THE UNIVERSITY OF CHICAGO

ENABLING HAPTIC EXPERIENCES ANYWHERE, ANYTIME

A DISSERTATION SUBMITTED TO

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Abstract

My research is driven by the question: Why are technologies for generating the sense of haptics (e.g., vibration), so much behind those for vision (e.g., 3D headsets) and audio (e.g., high-fidelity headphones), on our personal computing devices?

While haptic devices that provide more expressive and realistic sensations, including the sense of touch and forces, have been around mainly built for teleoperation and specific use in Virtual Reality, I argue that it is not trivial to bring these haptic devices directly to mobile and wearable interactions—the interactive paradigm that has prevailed in recent decades.

In this dissertation, I examine the fundamental challenges behind this transition of haptic devices from stationary use to mobile use, and propose novel systems including software and hardware, to solve these challenges in different approaches. Accompanying technical & user-study validations and new interactive applications, I demonstrate a roadmap toward a new generation of haptic devices that will enable haptic experiences **anywhere and anytime**.

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Acknowledgments

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Introduction

Mobile and wearable devices accompany us wherever we go. These devices opened new ways to assist users in real time by delivering visual or auditory information. While **haptic feedback** has been an important factor in more immersive and dexterous experiences [141, 176], it is still left at a minimum (e.g., only simple vibrations for notifications). My research is driven by the question: What fundamental restrictions are limiting the advancement of haptics towards mobile and wearable, and, more importantly, can we tackle these to enable a world where **more haptics** is possible **anywhere & anytime**?

I argue that roadblocks come from the fact that immersive haptic devices, those that can provide the sense of touch, forces, etc., were engineered as a piece of **infrastructure**, rather than as **personal devices**. Existing haptic devices, while rendering realistic senses, are usually stationary (i.e., they work well in hospitals for surgical training, and in Virtual Reality (VR) for immersive experiences in theme parks). They are designed with the main goal of optimizing the rendering of virtual sensations [153, 161], in other words, achieving high **haptic fidelity**. These realistic haptic sensations are typically realized by integrating many actuators that offer various haptic modalities (vibration, pressure, temperature, etc.). Unfortunately, as more actuators are added to the device to increase realism, the device becomes larger and heavier. In addition, to effectively deliver haptic sensations, the devices are often designed to be used in a place with maximum resources (e.g., space, power) and minimal distractions (e.g., noise, multitasking). These ways of thinking about optimizing haptic fidelity left haptics to be largely explored in VR or use cases where the user is isolated from their context (e.g., robotic teleoperation).

Towards haptic experiences anywhere, anytime

In this dissertation, I re-envision the use of haptic devices and demonstrate that we can bring the benefits of haptics to the most important interactive computing paradigms—**mobile & wearable**, and soon to be, **Augmented Reality (AR)**. I envision more haptics to be experienced anywhere, anytime, e.g., the user can type anywhere and feel the touch from virtual keyboards or interfaces, feel any shape or textures when interacting with 3D models, or feel the forces on their limbs for training when exercising outdoors. However, I posit that fundamental challenges exist behind this development. I identify and examine the challenges when applying haptics to mobile and wearable contexts (e.g., blocking real-world sensations and tasks, failing to work effectively under diverse mobile contexts). I argue that if they are not solved, their applications can be greatly limited, i.e., remain only for Virtual Reality or teleoperation.

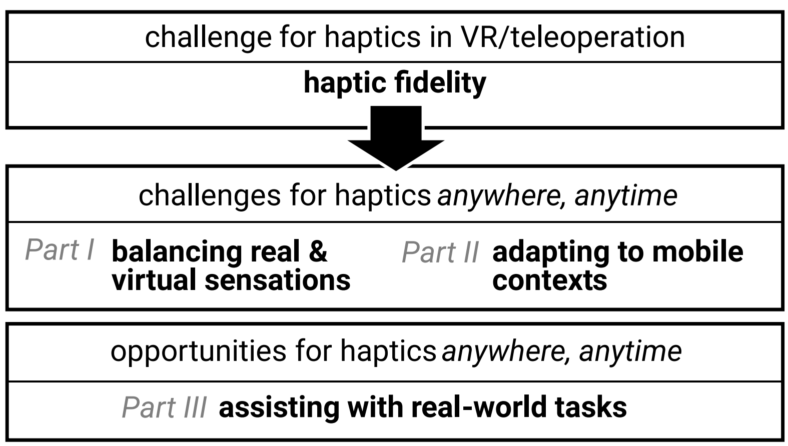

Figure 1: Structure of the dissertation.

Extending the traditional challenge of delivering high haptic fidelity, I put forward additional challenges for engineering haptic devices for mobile and wearable scenarios (Figure 1): **balancing real & virtual sensations (Part I)**; and **adapting to mobile contexts (Part II)**. I demonstrate how I address them by developing novel research prototypes involving new hardware and software systems, with technical and user evaluation.

Furthermore, taking into consideration these challenges, I envision **new opportunities (Part III)** with a research prototype to illustrate the potential benefits of having haptics as everyday physical assistance for Blind users.

The individual components presented and explored in this dissertation were published at ACM CHI and ACM UIST.

Contribution

My research advances in the field of **haptics** and **Human-Computer Interaction (HCI)**. The key contributions include:

1. **Proposing new directions for haptic research**. My research extends and transforms the research from the traditional field of haptics to multimodal interactions including wearable computing and Augmented Reality.
2. **Novel haptic mechanisms and system design**. I propose novel research artifacts, including an original mechanism for delivering haptics [200] and a computational system for rendering haptics [201].
3. **New applications & user evaluations**. I push the boundary of haptic research by building new haptic applications and conducting new user studies in mobile scenarios (including repairing in Augmented Reality outdoors [196, 200]) that are rare in prior works.

Part I – Challenge: Balancing virtual & real-world sensations

Haptic devices have largely been explored in **isolation** from considerations of user's physical interactions with surrounding objects. In other words, almost all of the tactile devices in the state-of-the-art were designed to optimize the realism of the sensations that the device communicates to the user [153, 161] (or **haptic fidelity**, the degree of realism replicating physical sensations), but rarely considering the fact that users also need to feel **physical objects** (e.g., any tool users are operating, putting on/off a VR headset, shaking someone's hand, etc.). Haptic media researcher David Parisi has put it well observing how commercial haptic gloves and suits have been struggling to attract users in the market [162], "The benefits of sending hands into simulated haptic space may not be worth the costs of surrendering them to the interface."

I argue against pursuing haptic fidelity being the sole design objective that drives the development of haptic devices, and instead, I propose that researchers & practitioners should also optimize the **fidelity of the real-world haptic sensations** that the device allows the user to feel even while wearing it. For instance, haptic gloves that completely cover the user's fingerpads and palms might offer excellent **virtual haptic fidelity** (e.g., allows to feel haptic feedback that improves typing on a virtual keyboard) but drastically sacrifice **real-world haptic fidelity** (e.g., it would impair users while typing on a physical keyboard). One can take an analogy from Augmented Reality displays such as optical or video see-through headsets, which aim to preserve the real-world vision. Instead of preserving the lights, haptic devices should preserve the properties that consist of haptic fidelity from the real world, including sense of touch, skin deformation, textures, temperature, and so forth. Preserving haptic fidelity will increase our manual dexterity in physical tasks and allows haptic devices to be integrated with in the real world more seamlessly.

In contrast to pursuing only virtual haptic fidelity in traditional haptic devices [48, 77, 104, 128, 176, 185, 207, 228], few research has advanced haptics to be less obstructive, such as offering haptics through very thin actuators [74, 129, 220].

I show that we can venture more into real-world haptic fidelity (Figure 2). I propose two approaches in the following sections including **revealing part of the fingerpad** to preserve more tactile perception of real-world objects, *Haptic Permeability* [196], and **leaving the entire fingerpads free** when the user is not interacting with virtual interfaces through foldable actuators, *Touch&Fold* [200].

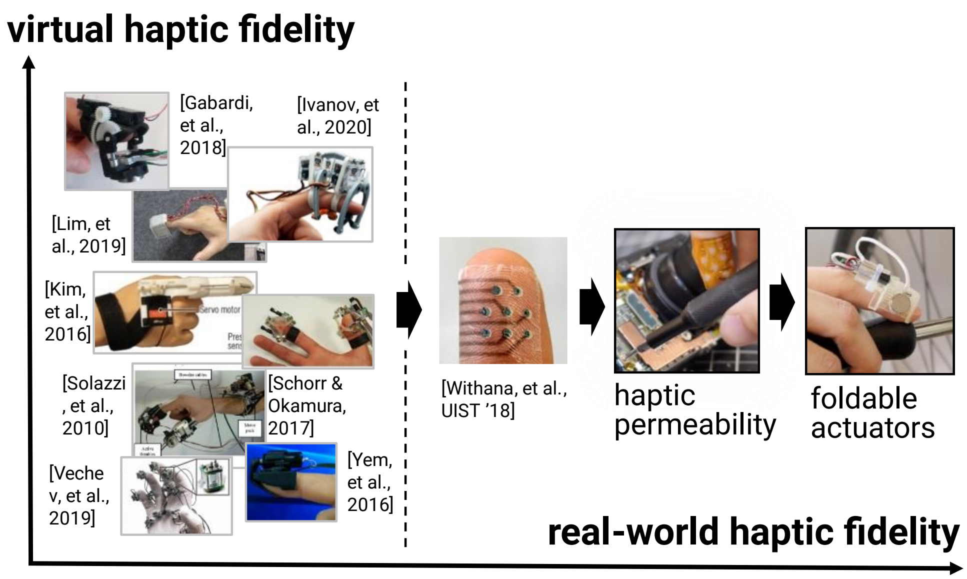

Figure 2: I propose balancing virtual & real-world haptic fidelity.

Haptic permeability: increasing dexterity of tactile devices

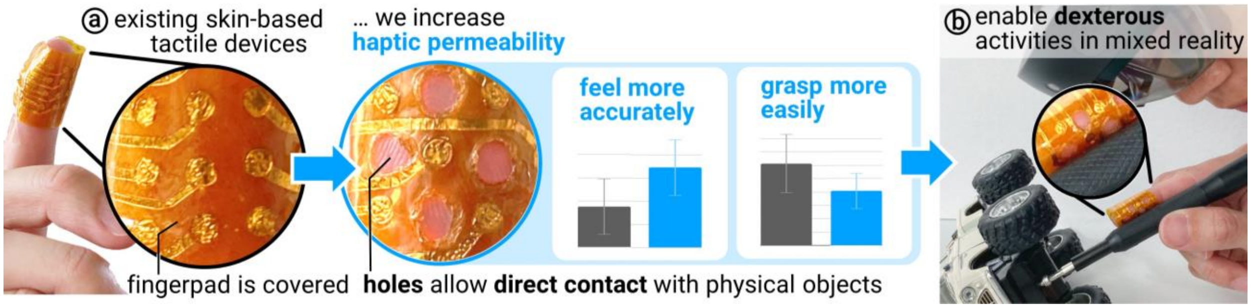

Figure 3: We propose & evaluate how adding *holes* to electrotactile devices significantly improves the haptic users' abilities in dexterous activities, including manipulating tools. Photos taken by author unless otherwise cited.

Motivation for haptics of the virtual and the real world

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 [104, 128, 161, 177, 228], AR [61, 200]).

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 [61, 220]—one successful example of this is electrotactile stimulation [99, 220].

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 [157].

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.

Our approach, which we depict in Figure 1, offers design flexibility, and can be used in four ways, each with their own tradeoffs: (1) swapping unused space, (2) rearranging the traces, (3) rearranging the electrodes, and (4) replacing electrodes, for adding holes—purposefully trading-off some virtual rendering for more permeability to feel physical cues.

In our studies, we found that 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.

Taken together our three studies validate how our approach 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.

Prior work towards less cumbersome haptic devices

The work presented in 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 allow users to feel real-world surfaces under their fingerpads, we focus on electrotactile interfaces, which are built from thin-film actuators, most suitable for interactions involving feeling virtual & real objects. Thus, we succinctly review the field of electrotactile stimulation (yet a more complete review can be found at [113]). Especially, we turn our attention to how researchers have explored the thickness of electrotactile films to improve the amount of sensation felt through the film, despite how it covers their fingerpads completely—this is where we take inspiration for proposing *haptic permeability* (via holes).

The role of touch in our interactions

Touch sensitivity is a crucial mechanism in enabling users to perform dexterous tasks and discriminate subtle textures. Mechanoreceptors under our skin contribute to this remarkable tactile sensitivity by translating forces and vibrations felt at the skin to nerve signals that we can make use of while interacting with the world (e.g., these are needed for any type of physical manipulation, from simply pressing a button to grasping an object without slipping). Given the aforementioned importance of the fingerpad in mediating most of our physical interactions with tools, technology and each other, it is not surprising that it is one of the most sensitive areas of our skin [165].

Texture Discrimination. Texture discrimination at the fingerpad is important for many tasks such as recognizing different fabrics, physicians detecting abnormal tissue textures, or factory workers detecting defects. Tactile receptors under the skin include mechanoreceptors (for vibration, pressure, deformation), thermal, and chemical receptors [87]. Naturally, materials that we touch stimulate many of the receptors (e.g., it creates vibrations, deformations on the skin, conducts heat) and, temporally, this forms the sensation of texture [168]. Besides the sensitivity to the intensity of multiple stimuli, spatial acuity in a patch of skin (i.e., how well we can perceive tactile sensations in a location) is critical—it correlates with the density of the mechanoreceptors in that area [86]. Fingerpads are one of the densest tactile zones and can detect stimuli within the distance of 1-2 mm, compared to 40 mm at the forearm [165].

