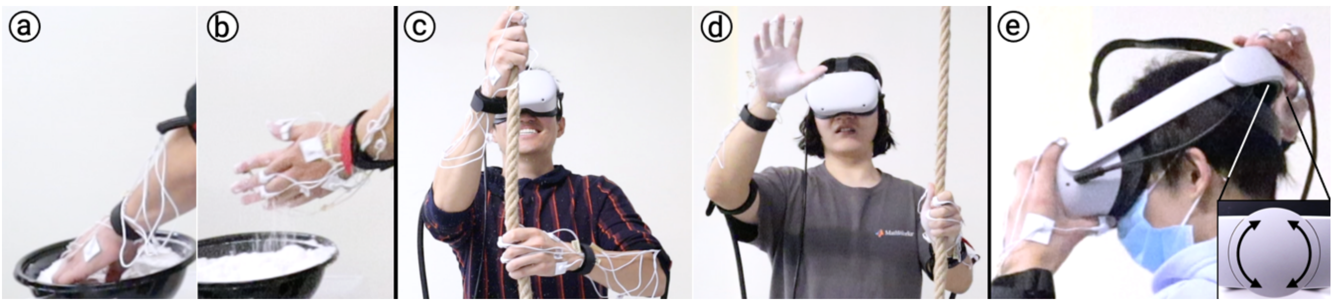

Figure 13: (a) putting the chalk. (b) rubbing the chalk against the palms. (c) grabbing the rope and pulling it down. (d) exiting the physical (the rope) part of the experience by grabbing the virtual peg. (e) putting on/off the headset, rotating the adjusting knob.

supposed to feel (pointing the fingerpads and the center of the palm)" (P5), or "[it] made the experience more realistic" (P7).

Perceived sensation of the stimuli. While describing their experiences with the virtual feedback, four participants expressed how the stimulation felt: "it felt like vibration, while I was grasping the bear" (P1); "it was tingl[ier] than what [a bouldering hold] was supposed to feel" (P6); "it felt like short, light pressure [while pressing the button]" (P7); and "the feeling itself was warm and tingly" (P8). Both P6 and P8 added that they got used to the "tingling" feeling over time. For instance, P8 stated, "it was a little surprising at first but at some point, I got used to it". Next, we turn to the participants' qualitative feedback regarding the interactions with the physical objects.

Kneading the clay. Figure 12 depicts how participants manipulated the clay in a variety of ways: (a) rolling; (b) squeezing, or (c) pinching. In terms of the encumberment from our device (including the cables and the electrodes), six out of eight participants reported it did not encumber them. Their comments included "they were not in the way (. . .) actions were all about my palm and the cables and the electrodes were on the back of my hand" (P7). For the remaining two participants, they reported some encumberments to their manual actions by stating: "[while rolling the clay], I was more aware of the electrodes, so I rolled less frequently compared to not having anything" (P4) and "I was trying not to move as fast as natural [while wearing the device]" (P5).

Overlaying the virtual and physical objects. Three participants commented on how our device allowed them to compare virtual vs. physical objects also via its tactile feedback, as depicted in Figure 12 (d, e). P4 stated that "I put the clay [right at the same position as the virtual bear] to check if my bear was proportional (. . .) I felt the bear and my clay at the same time"; similarly, P5 liked the experience itself of touching the virtual bear augmented with the physical clay: "I liked that the play-doh added the pressure when I touched the head of the [virtual] bear".

Feeling different textures. None of the participants mentioned that our device encumbered them while feeling the texture sheets, which they used as an AR prop to place their clay bear on (Figure 12f). P1 and P5 supported their responses by adding: "since it's at the back of the hand (. . .) there were no hurdles for (. . .) palm or the fingertips" (P1) and "not at all encumbering because (. . .) I knew how secure they were (. . .) if I say nothing on my hand is 10/10, this was 9/10" (P5).

Chalking their hands before VR bouldering. All but two participants noted that the device did not directly encumber while putting the chalk (Figure 13 a, b), the comments on encumberment included, "I was a little worried accidentally breaking the wires" (P3), or "I was aware of the stuff [back of the hand] and didn't want to disrupt it" (P5).