Grip Control. Our ability to grasp objects firmly with our fingers without slipping relies heavily on tactile sensitivity to precisely sense friction [184, 214]. Receptors can sense micro-deformation of the skin that is in contact with the object and thereby adjust the required force to grasp it. The ridges on our 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 [6, 103, 236]. Altogether, these features help us grasp with optimal force (by using the least energy needed).

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

Historically, most tactile devices were engineered using rigid & thick mechanical actuators—the most popular (still today) are vibration-motors. While these offer some advantages in their low-cost, control simplicity, and haptic capabilities, researchers have realized that 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) [81, 159]. This led to research in soft and thin actuators [19], including microfluidic actuators [61, 62], magnetic actuators [149, 234], dielectric elastomers [110, 232], piezoelectric actuation [84, 241]. While all of these are 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 [90, 99].

Electrotactile interfaces

Given that electrodes can be made smaller than a mechanical actuator (which requires physical displacement and that requires more empty space), electrotactile devices can be made into arrays, suitable for the fingerpad [1, 90, 95, 113]. As such, electrotactile has been mainly used as a haptic device for fingerpads, to deliver textures [50], shapes [171], softness [230] or touch information in virtual environments [220, 227]. Figure 4 depicts five canonical examples of electrotactile devices for the fingerpads, with particular detail on their electrode layout. Importantly, note how there is usually around 2 mm or more of empty space between pairs of electrodes; this is because users can only distinguish electrotactile stimuli that are 2 mm apart [65] and because insulation between pairs is also needed.

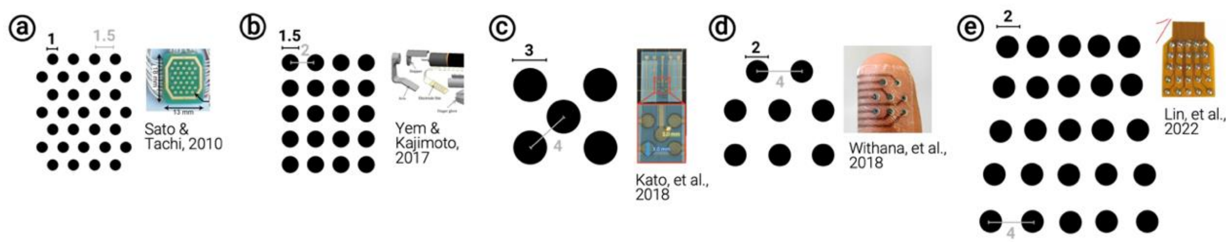

Figure 4: Layouts of exemplary electrotactile on the fingerpad: (a) [171]; (b) [227]; (c) [99]; (d) [220]; and, (e) [129]. All units in mm.

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

Recently, researchers argued that it is not only important to render haptics on the fingerpad, but also need to *preserve* haptic sensations from the real world [170, 192, 194, 200, 220], as they are critical for achieving precise manual tasks.

Making devices thin and soft is one way that researchers explored preserving cues from the real world. For instance, HydroRing [61] presented a ring worn on the fingerpad that used pumped water for haptics. Moreover, its relatively low thickness resulted in an unobtrusive device that could be used in MR to still be able to feel some tactile sensations. Similarly, making devices even thinner and more conformable allows even more sensations to pass-through the device and reach the fingerpad. For instance, Tacttoo [220] is an electrotactile device based on layers of temporary tattoo papers (35 um thick) [220]. This can be taken a step thinner, as shown by Ji et al. in their 18 um thick dielectric elastomer [82]. 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 the interact with physical surfaces, such as rough textures) [157]. More importantly, as we will see next, researchers have found that any type of film applied to the fingerpad limits tactile sensations to some degree [157].

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 [43, 237]. Similarly, it has also been shown that the required grasping force increases in lifting and holding task while wearing gloves [108].

Most relevant to electrotactile research, Nittala, et al. conducted studies with various thickness of films, ranging from 2.5μm to 177μm, 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) [157].

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.*

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.

Direct skin contact. Figure 5 illustrates the principle behind adding holes. In this ink-test, a finger was coated with red ink atop the haptic interface. In this case, instead of wearing an existing thin-film device (e.g., [220]) that would cover every square centimeter of their fingerpad, the user is wearing a film modified with our approach. The film is the same (same thickness/material as [220]), 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 with the paper—even the fingerpad ridges are visible, which implies that the reverse is also true, i.e., small features that the user is touching are in *direct contact* with the skin receptors.

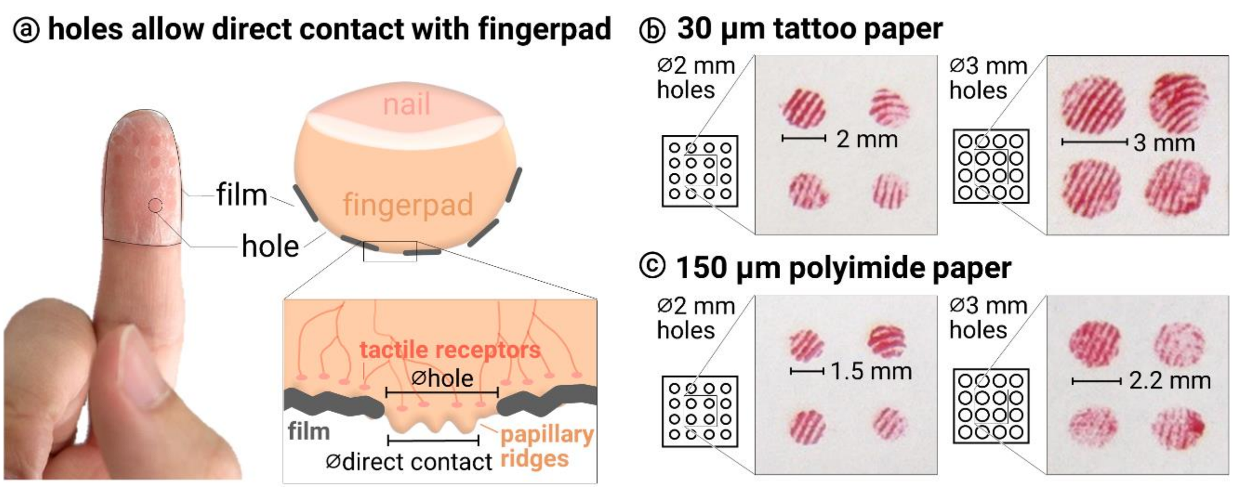

Figure 5: Holes on the film allow direct contact with fingerpad, revealing papillary ridges and can directly transmit tactile signal to receptors.

Tactile receptors. Now, while 2 mm of opening might sound small, it contains ~eight mechanoreceptors [86] and ~five ridges. As humans are sensitive to a stimulus on one single ridge [79], 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. Furthermore, 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 [236]. This yields our second hypothesis: exposing parts of skin help 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. Now the most naïve approach to adding holes would be to simply turn *all* unused space (i.e., space that is not an electrode or a conductive trace) into a hole. In fact, one could even the this to the extreme and create a negative of the electrode array. However, cutting out too much negative-space into the electrotactile film is not without structural limitations: (1) these films are adhesive (i.e., the larger the surface area the stronger they bond to the finger), thus loosing adhesive risks the device coming off the user's finger; (2) the less material envelopes electrodes (i.e., in the extreme case, almost nothing, as they would be held only by the adhesive under their shape and a small trace) 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 engineered using different shapes, circular holes provide a suitable solution that minimizes both aforementioned issues: (1) less likely to get caught in materials since there are no sharp transitions (no acute/sharp angles in a circle, as there would be in a square or other polygonal shapes); and, (2) they have less impact to the overall bonding force of the adhesive, since a circular holes is supported on all sides, thus these are less likely to allow electrodes to get dislodged. In fact, circular holes are shown to be the most stable hole shapes [224], which would make our thin devices more durable for longer use. In our third study where users interacted with real world objects while wearing our holes-based electrotactile devices, no user was caught or dislodged their device, despite interacting with objects with high friction (e.g., screwdriver) and small parts (e.g., wires).

Applicability & design options. Figure 6 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 constraints (e.g., resolution, unused space, layout of the conductive traces).

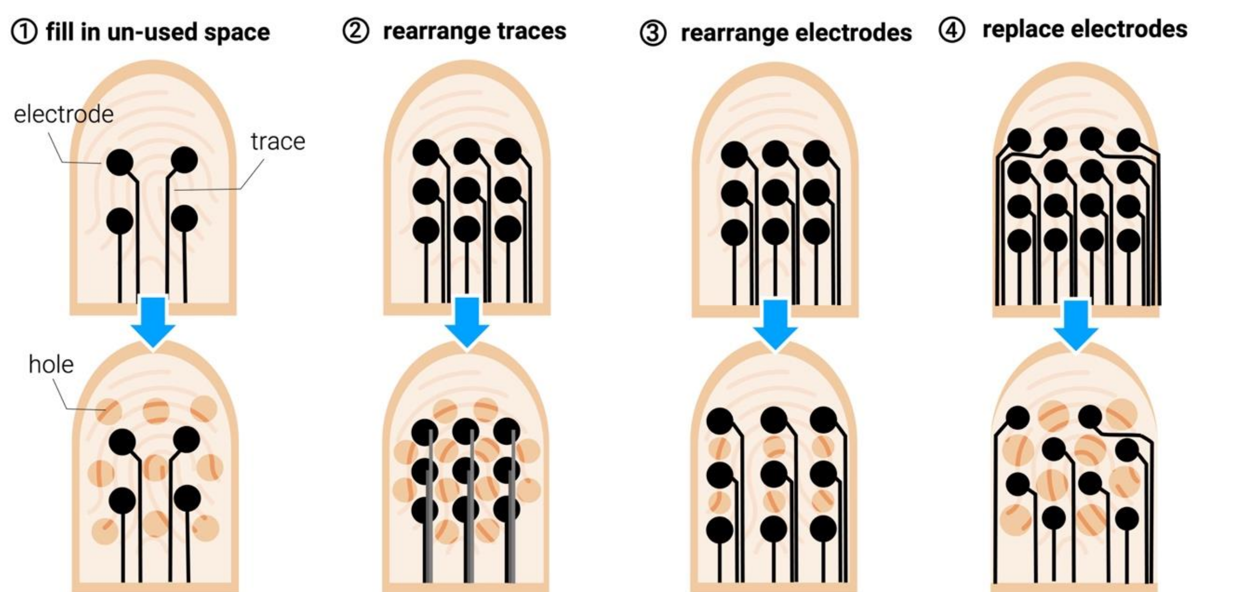

Figure 6: Four design options to implement haptic permeability on an electrotactile device.

We envision four different ways a designer can use our approach, presented in ascending order of how much they tradeoff the resolution of the virtual-rendering capabilities of the target electrotactile device: (1) swapping unused space for holes—virtually 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. These design options are depicted in Figure 6 and detailed as follows:

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 [99]), 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**: the conductive traces can be re-arranged to make space for holes. This can take two forms: re-arranging the traces to pass through to the backside of the electrode film using a *via* [246] or rearranging the traces to optimize empty space—these options are useful in that they have no impact on the final position of the electrodes, and yet, when successful, they can free up space to add holes.

3. **Rearranging the electrodes to add holes**: the electrode positions can be enlarged/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 [210]).

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.

Benefits, contribution & limitations

Our key contribution is the defining & exploring the concept of *haptic permeability*, i.e., the ability of a haptic actuator to allow parts of the skin to physically contact the real-world. We explore & implement this by adding holes to electrotactile interfaces, which become improved, allowing users to feel more of the real-world—as validated in our studies, which contribute with precise measurements of how much covering up the fingerpads (even with very thin films) decreases participants tactile sensitivity and grip force; we expect these study findings to be readily usable by future researchers & designers of haptics.

Our approach has four key benefits: (1) it offers a new way to expand existing approach towards building feel-through devices beyond making actuators thinner; (2) increases tactile sensitivity—adding holes is expected to allow users wearing electrotactile to perform better when tasks require feeling precise cues from the real-world (e.g., feeling fabric samples while working on a fashion design in VR [155]); (3) increases grip control—adding holes is expected to allow users wearing electrotactile to perform better on a wide range of grasping tasks (e.g., in AR assembly-tutorials [67]); and, (4) improves existing electrotactile interfaces through four unique design strategies.

Moreover, we acknowledge that our approach and implementation is not without its limitations: (1) at a certain thickness exposing holes offers no gain since the fingerpad stops making contact with a surface; (2) our studies are focused on replicating standardized tests (i.e., groove orientation and grip force) and a specific interactive application (i.e., assembly in MR), and, thus, do not represent all the complexity of touch behavior in real-world.

Study overview

We conducted three user studies to inform, understand & measure 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: (1) In our first study, 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%, compared to when their fingerpad was fully *covered*. (2) In our second study, we assessed grip control, using a standardized grip-force test (amount of force needed to grasp without slipping); we found that participants were able to have better grip control with the *holes*, using 34% less force than while *covered*. (3) Finally, in our third study, participants experienced a mixed reality experience 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 (RB23-1225).

Study #1: Holes improve tactile perception

In our first study, we aimed to understand adding holes to thin-film haptic devices would affect the feel-through perception of physical objects. As such, we conducted a **tactile perception** study using the standard grating orientation test [38, 238]. In the typical grating test, participants are presented with gratings (thin grooves that run across a material sample) 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).

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 [38]. As we are interested in fine textures that could be affected by thin film covering, we chose a relative difficult grating spacing 1.5 mm. Note that at 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 [220], comprised of stacked layers of tattoo paper. For films with holes, we used a paper plotter to cut the holes.

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. The participant's index finger of their dominant hand was attached with the experiment film on the finger pad and performed 20 trials per condition. Moreover, condition order (*holes* vs. *covered*) was counterbalanced across all participants. In total, we collected 480 trials across all participants (i.e., 4 directions × 5 repetitions × 2 conditions × 12 participants).

Results

Figure 7 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.

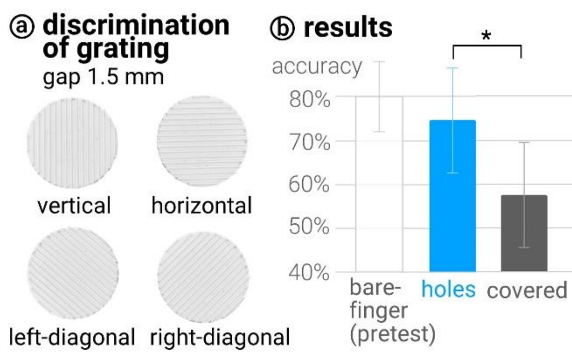

Figure 7: Tactile sensitivity task (grating orientation).

Study #2: Holes improve grip control required to grasp without slipping

In our second study, 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 [214] (i.e., sense if an object is slipping) and control it by adding pressing force. To this end, we assessed it using a standardized grip-force test, which measured the amount of grip force needed to lift & hold objects without these slipping from under the user's fingers—a popular task in psychophysics to measure grip control [71, 108].

Hypothesis. We hypothesized that since adding *holes* exposes skin, namely fingerpad ridges which contribute to friction and grip control [236], 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.

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.

Results

Figure 8 shows our findings regarding grip control. We tested the data with one-way ANOVA and found a significant differences ($F(2, 105)=75.06$, $p=0$). 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 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. Taken together, these confirm our hypothesis that adding *holes* improved grip control when compared to a *covered* film.

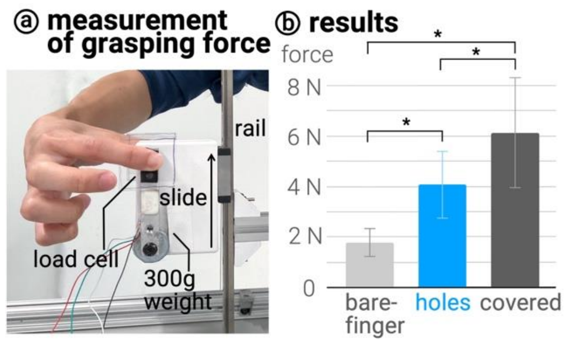

Figure 8: Lift-and-hold task.

Study #3: Holes improve dexterity during mixed reality assembly tasks

Now that we have validated how holes can improve tactile recognition and decrease grip forces, we turn our attention to interactive scenarios. In this study, we aimed at understanding how holes added to tactile devices affect the 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 6(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.

Study Design

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

Figure 9: Study setup.

Tactile devices. As the study requires robust devices that can handle dexterous manipulations with lots of friction, pulling & pushing, we opted for polyimide films for our electrotactile devices, as depicted in Figure 9; in contrast to tattoo paper which is known to be easily scrubbed off during interactions (as reported by [157]; we also confirmed in our early pilots that when using the screwdriver, the tattoo paper rubbed off on the thumb and/or index). Our electrotactile device was thus comprised of flexible polyimide with copper traces (cut using a plotter). 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 5 (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 technically challenging (and not done in almost any prior work). Thus, for the sake of setup-simplicity (and to avoid complicated 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 10. Note that, since our *holes* condition traded-off some electrodes for holes, the haptic stimulation becomes distorted in 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.

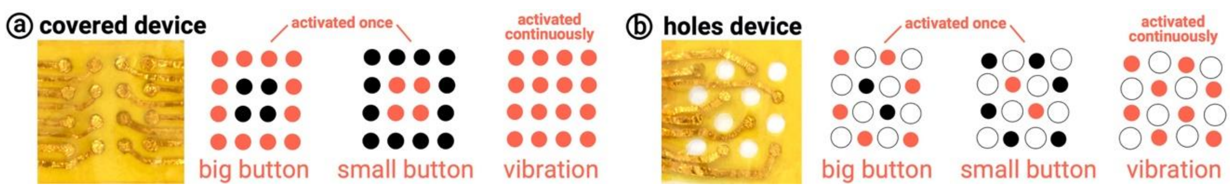

Figure 10: Study devices and their stimulation patterns.

Haptic apparatus. We utilize a medical-compliant stimulator to generate electrotactile (Rehamove 3). To multiplex between all 16 electrodes, we utilize a custom-made multiplexer (similar to [204]). For every stimulation 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 resulting setup requires ~1 ms to cycle through all stimulation channels. The final circuit was worn on the participants' wrist.

MR apparatus. A 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 (⌀), 18 mm thickness, and connected via a metal axle (⌀ 2 mm). All screws were 30 mm long hex-screws (⌀ 3 mm). The truck featured an antenna (⌀ 0.8 mm wire, length 28 mm). Participants were also handed a screwdriver (model F145-419-1, aluminum-construction, ⌀ 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 11. 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).

Figure 11: Steps of the MR assembly.

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).

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.

Reported dexterity & realism. Figure 12 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**.

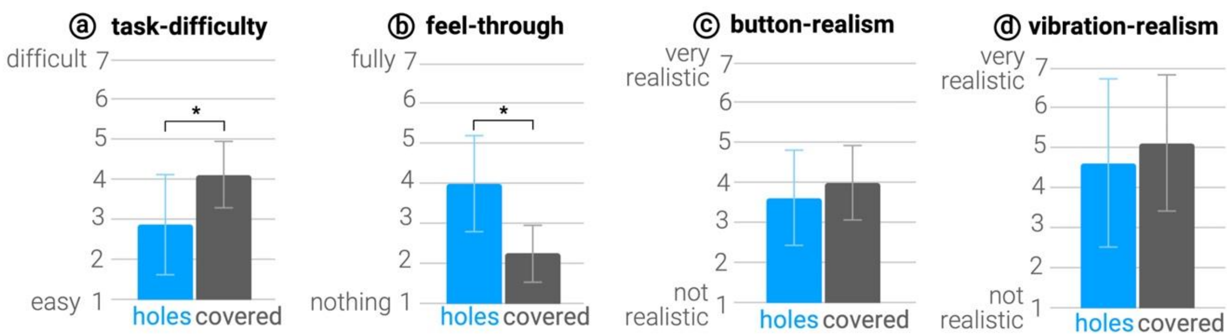

Figure 12: Results of participants' ratings.

Observed dexterity. With this study being focused on observing participants, we annotated videos and depict, in Figure 13, some illustrative examples where the same participant experienced visible differences between manipulating a tool across conditions. For instance, Figure 13 (a) shows P7 successfully manipulating a screw with the *holes* device, but letting it slip with *covered*. Similarly, Figure 13 (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 13 (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 13 (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).

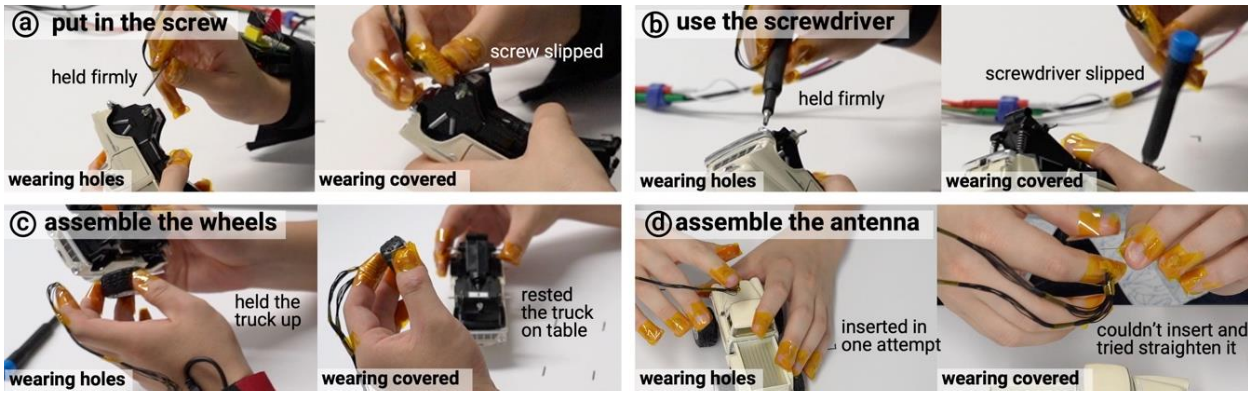

Figure 13: Some exemplary interactions from participants observed in this study.

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.

Distinguishing virtual shapes. 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".

Virtual realism. 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).

Summary of findings & limitations

Summary of findings: We confirmed that adding holes to fingerpad electrotactile devices improves tactile sensitivity and grip control. For grip-control, not only did our participants rated the task as easier using the *holes* device, but we observed less issues during manipulation (e.g., less slips of the screwdriver). Similarly, for tactile sensitivity, both the rating and participants own accounts confirmed that holes improve this aspect of dexterity.

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 are 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 device 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. That being said, participants' own experiential accounts point to this trade-off occurring.

Discussion of how researchers/designers can apply our findings to their devices

How our approach can improve haptic permeability of existing electrotactile devices

Our approach can be immediately applied to state-of-the-art devices, namely Tacttoo [220]. 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 14 (a). Since our Study 1 & 2 were based on the material of this device, the improvements we observed regarding tactile sensitivity & grip control should apply to Tacttoo [220] . That being said, we expect that many more electrotactile devices can be improved by utilizing strategies laid out previously. For example, the routing of [1] can be changed to the backside, allowing spaces for holes, as depicted in Figure 14 (b). Our approach is likely to be beneficial beyond the fingerpad, for instance it should extend to the whole hand. For electrotactile arrays with already extremely high resolution [230], researchers can now explore how trading-off electrodes with holes might improve tactile sensitivity, as depicted in Figure 14 (c). Finally, we also found that the ink test we introduce in Section 3 (Figure 5) can be helpful. Devices with various thickness can use this test to see if the holes can let the skin directly contact with a surface, and thereby determine a suitable hole size [58].

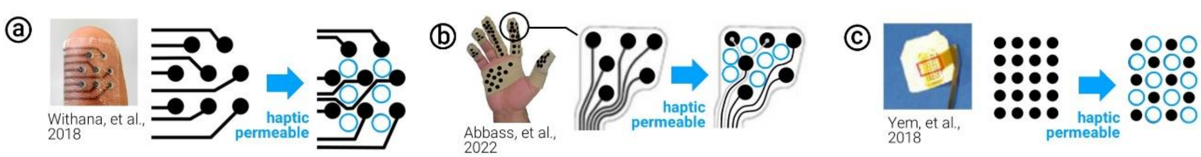

Figure 14: Use our approach to improve the existing electrotactile devices for more tactile sensitivity by adding holes. (a) [220]; (b) [1]; (c) [230].

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 applications and usage scenarios, 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). Following this, they can determine a suitable hole vs. electrodes count and their sizes (again, they can utilize our ink test to see ridges revealed by holes, see Figure 5). We hope this leads to new designs that can best balance the virtual haptics without obstructing much sensations from the real world.

Haptic permeability beyond electrotactile

While our exploration was centered around how haptic permeability of electrotactile interfaces, and we warrant caution when extrapolating our findings beyond these, it is entirely possible that the idea of holes is applicable beyond electrotactile. For instance, on-skin interfaces made with dielectric elastomers, for example [110] have similar actuator layouts and thickness (210 µm); yet one should note that the mounting should be stable with mechanically-moving actuators. Devices made of miniature piezo actuators [84] could potentially be improved with holes on the substrate; however, with the change of material, one should pay attention to its resonance frequency.

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 means of adding holes. Yet, it is entirely possible that other forms of permeability might be possible and that researchers use our concept as inspiration to explore those. For instance, our design with holes also can achieve *air permeability*, similar to [127, 231], allowing the user to feel wind and also let sweat evaporate (as we observed in user study, noticeable sweat accumulates with covered devices). Similarly, if a tactile interface will be used in an interactive 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.

Summary

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 creating sensations via thin devices—e.g., electrotactile stimulation. While these can be engineered to be thin, not all of the important haptic cues can pass through the thin layer, which our three studies confirmed. To contribute a new technique that improves the feel-through effect of haptic devices, we proposed & evaluated how *adding holes* to thin electrotactile. 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 critical aspect, which has been understudied, that needs to be brough to the foreground.

This work highlights the fact that a small portion of fingerpad revealed can significantly improve the tactile perception when touching physical objects, but the perception is still impaired compared to fully revealed fingerpad as shown in the studies. Is it possible to design a haptic device that can render haptics on the fingerpad, **yet it doesn't cover the fingerpad?** I will introduce an approach to push further on how devices should preserve the haptics from the real world.