Grabbing the real rope in VR. None of our participants mentioned encumberments while interacting with the rope, which is depicted in Figure 13 (c, d). They described that they could feel its texture while pulling it down: "it made me forget about the electrodes (. . .) I perceived the roughness of the rope without fault" (P1), or "I was able to grab the rope without noticing the cables (. . .) [the rope's texture] felt natural" (P8).

Putting on/off the headset. Lastly, in both tasks, while the participants were able to put on/off the headset without any serious problems, four participants mentioned our device getting in the way of adjusting the tightness by rotating the rear knob: "the wires were a little bit annoying when I put my hand back of the headset to rotate the knob" (P5).

Study conclusions. Taken together, qualitative feedback from our participants suggests that our device was able to preserve the participants' dexterity and tactile acuity on the palmar side of their hand for most interactions that included either virtual or physical object manipulation. We also noted that while we focused primarily on our electrode arrangement we did not specifically research ways to keep the cables out of the way. As such, users mentioned that they felt some minor encumberment by the electrode cables. However, this did not prevent them from really completing tasks involving a high degree of precise finger movements, such as modeling clay or putting on a VR headset by themselves.

9 FUTURE WORK

The focus of our paper was formalizing and evaluating the feasibility of stimulating the palmar side exclusively via electrodes attached to the back of the hand and the wrist, as such, there is room for follow-up research and exploration.

Understanding evoked sensations. While we observed some participants' comments regarding evoked sensations in Study 2, there is still room for more refined evaluations. First, further characterization of the evoked sensation is important. One possible way is to follow the methods employed in prior work [6, 62], and collect data from participants regarding how their perceived sensation and intensity compare to physical stimuli (e.g., vibration). Second, since our approach is built on referred sensation, its operational principle is inherently different from typical electro-tactile methods that stimulate on top of the mechanoreceptors. As such, a follow-up comparison between ours and the typical electro-tactile stimulation is possible, i.e., evaluating whether the typical method evokes clearer sensations or not; and how much they encumber manual dexterity compared to ours. Lastly, further research is needed to measure how the stimuli might interact with haptic sensations from physical objects or the environment (e.g., sense of temperature).

Exploring texture augmentation. As demonstrated in our MR application, our approach allows the user to feel *both* physical and virtual objects concurrently. Follow-up work might choose to explore if this allows for altering the texture of physical objects such as stiffness and roughness by modulating the stimuli in correspondence with the hand motion; while Yoshimoto et al. [75] modulated the perceived roughness of materials at the fingertip, our approach might further extend these illusions to more areas of the user's palmar side of the hand.

Measuring the stimuli at the target receptors. As with any non-invasive electrical stimulation based on electrodes, our stimuli can be affected by the impedance and capacitance of the body tissue while passing through it. A precise measurement of the stimuli at the target receptors would be beneficial to optimize the sensation, for instance, by using implanted electrodes [23].

Miniaturizing electrodes. As we observed in the participants' comments, while our approach kept the palmar side free, the electrodes on the dorsal side still affect the users' movements. We expect that recent advances in fabrication (e.g., custom screen-printed electrodes [71, 72]) can further miniaturize the hardware and address this issue.

10 CONCLUSIONS

We proposed and validated a method to render tactile feedback to the palmar side of the hand while keeping it unobstructed—thus, maximizing the hand's dexterity during interactions with physical objects. We implemented this by applying electro-tactile stimulation only to the back of the hand and to the wrist, in contrast to the traditional approaches that attach electrodes to the palmar side. Yet, as we demonstrated in our first user study, tactile sensations occur at multiple locations on the palmar side of the hand. Moreover, we demonstrated exemplary applications that our technique allows us to build, such as VR experiences that rely heavily on manipulating physical props or feeling tactile notifications during dexterous activities. Finally, in our second user study, we investigated participants' experiences while using our device in two applications and found that our approach allowed participants to use their full hands to manipulate physical objects, feel the object's textures, and even apply force with minimal encumberment, all while still enjoying tactile feedback when touching any virtual or augmented objects.

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