Touch&Fold: a haptic actuator for rendering touch

Motivation for fingerpad free haptic devices

Augmented Reality (AR) or Mixed Reality (MR) allows overlaying digital content with our real-world surroundings, creating powerful new tools. Many argue that the next challenge of mixed reality is the addition of haptics. Over the last decades, an impressive number of haptic devices have allowed users to feel the forces (e.g., exoskeleton gloves [22, 33, 34, 70, 247]) and contacts from interacting with virtual objects (e.g., vibration on the fingerpads [46, 105, 106, 229]). However, researchers argue that haptics for MR are inherently different from haptics for virtual reality (VR), as they must leave the user's hands free so that the user can also interact with real objects [4, 16, 140, 221, 229].

Figure 15. We engineered a foldable haptic device worn on the user's fingernail that renders touch in mixed reality (MR) without preventing users from also touching real objects.

This is imperative as many powerful uses of MR involve holding tools such as for repairs [66], construction [188], or tangible interactions [69]. Therefore, haptics for MR must not impair the user's ability to feel the world through their fingerpads. Recently, researchers proposed unencumbered force-feedback in MR by using electrical muscle stimulation instead of the traditional exoskeletons [140]. However, this only provides the sense of pushing against an object and does not stimulate the sense of touching an object.

As of now, there is no device that provides users with a sense of contact at the fingerpad in MR without covering up their fingerpads. Existing approaches involve applying actuators on the fingerpads, such as thin electrodes [92, 221, 229] or soft actuators [60]. While some of these are also driven by the goal of minimal interference with the user's tactile sensation, adding these thin patches decreases one's ability to perform discriminate textured surfaces because these patches impair the tactile acuity of our fingerpads [158].

When it comes to rendering touch in MR without covering up the fingerpads, the most promising solution remains placing a vibration motor on the user's fingernail [3]. While this leaves the fingerpad free, it has two main disadvantages: it does not create pressure, and its feedback is unrealistic, as it occurs on the fingernail rather than on the fingerpad.

We tackle this challenge by engineering a foldable haptic device that provides virtual objects with haptic feedback by pressing against the user's fingerpad, yet, quickly tucking away when the user grasps real objects. Our device, depicted in Figure 15, works by unfolding a cover that wraps around and presses against the user's fingerpad. The key to its compact form factor is that the unfolding cover can be retracted and stored on top of the fingernail via a motor-driven rail. Furthermore, besides rendering the sense of touch, it also renders textures by means of a linear resonant actuator (LRA) embedded in its cover, as depicted in Figure 16.

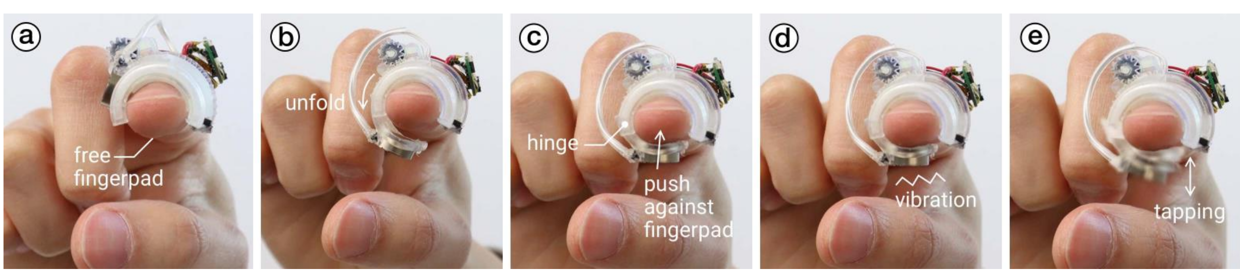

Figure 16. The mechanism of the foldable actuator.

Besides being a one-of-a-kind device for MR haptics, it is also completely *untethered* and *self-contained,* a feature not seen in any existing haptic device of this kind. In its small footprint

(24×24×41 mm and 9.5 g), it includes actuators, electronics, battery, and wireless communication through Bluetooth. We demonstrate how our device renders haptic sensations such as taps, button presses, and low- or high- frequency textures. In our first user study, we found that participants felt that our device was more realistic than our baseline (attaching a vibration actuator to the fingernail). In our second user study, we investigated the participants' experience while using our device in a real-world task that involved physical objects. We found that our device allowed participants to use the same finger to manipulate handheld tools, small objects, and even feel textures and liquids, without much hindrance to their dexterity, while feeling haptic feedback when touching MR interfaces.

System Walk-through

We demonstrate the key qualities of our device with the example of an MR application for bike repairs. Here, the user wears our nail-mounted device as well as a HoloLens 2 (Microsoft), which displays the MR content and tracks their hands via built-in depth cameras.

Keeping the user's fingers free to manipulate tools

The user cycles between interacting with the MR repair guide and working with physical tools (Figure 17a). The user taps the mid-air "next" button to reveal the instructions for removing the wheel hub nuts (Figure 17b). Immediately, our device unfolds and pushes its cover against the user's fingerpad, rendering the pressure of the contact with the MR button. Our device takes 92 ms to unfold. Then, as soon as the user's finger leaves the MR interface, the cover retracts backward, leaving the user's fingerpad free to adjust the wrench's jaw while still even wearing our device, as depicted in Figure 17c. Note this is a dexterous task, and would not be possible with existing haptic devices, as they would interfere with the user's tactile acuity and disrupt the task.

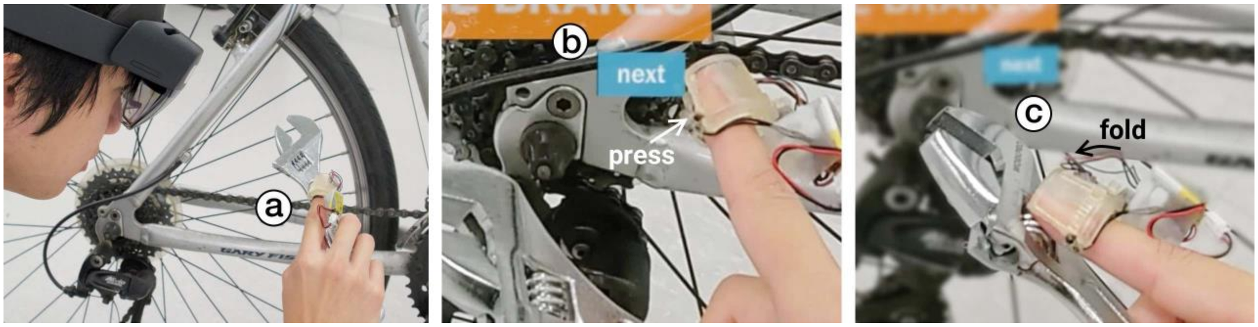

Figure 17. The user holds a wrench while wearing our haptic device for rendering the sense of buttons in the virtual instructions.

Now that the wheel has been removed, the MR guide displays two different virtual tire profiles (mountain tires vs. racing tires). The user compares their tire with the virtual tires. Our device not only keeps the user's fingerpad free to feel their actual tire's texture (Figure 18a) but also unfolds to create the textures of different virtual tires.

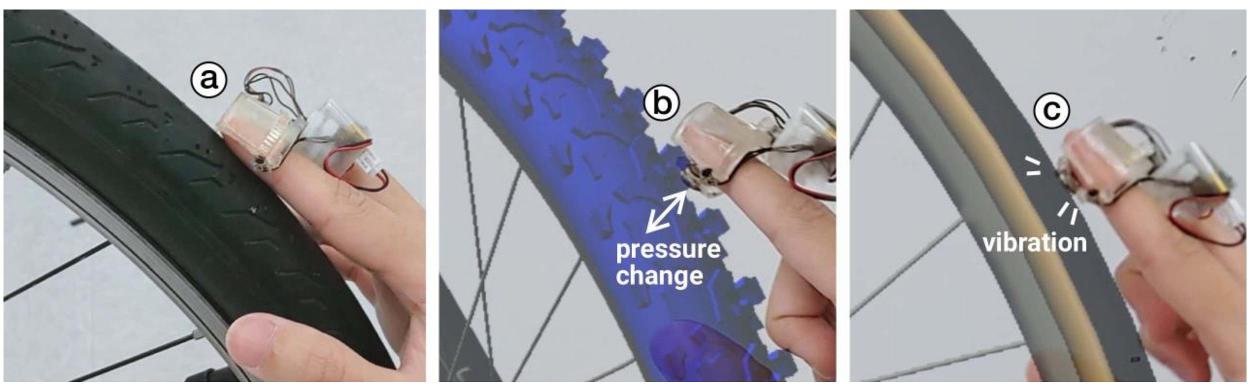

Figure 18. The user feels the texture of their real tire, the bumps of a rough virtual mountain tire, and the fine texture of a virtual racing tire.

In fact, our device renders two different textures for two different virtual tires. First, as depicted in Figure 18b, the user strokes their finger across the virtual mountain tire; our device unfolds its cover around the fingerpad and quickly rocks the cover back and forth to render the low-frequency texture of the tire bumps. Then, as depicted in Figure 18c, the user feels the profile of the virtual racing tire. Here, our device unfolds and pushes the cover against the user's fingerpad. Then, as the user strokes across the tire, the embedded vibration actuator (LRA) renders the fine, high-frequency texture typical of a racing tire.

Providing haptics to general MR widgets

After replacing the tires, the user bikes to their friend's house using the MR interface for driving directions. Figure 19a depicts the user grasping the bike's handle, while still wearing our device. When the user types in the address on a virtual keyboard, our device creates contact feedback for each keystroke by unfolding and pressing its cover against the user's fingerpad (Figure 19b). When the direction is being shown in a virtual map, the user zooms using the map's slider. Here, our device provides not only contact but also haptic detents using vibration motor to depict the different magnification levels (Figure 19c).

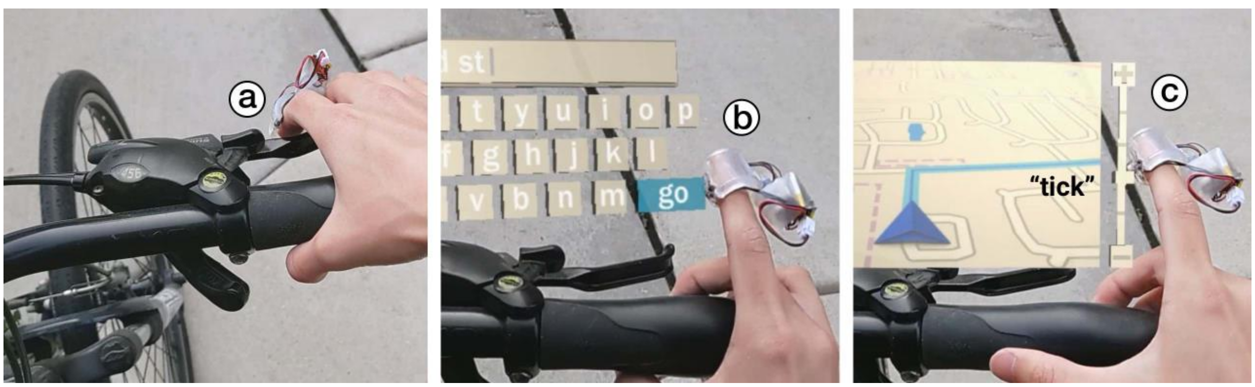

Figure 19. User grips the bike handle while wearing our device to render the clicking of the keys and haptic detents that depict the magnification levels.

Prior work on expressive haptics for the virtual and augmented worlds

Our work builds on the field of haptics; in particular, on wearable tactile haptics for virtual and mixed reality.

VR and MR demand wearable haptics

As real-walking VR increases in popularity (e.g., VIVE's lighthouse [248]), most recent advances in haptic feedback have focused on wearables. These are devices mounted onto the user's body, delivering haptic sensations anywhere. In the case of MR, this wearability requirement is paramount since most of AR devices are untethered, such as HoloLens [249], MagicLeap [250], or even smartphones [175].

Force feedback & tactile feedback in VR

Haptics devices can be categorized into two main streams: force feedback and tactile feedback [120]. While force feedback devices render the forces that arise with contacting a virtual object (e.g., feeling the weight of a virtual object [80, 173]), tactile feedback devices render the contact with the object's surface (e.g., texture [182, 215], temperature [251]). To maximize realism, researchers seek combinations of tactile and force feedback (e.g., [115, 206]).

Wearable force feedback

Wearable force feedback, especially in VR, is often provided through the means of motor-based exoskeletons [247] or ferromagnetic fluids [219]. More recently, researchers have explored alternative avenues to miniaturize these exoskeletons using smaller semi-passive actuators, such as brake mechanisms [33, 34, 56, 70], or pulley mechanisms that provide force feedback to the arm [203] or fingertips [45, 211]. Pseudo-force feedback was proposed as an alternative [2]. On the other hand, electrical muscle stimulation (EMS), which bypasses motors entirely and directly stimulates the user's muscles [134], has been used to enable a smaller hardware footprint for force feedback in both VR [138] and AR [140].

Wearable tactile feedback

Wearable tactile feedback is typically achieved by attaching vibration motors to the user's body, most commonly on the fingerpads [252]. Vibration was used to emulate textures [189], compliance [107], or even to create force illusions [166]. The advantage of vibrotactile devices is that the actuators are small and thus wearable. The typical vibrotactile device takes the shape of a "haptic glove", typically containing multiple vibration motors underneath each fingerpad [252].

However, feeling a vibration is different from feeling pressure [118, 137]. Pressure triggers the Merkel cells, while vibrations mainly activate Pacinian corpuscles [118]. As such, when prioritizing haptic realism over form factor, researchers opt for devices that generate the sense of pressure at the user's fingerpad. Examples of this include: Schorr et al.'s finger-mounted and motor-based device, which creates pressure in 3DOF [178]; *HapCube*, a finger mounted device that renders stiffness, friction, and pressure by deforming the skin surface [106]; *FinGAR*, a finger glove device that renders pressure, low- and high- frequency vibration, and shear forces using mechanical actuation and electrical stimulation [229]; and, lastly, *HapThimble*, a finger glove that emulates button presses by using a servo motor to push a pad against the finger in addition to a vibration motor [105]. A more general and thorough review of wearable tactile haptics can be found in [160].

Unfortunately, while these devices provide realistic haptic feedback (i.e., pressure and not just vibration), they are too cumbersome to use in MR as they cover the user's fingerpads, hindering the haptic sensations elicited by real-world objects. Users would have to remove these devices before they can touch a real-world object. Thus, existing tactile devices have found their use in VR but rarely in MR.

VR tactile haptic devices that avoid encumbering the hand

Because preserving user's dexterity and tactile feedback is important, researchers started turning into mechanisms that deliver haptic feedback to the user's hands without constantly covering it up. *PuPoP* is an example of such a haptic device that mounts inflatable pads into the user's hand; these pads only inflate on demand to create haptic feedback as the grabs virtual objects [199]. Similarly, *Haptic PIVOT* is a VR haptic device that leverages a similar approach but is implemented via motors; it mounts a motorized handle to the wrist, which can pivot, on demand, to touch the user's palm as they grab virtual objects [114]. However, none of these devices can target a particular fingerpad; they simply push their actuator against the user's entire hand at once.

We take inspiration from these approaches that leave the user's hand free and take a step further into leaving the user's fingerpads free. This requires engineering mechanisms much smaller and lighter than any of these hand-based feedback devices because we intend to target the fingerpad itself and not the hand.

Tactile haptics specifically engineered for Mixed Reality (MR)

Researchers have been exploring ways to provide haptic feedback without obstructing the fingerpads for MR. Arguably, the most MR-ready device is the fingernail vibration by Ando et al. [3, 5]. In their approach, a vibration motor mounted on the fingernail augments touches on virtual objects. While this device keeps the fingerpads absolutely free, it has two main limitations: it does not generate pressure (only vibrations), and its tactile feedback happens at the fingernail instead of at the fingerpad, which can lead to unrealistic sensations due to the spatial incongruence.

Another popular approach is to use thin actuators that, while still covering the fingerpad, try to minimize this interference. Examples include: *Haptic ring*, a device that squeezes the fingerpad by pulling wires wrapped around it [7]; *Tacttoo*, a device comprised of a thin electrode sheet on the fingerpad and a stimulator at the wrist, which electrically stimulates the fingerpad [221]; or *HydroRing*, a finger-worn liquid chamber and a wearable pump, which creates pressure, vibration, and temperature on the finger using hydraulics [60].

Unfortunately, while using the aforementioned devices, the user still feels these thin actuators (e.g., wires, electrodes, etc.) every time they touch a real object, impacting their sensation of textured surfaces [158]. Furthermore, with thin actuators, the resulting haptic feedback is mostly limited to vibrations (e.g., [221]) or small contact areas (e.g., [7]). Unlike these approaches, we propose the first tactile device capable of rendering both pressure and vibration, that can also tuck away when the user is interacting with real objects.

Key contributions and limitations

Our key contribution is engineering the first foldable actuator that can provide the missing tactile haptics of mixed reality, while also being able to tuck away to let the user still interact with real objects. The key technical insight that enables this unencumbered feedback is our compact folding mechanism.

Our approach has four benefits. (1) It provides on-demand haptic feedback to the user's fingerpad, i.e., the fingerpad remains unobstructed when the user is not interacting with virtual objects. (2) Its tactile feedback is realistic as it combines pressure with vibrations, thus rendering a wide range of sensations such as contacts, mechanisms, and textures. (3) Our device is untethered and self-contained, fitting entirely around the user's fingernail. In contrast, most haptic devices of this kind require cables running from the user's hand to external power supplies, circuitry, pumps, etc. Lastly, (4) not only is the hardware footprint optimized for mixed reality by using only surface mounted electronics, but its encasing was printed in clear materials to minimize visual interference. Furthermore, as we will show later, other actuators (e.g., such as a heating Peltier element) can also be integrated into our device, allowing an even wider range of haptic sensations.

Our device is not without its limitations: (1) while we optimized its footprint, it still covers up the user's fingernail, and obstructs the side of the fingertip at certain angles; (2) while we fabricated it to fit the average adult finger [40], it might need adjusting for different finger sizes; lastly, (3) as with any mechanical haptic device, it has its inherent latency (92ms), which we currently compensate by enlarging the collision detector volumes in our MR applications.

Implementation

To help readers replicate our design, we now provide the necessary technical details. Furthermore, to accelerate replication, we provide all the source code, 3D files, firmware, and schematics of our implementation[1].

Figure 20 depicts our self-contained prototype, which was 3D printed using a Form Labs 3 with clear resin to minimize visual interference with the real world. Its complete footprint is 24×24×41 mm and weighs 9.5 g, including its battery. It attaches to the user's fingernail using double-sided tape.

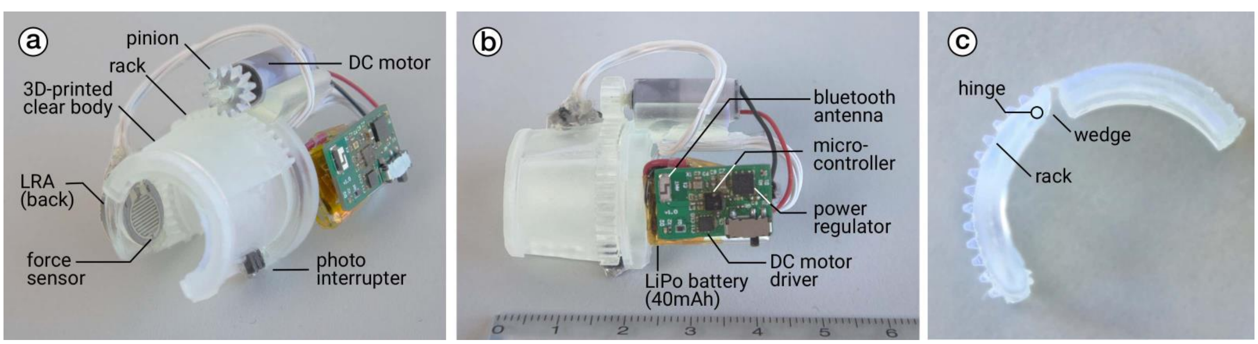

Figure 20. Our self-contained haptic device (ruler unit in cm).

[1] http://lab.plopes.org/#touchfold

Folding Mechanism

At the core of our contribution is our folding mechanism, depicted in Figure 21. Its key design feature is a hemispheric rail from which our “cover” unfolds. Once extended, the cover presses against the user’s fingerpad.

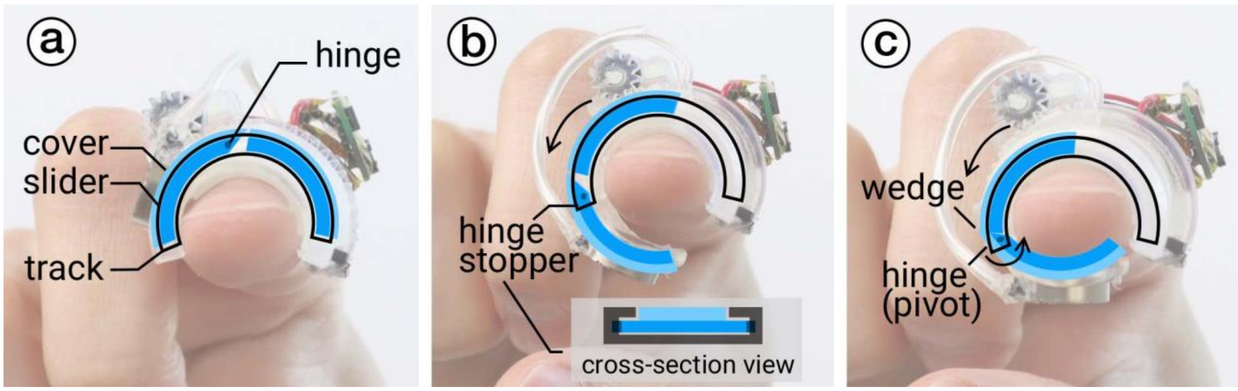

Figure 21. Our unfolding mechanism.

The cover is comprised of two segments connected via a thin plastic sheet. To fold or unfold, we actuate the cover using a rack and pinion drive. Figure 21a depicts the initial configuration, in which the cover’s front segment stays in the case. Figure 21b depicts the cover’s front segment is pushed as it is driven by the pinion to the point where the front segment is fully extended and hits a hinge stopper at the end of the rail. Figure 21c depicts the last stage in which a wedge in the cover pushes and causes the front segment to pivot around the hinge and land flush against the fingerpad. The shape of our casing, cover and its hemispherical rail are all conical in order to ergonomically follow the finger’s shape, allowing the cover to fully contact with the fingerpad.

Actuation: pressure and vibration

Our device unfolds using a DC motor (26:1 Sub-Micro Planetary Gearmotor 0.1 kg-cm, Pololu) mounted on our 3D printed rail drive (rack with 26 teeth and pinion with 12 teeth).

To increase the expressivity of our device, we embedded a linear resonant actuator (LRA C10-100, Precision Micro Drives) in the cover that touches the user’s finger. Our LRA renders high-frequency textures, allowing our device to render both contact pressure and a wider range of textures. We drive our LRA using a MOSFET between 150-190 Hz; its resonant frequency is at 170Hz.

Lastly, a force sensor (FSR 400, Interlink Electronics) and a photo interrupter (SG-105F, Kodenshi) close the control loop by acting as limit switches. The force sensor also doubles as a feedback signal for fine-tuning the amount of pressure applied on the fingerpad. Thus, our device not only creates pressure but also constantly measures the applied force, which we demonstrate next in a brief technical evaluation. Finally, we used the photo interrupter to sense whenever the cover is fully retracted, which serves as the signal to stop actuating our DC motor.

Measuring speed, force & noise

We further characterized our device by measuring its speed, haptic force, and noise level.

Latency: The mechanism takes 92 ms to actuate, which is measured using slow motion camera (240 fps). This relatively fast speed allows us to create low-frequency vibrations by driving our motor back and forth when already in contact with the fingerpad. We measured the Bluetooth communication latency using the same method to be 40 ms.

Force: We measured force using a load cell with error of 9.8×10^{-5} N, with our device clamped on a 3D printed support. When unfolded, it creates a sustained force of 0.34 N against the user's fingerpad, with a short overshoot peak of 0.41N before the force stabilizes.

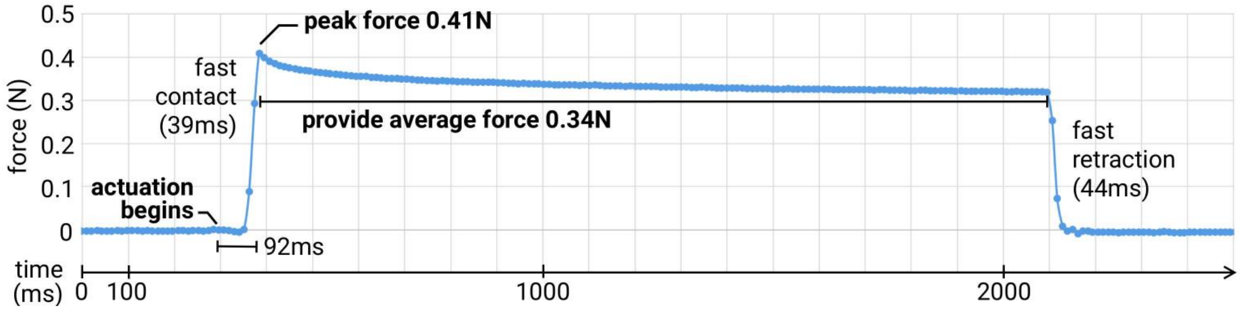

Figure 22. Plot of forces generated by our device.

Operational noise: We measured its operational noise using a microphone. Our mechanics are quiet, producing around 22.25 RMS dB when unfolding. This measurement was recorded at arm's length from the device and in reference to a quiet background. As reference, a clap is 65.01 RMS dB in this recording setup.

Measuring contact area

A relevant factor in haptic perception is the contact between the actuator and the user's fingerpad. As such, we set out to measure the contact area that our device makes with a finger. To measure this, we constructed a simple artificial finger made from a rigid portion (using PLA, which emulates the nail) and a soft portion (using Ecoflex 00-30), depicted in Figure 23a. Then, we attached our device to the artificial finger and coated our device's cover (the part that contacts the finger) with washable red ink. This is a typical method used to determine contact between fingerpads and haptic actuators employed, for instance, by Hauser et al. [64]. Then, we actuated our device so that it contacts the artificial finger and leaves an ink imprint, which we depict in Figure 23b. Our result shows that, as expected, our device makes stable contact with the finger at its center, which is ideal as the vibration motor is placed in that location. However, we also observed some unwanted side, yet much smaller, contact caused by the unfolding mechanism's rail.

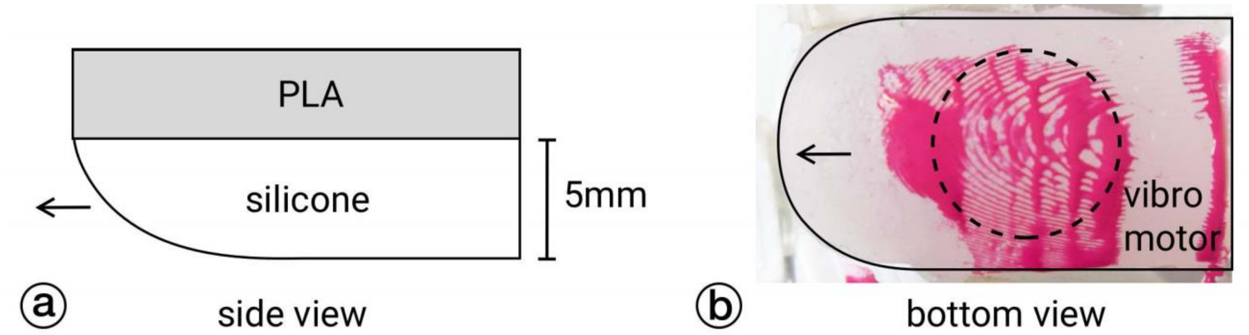

Figure 23. Ink contact test (arrows point to the fingertip).

Electronics: printed circuit board and schematics

Figure 24 depicts the electronics schematic of our device. Our 16.8x10.3 mm PCB houses at its core a microcontroller with Bluetooth Low Energy (nRF52811, Nordic Semiconductor). To decrease its footprint, we used a ceramic chip antenna (W3008C, Pulse Larsen), instead of the traditional zig-zag PCB antennas.

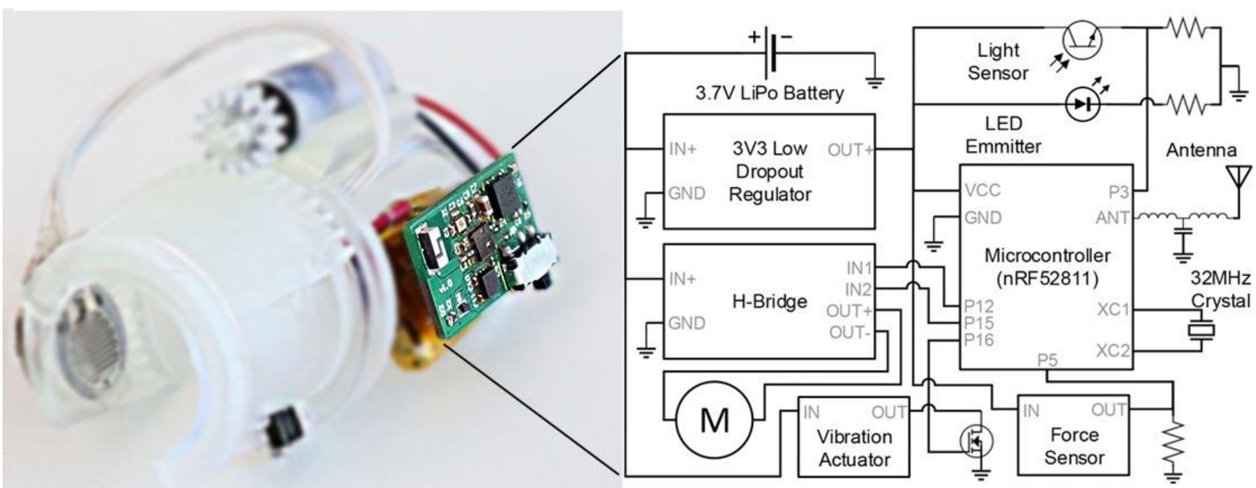

Figure 24. Electronics schematic of our PCB.

We power our device using a 40 mAh LiPo battery. We measured a current of 200 mA when it unfolds, which takes 184 ms per interaction. As such, our device can be used for 12 min of continuous tactile feedback. It is worth noting that in typical interactions with MR interfaces one just expects to feel a few hundred milliseconds of contact (e.g., tapping a button), thus our device's battery tends to last for many hours of on-demand use.

Rendering four haptic sensations

To enable a range of haptic sensations, we control the actuation profiles of both the rack & pinion (pressure) and of the linear resonant actuator (texture) as follows:

1. **Simple surface contacts**. To render touches with virtual surfaces, we unfold the actuator until the force sensor reports contact with the fingerpad. Then, the mechanism keeps pushing at a predetermined speed while the finger remains in contact with the virtual object.

2. **Mechanisms (e.g., a button's spring)**. To render mechanisms with variable force, we unfold the mechanism until force sensor detects contact. As the user presses further down on the virtual button, the device pushes the unfolded cover even harder against the fingerpad to simulate the counterforce of the button's spring.

3. **Low-frequency textures (e.g., corrugated paper)**. To render textures up to 25 Hz, we unfold the mechanism until there is contact with the fingerpad. Then, we drive the cover up and down, against the fingerpad as the user runs across their finger on the virtual textured surface.

4. **High-frequency textures (e.g., sand paper)**. To render textures from 150-190 Hz, we first unfold the mechanism until there is contact with the fingerpad. We then drive the LRA at the desired frequency to render the actual texture as the user runs across their finger on the virtual textured surface.

Tracking and Display

To display the graphics to the user, we used a HoloLens 2. Built-in depth cameras on the headset are used to track their hands. We unfold our device to tap the user's fingerpad only when the finger collides with a virtual object. Then, whenever the user's finger leaves the virtual object's collider (the "touch" area programmed in our Unity3D demos), we immediately retract the cover back onto the fingernail to leave the user's fingerpad free. We implemented this strategy as it is ideal for MR, since it prioritizes real-world interactions over virtual interactions. To trigger our device when the user touches an MR object, we expand the finger's collision box in Unity3D to the radius of our device, which further compensates for its aforementioned latency. While we utilized the built-in tracking from a HoloLens 2 headset, our system can also be paired with alternative tracking systems, such as the proximity sensors or optical motion capture.

Demo applications

To illustrate the key benefits that our device offers to mixed reality, we implemented three additional demos beyond the bike repair guide, which was previously shown in Figures 3-5. Our demos were built in Unity3D and displayed using two MR headsets (Project North Star & HoloLens 2), which were connected to our device via Bluetooth.

Application#1: feeling on-body interfaces

This application depicts how our foldable haptic actuator does not interfere with the haptic sensations elicited by touching an on-body interface. Figure 25 shows an interface displaying physiological data (steps, temperature, and heart rate from health trackers) projected onto the user's non-dominant arm; this was inspired by popular MR interface designs, such as TapTap [10] or HoverUI [243]. Here, our foldable haptic actuator allows the user to *feel their skin* when tapping on the interface projected on their arm as well as feeling haptic feedback when touching midair interfaces.

Figure 25. Our quantified-self MR application.

Application#2: feeling haptic transitions between physical and virtual

We depict how our foldable haptic actuator allows to render surface contact and texture even as the user transitions between physical-virtual objects, or vice versa. To demonstrate this, we implemented a simple MR furniture editor inspired by [130, 140]. Figure 26 depicts a user transitioning between *feeling their real table* to feeling the texture and contact of the table's virtual extension.

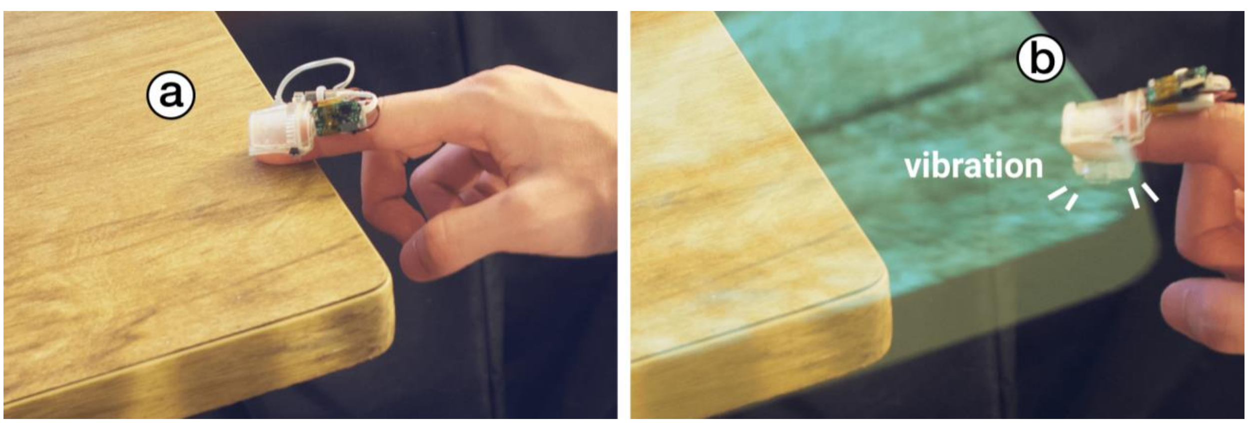

Figure 26. In our interior design application.

Application #3: enabling multi-finger haptic feedback that does not occlude fingerpads

To render the feeling of contacting with more complex objects, which typically requires multiple fingers, the user can *wear two (or more) of our devices.* Figure 27a depicts how, while the user is cooking, our two devices leave the fingerpads free, allowing the user to rotate the physical knob on their stove to turn on the gas. Then, as depicted in Figure 27b, the user sets the MR kitchen timer to five minutes. When the user grasps the timer knob using their index finger and thumb, both of our devices unfold and press the fingerpads to create the sensation of contact. Also, our device creates vibrations to render the timer knob's detents.

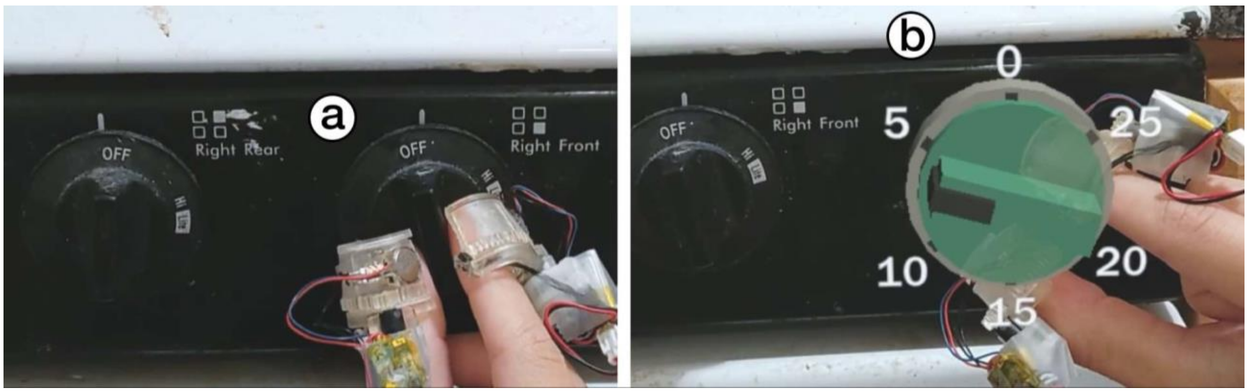

Figure 27. A user wearing two of our foldable haptic actuators to interact with a MR kitchen-timer.

Generalizing by adding haptics to existing MR toolkits

Finally, we generalize the usage of our haptic actuator to existing MR toolkits. In this case, we add it to the HoloLens Mixed Reality toolkit (MRTK). As depicted in Figure 28, we add the missing haptics to MRTK demos (from the Hand Interaction package [253]). Here, contact haptic feedback is rendered when the user presses any widget, such as buttons (Figure 28a) or even piano keys (Figure 28b). Furthermore, by wearing two of our devices, we also render contact haptic feedback for pinching (Figure 28c) or grabbing virtual objects (Figure 28d).

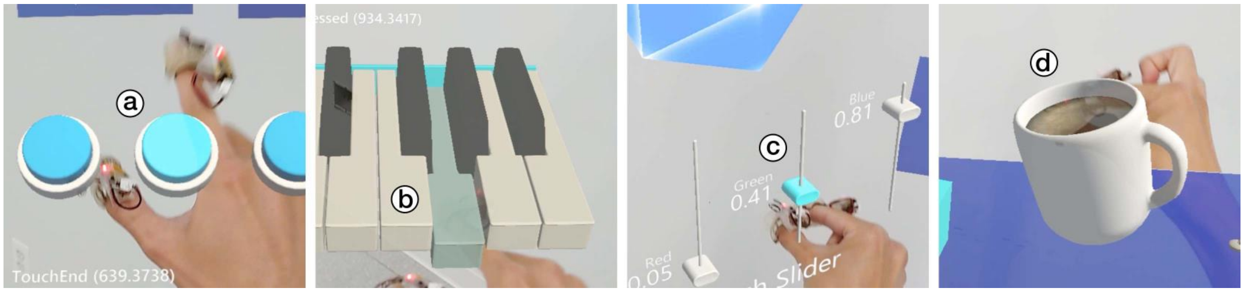

Figure 28. Adding contact haptic feedback to GUI widgets in existing Microsoft HoloLens Mixed Reality Toolkit (MRTK).

User study #1: Haptic feedback

The objective of our first study was to validate our device's ability to render touch in MR without encumbering the user's finger. Therefore, we compared it to fingernail vibration (inspired by [3]), which is the most relevant haptic device specifically designed to not obstruct the fingerpad. Our hypothesis was that touching MR objects with our device would feel more realistic than with the baseline device, since our device provides not only vibration but also pressure. Our study was approved by our ethics committee (IRB20-0276).

Apparatus

Participants wore a North Star headset [254]. We used the headset's depth camera for finger tracking. Our Unity3D application provided a simple MR environment that included one interactive object at each time.

Conditions

Participants were asked to touch these objects in two conditions: (1) a USB version of our **foldable actuator**, which bypassed its Bluetooth communication, and (2) **fingernail vibration**, by means of an LRA at 170Hz firmly attached to the participants' fingernails. Condition order was counterbalanced across participants.

Tasks

Participants were asked to touch five different mid-air virtual objects rendered in MR, which visually resembled a slab of concrete, cloth, a button, corrugated paper, and sandpaper (Figure 29). For the slab and cloth, participants were instructed to touch on the surface. For the button, participants were told to press it. For the corrugated paper and sandpaper, participants were told to run their finger across the object's surface.

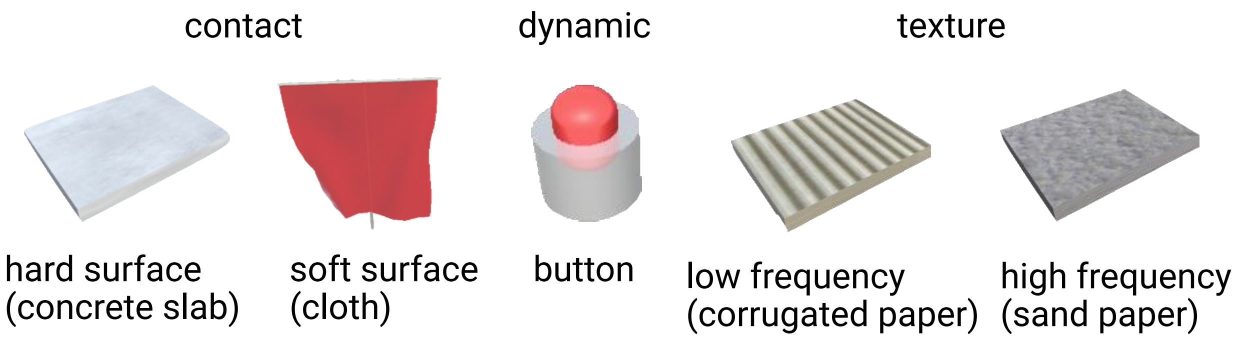

Figure 29. The five MR objects presented in our study

After touching an object with either our device or the baseline, participants were asked to rate the perceived realism of the haptic feedback on a 7-point Likert scale, ranging from 1="felt artificial" to 7="felt real".

Participants performed a total of 30 trials: 3 repetitions × 5 objects × 2 conditions. Trials were presented in randomized order. At the end of the study, we asked participants which interface condition they preferred.

Participants

We recruited 10 participants from our institution (M=25.6 years old, SD=2.2; seven identified as female, three as male). Four participants had previously experienced MR, but none with haptics. Participants were compensated with 10 USD for their time.

Results

Our main findings are depicted in Figure 30. We analyzed our data using two-way repeated measured ANOVA. We found significant difference in average yield by both conditions (**foldable actuator** and **fingernail vibration**, $F(1)=164.51$, $p<.001$) and virtual objects ($F(4)=83.9$, $p<.001$). We also found a significant difference in interaction of these terms ($F(4)=69.1$, $p<.001$). Thus, pair-wise Tukey multiple comparisons were conducted.

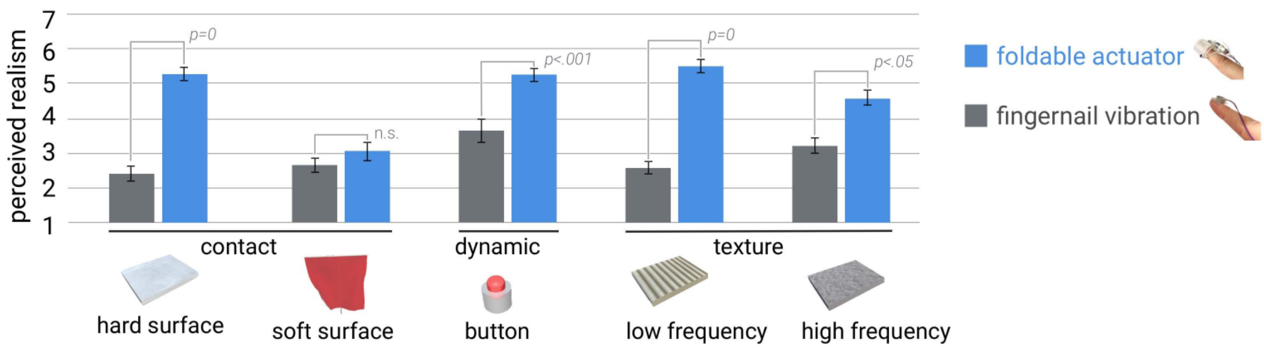

Figure 30. Participants' perceived realism in both conditions.

We present our findings regarding perceived realism while interacting with each object in both conditions:

1. **Hard surface**: We found a statistically significant difference between conditions ($p=0$): **foldable actuator** was perceived as more realistic (M=5.27, SE=0.20) than **fingernail vibration** (M=2.4, SE=0.21).

2. **Soft surface**: No significant difference was found in between conditions ($p>.5$), while comparing **foldable actuator** (M=3.03, SE=0.26) to **fingernail vibration** (M=2.63, SE=0.21).

3. **Button**: We found a statistically significant difference between conditions ($p<.001$): **foldable actuator** was perceived as more realistic (M=5.23, SE=0.20) than **fingernail vibration** (M=3.63, SE=0.33).

4. **Low-frequency texture**: We found a statistically significant difference between conditions (p=0): **foldable actuator** was perceived as more realistic (M=5.5, SE=0.19) than **fingernail vibration** (M=2.57, SE=0.18).

5. **High-frequency texture**: We found a statistically significant difference between conditions (p<.05). Participants perceived our **foldable actuator** to be more realistic (M=4.57, SE=0.21) than **fingernail vibration** (M=3.2, SE=0.22).

Figure 31 shows participants' preferred interface for interacting with each of our MR objects: all 10 participants preferred the **foldable actuator** for hard surfaces; preferences were split regarding soft surfaces, with half of the participants preferring the **foldable actuator**; eight participants (out of 10) preferred the **foldable actuator** for buttons; and, lastly, all 10 participants preferred **foldable actuator** for both high- and low-frequency textures.

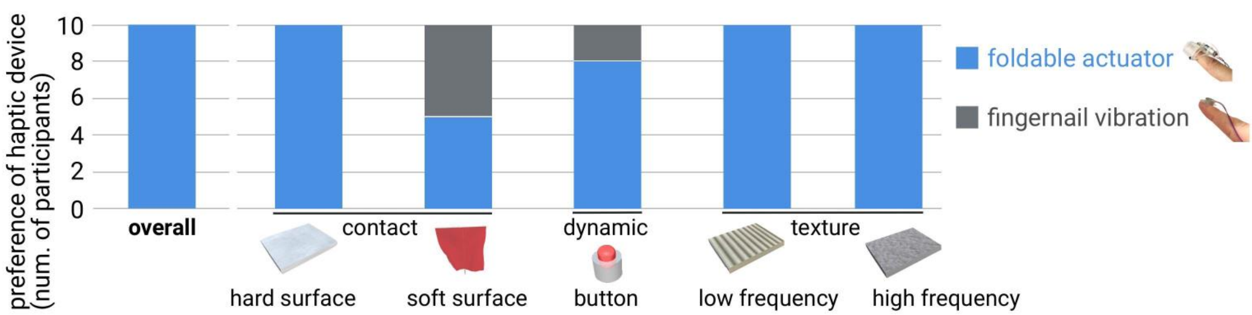

Figure 31. Participants' preferred interface for each MR object.

Qualitative feedback

When asked about their experience, all participants mentioned that using the **fingernail vibration** felt unrealistic as sensations did not arise at the fingerpad. For example, P9 stated "very obvious it's the nail" and P2 added "nothing is felt with my fingerpad". Furthermore, P10 and P7 commented on their perception: "vibration [alone] is weird for simulating touch" (P10) and "it feels real having something covering my fingerpad" (P7).

Interacting with the soft surface using our **foldable actuator** led to a haptic mismatch, as some participants perceived it as “too hard” or “too strong” (P1, P6, P8, P9), or unrealistic due to the fact that our “[pad] is solid” (P2). P4 added that “both [interfaces] are not good [for feeling the cloth]”. P3 explained their preference for the **fingernail vibration** by stating that “[its] vibration is lighter”.

When asked about the button, participants had varied expectations of the button’s feedback. Some consider vibration more important than pressure: “I expect buttons to have vibrations like [a] rusty spring” (P3, and similarly P4), while others believed pressure added realism as it related to “pressing something with force” (P5). Lastly, P4 added, “they are both suitable for [simulating] a button”.

Many participants commented that the **foldable actuator** was more realistic for textures (P7, P8, P1, P6). P1 explained that they “can feel the curves on the cardboard” and P6 stated that “first feeling contact with a surface and then feel the texture makes more sense”.

When asked if they felt any movement from the deployment of the **foldable actuator**, all participants reported to not have felt any motion artifacts. P2 and P8 commented that this could have been caused by the fact that “[they] were so focused on the objects”. P6 added that they might have felt some directional pressure, but that “the feeling became unnoticeable the longer I touched”.

User study #2: Interacting with real-world objects and virtual interfaces

The objective of our second study was to understand the user experience of using our foldable actuator when engaged in a task that involved both real-world objects and virtual interfaces. Specifically, we wanted to interview participants regarding how our device preserves or encumbers the haptic feedback of the real world.

We asked participants to perform a physical repair task by following instructions depicted in Mixed Reality, which they browsed by touching the MR interface while wearing our device. This study was designed to test using our device in conjunction with manipulating virtual interfaces alongside handheld tools (e.g., screwdrivers) and even oily parts, all of which require significant dexterity and unimpaired tactile acuity.

Apparatus

Participants wore our foldable actuator on the index finger of their dominant hand and a HoloLens 2 MR headset. We used the headset's depth camera for finger tracking. Our Unity3D application provided a simple MR interactive guide with repair instructions. We also provided participants with real objects, including two pairs of bicycle V-brakes (detached from the bicycle), a screwdriver, and a bottle of lubricant.

Task design

Participants were asked to "fix the brakes by following the MR instructions". These instructions we comprised of a step-by-step guide, depicted in Figure 32a. To navigate the next instruction, participants tapped on the mid-air graphics displayed by the HoloLens. For instance, tapping "next" to proceed to the next step. Every single interaction with the MR interfaces was accompanied by haptic feedback rendered by our device.

The experimental task involved five steps: (1) find out which brake pad needs to be replaced by feeling for any scratches on its surface; (2) unscrew the brake pad using the screwdriver; (3) screw a new brake pad onto the V-brake by holding and turning the nut using the fingers; (4) find the oily part on the bicycle brake, (5) put more oil on the part using the plastic oil bottle. All together, these sub-tasks account for three interaction types: (1) feeling *textures* (scratches on brake pad and oil); (2) using *handheld tools* (screwdriver and bottle); and (3) manipulating *small objects* (screwing the nut).

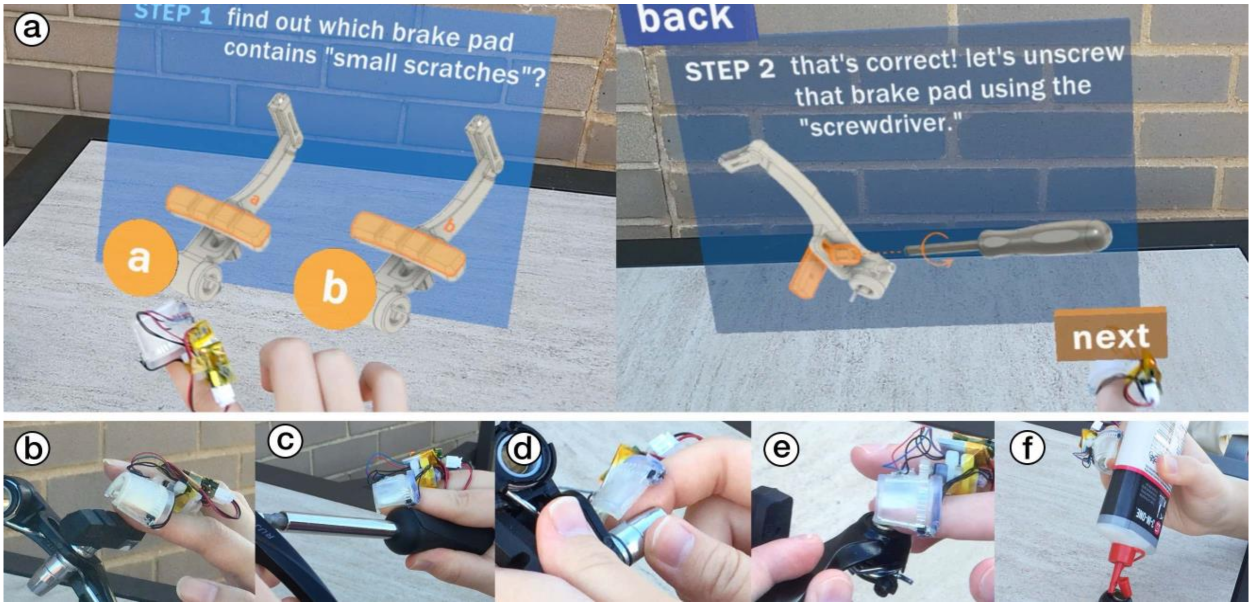

Figure 32. The participants' interactions in the study. All shots were taken during the task in user study.

Prior to starting the task, we encouraged participants to "think aloud". We recorded participants by means of the HoloLens camera, which overlays also the MR content and via an external camera. After the task was completed, we conducted a semi-structured interview with each participant.

Participants

We recruited seven participants from our institution (M=25.6 years old, SD=3.5; four identified as female, three as male). Four participants had previously experienced an MR headset but not in conjunction with haptics. Participants were compensated with 20 USD for their time.

Qualitative feedback

We present participants' feedback organized by the three types of interaction in our task: (1) feeling *textures* (scratches on brake pad and oil); (2) using *handheld tools* (screwdriver and bottle);

and, (3) manipulating *small objects* (screw). Lastly, we also present overall comments about the experience.

Feeling textures (brake pads & oily part). First, we asked the participants how they distinguished between the two brake pads. All but one participant (P3) mentioned that they could not visually distinguish the brakes, so they explored them by touching with their finger, which was instrumented with our device. For instance, P1 added "I looked at them [the brake pads]. They are both black and it's hard to distinguish. So I use my fingerpad to feel." While it is unsurprising that most participants used their index finger (we purposely added our device on their dominant index finger to create this situation), we observed that most participants did not perceive any impediment caused by our device in feeling the brake pad's texture. For instance, P2, P6 and P4 added explicitly "[the device] did not impede anything." (P2 and similarly P4). Only P5 and P7 felt the device during this interaction. P7 still used the index finger to complete the task but mentioned that "I worried [the device] would fall". P5 was the only participant that did not use the index finger for this task, remarking "I avoid using index finger because [of the device]".

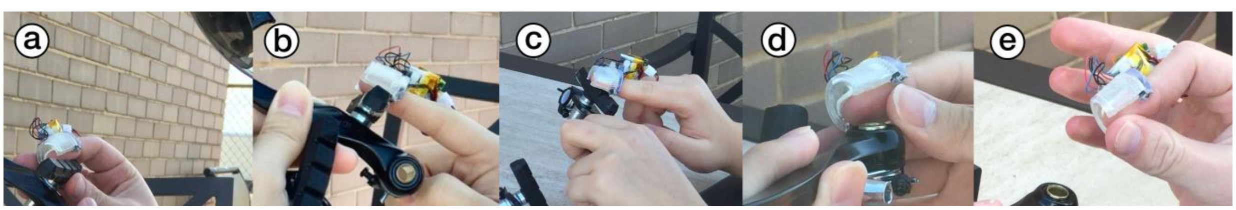

Figure 33. Examples of participants' interactions.

Next, we asked participants about their experience while feeling which part was oily. All participants mentioned that they did not feel any impediment from our device while feeling the oily part. The majority (six out of seven) used the index finger that was wearing our device and stated, for example, "No, it did not affect me at all, I could feel the oil easily" (P6, but also similarly

P1, P2, P4, P5, P7). All participants used multiple fingers to feel the oily part. Only P3 did not use the index finger that wore our device for feeling the oil but remarked that "I did not think of it, I find it more convenient to feel that with [my] thumb". P4 and P6 even rubbed their index finger and thumb to feel the friction while determining if it was oily (Figure 33e).

Using handheld tools (screwdriver and lubricant bottle). First, we asked participants about their experience while manipulating the screwdriver, which requires dexterity from any finger that grips. All participants turned the screwdriver while wearing our device, most of them stating they felt no impediment. For instance, "The device did not affect me when turning the screwdriver." (P2) or "I didn't even notice the device when I started turning the screwdriver." (P1). P3 mentioned that they felt that "the sides of the device seem to touch the screwdriver" and we observed them adjusting their index finger angle on the grip. P5 added "It worked well! [I] grip it properly [and] it feels fine", adding later, "I can very easily become used to it". P6 noticed that they raised the index finger unconsciously, but put the finger back on the screwdriver handle when they need to apply more force, as depicted in Figure 34c.

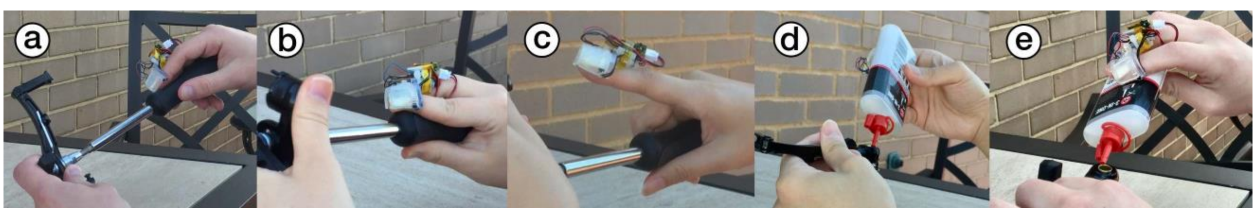

Figure 34. Examples of participants' interactions.

Next, we asked participants about their experience while manipulating the lubricant bottle, which requires a controlled force to squeeze the right amount of liquid. Six participants out of seven used the index finger that wore our device to squeeze the bottle (usually alongside other fingers as depicted in Figure 34d,e), only P3 added that they unconsciously did not use that finger at all. From the six that used the finger wearing our device, five reported that the device did not interfere with manipulating the bottle in any way. For instance, “ [I] Grip with all fingers without problems (P6) or " it felt smooth when I did the task." (P4). P6 and P7 even added that they felt that the device did not interfere with their force control, adding "I slightly squeezed the bottle with my finger." (P6) and "I squeezed with all my fingers slightly without impediment" (P7). Only P2 reflected on a possible impediment, " I noticed that I sometimes unconsciously raised my index finger. I guess I was just not used to it. It was a bit like bandage, so I intuitively didn't want to use that [finger]".

Manipulating a small object (manually tightening the nut). We asked participants about their experiencing while tightening the small nut by hand, which requires dexterity from any finger that grips it. All seven participants performed the task using the finger that the device was attached to. Five out of seven reported no difficulties nor that the device got in the way. For instance, "The device did not get in the way." (P1) or "Not interfering with my grip." (P5). Only P2 and P4 noted some interference in this task. P2 noted "Because the place to screw is small, I was worried to hit the fingernail device when turning the nut.", and P4 added "Sometimes the device touched the brake".

Haptics while touching the MR repair guide. All participants said they always felt the haptic feedback, which our device rendered using its unfolding mechanism, when tapping any virtual interface, such as “next” or “back” buttons. Unprompted, three participants added that it felt “pretty satisfying [to get tactile feedback in MR]” (P6, similarly P1) and “felt natural” (also P6).

General feedback. Lastly, we let participants add any open-ended feedback they felt was important. P4 added "Overall, it doesn't affect touching things. But the shell sometimes gets in contact with things." P5 added "With more task I might get used to it". P3 added “I am not used to wearing anything when doing precision tasks.". P3 also had a larger fingerpad than most users, and we noted that our device was not custom fit for any user.

Discussion

Limitations of our foldable actuator

First, our device still covers up the user's fingernail, and obstructs the side of the fingertip at certain angles. However, in our second user study, we found little perceived impediment for users manipulating and feeling physical objects.

Second, while our device provides pressure with a slightly tilted angle due to the compact mechanism design, only one out of our 17 participants realized that. Moreover, as any foldable actuator moves, it creates inertia, which could generate unwanted tactile perception. However, our participants never mentioned perceiving inertial forces; this was likely due to our lightweight cover (3g). Also, as noted in Figure 22, we found that our mechanical design resulted in an overshoot of <0.1 N when contacting the fingerpad. One potential way to mitigate the overshoot would be to add a PID controller.

Third, we did not find that our device was able to realistically simulate a soft surface, which was achieved by stopping the DC motor as soon as the force sensor detected a contact with the fingerpad. A more refined approach would include slowing the unfolding mechanism when the cover approaches the fingerpad, which requires a position encoder with higher resolution.

Finally, with any mechanical haptic device, it has its inherent latency (92ms), which we currently compensate by enlarging the collision detector volumes in our MR applications.

Integrating a wide range of haptic actuators

To expand the expressivity of our device, we can add more actuators to it. For instance, in Figure 35, we repurpose the LRA driver to drive thermoelectric elements (e.g., Peltier). This allows our device to render not only the contact with a hot coffee cup but also its temperature. Optionally, adding a second h-bridge would enable this Peltier element to be in either hot or cold state. Furthermore, we believe that other haptic actuators, such as electrodes [221] can be integrated into our device as well.

Figure 35: Example of integrating a Peltier element onto our foldable actuator.

Encompassing tactile sensations across the spectrum of realities

Even though we focused on rendering the sensations for virtual objects overlaid in physical environments. Our device can also work for augmenting haptic sensation when touching physical objects. This can be achieved by "not unfolding" and providing haptic augmentation by "actuating the vibration motor on the fingernail". In this scenario, the user can feel the physical objects directly with the fingerpad free, and feels the augmentation on the fingernail, at the same time. This seemly fallback mode emulates fingernail vibration by Ando et al. [3].

Altogether, our device encompasses the reality-virtuality continuum [151] of tactile sensations (Figure 36), by preserving physical haptic sensation from the real world, augmenting haptic sensation of the real world, and rendering haptic sensation of the virtual world.

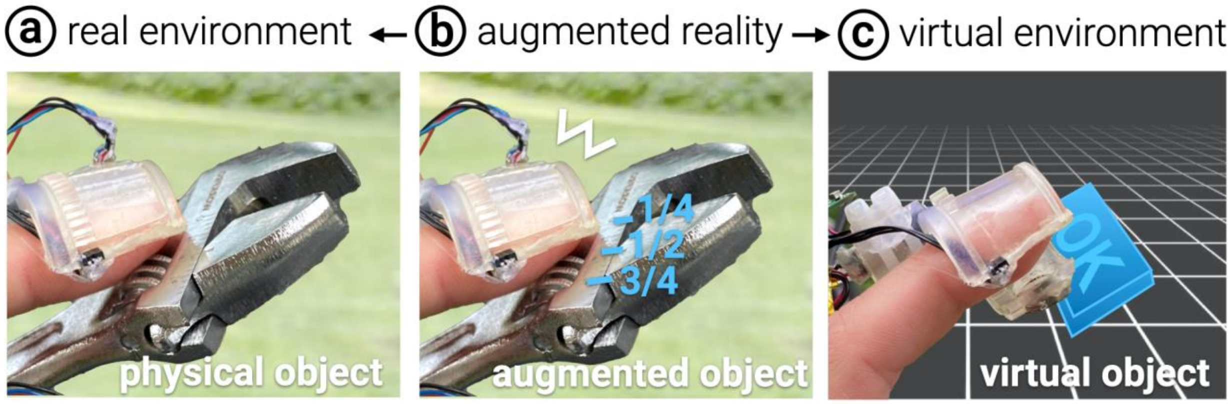

Figure 36: Our device encompasses the tactile sensations across the spectrum of realities.

Summary

We proposed the first foldable, nail-mounted haptic device that provides tactile feedback to mixed reality (MR) experiences while *quickly tucking away* when the user interacts with real-world objects. To achieve this unencumbered haptic feedback, we engineered a wireless haptic device, which measures 24×24×41mm and weighs 9.5g. Furthermore, our foldable end-effector also features a linear resonant actuator allowing it to render not only touch contacts (i.e., pressure) but also textures (i.e., vibrations). We demonstrated how our device renders contact with MR surfaces, buttons, low- and high-frequency textures. In our first user study, participants felt that our device provided a more realistic haptic experience than back-of-the-finger vibration did when interacting with a variety of objects, such as surfaces, textures, and button mechanisms, but not soft objects. In our second user study, we found that our device preserves the dexterity and haptic perception for manipulating and feeling physical objects, while providing haptic feedback for virtual interfaces, in MR.

This work marks a great difference from prior research on how haptic devices render haptics, which either cover the target body parts, e.g., fingerpads (including the previous section) or relocate the actuators, e.g., to the nail or to the wrist, and deliver haptics in another location. By making actuators foldable, haptic devices only contact “on demand”. Compared to “haptic permeability” approach, this foldable actuator does provide less spatial resolution. I envision electrotactile or other pin-based displays can be integrated in the future. The bulkiness added on the side of the finger due to the folding mechanism can impair dexterity. One can push it further by exploring slimmer materials and mechanisms.

To sum up, these approaches that I proposed preserve various kinds of real-world haptic fidelity (e.g., tactile sensitivity for touch) but also render different levels of virtual haptic fidelity (e.g., modality, bandwidth, resolution). While these approaches have room for improvement, I posit that in order to integrate more haptics into the real world for mobile and wearable interactions, developers should *balance* haptic fidelity from the virtual and the real worlds when designing haptic devices. I will discuss more in Conclusion & outlook.

Part II – Challenge: Adapting to mobile contexts

Haptic devices used for stationary VR and teleoperations are engineered as an **infrastructure** that requires sufficient space allocated, stable wall power, and communication, with the least distraction from the surroundings, and the user should only interact and experience the virtual or remote world. In contrast, in **mobile scenarios**, the context is often changing, if not rapidly. For example, we use our mobile and wearable devices hundreds of times a day, and they accompany us in diverse daily activities (e.g., working, running, cooking). Space, power, signals, and surrounding noises, which might have been presumably stable in the former case, are all subject to fluctuation. One can take an analogy from visual displays for which technologies are developed for mobile contexts, such as dropping frames for power-saving mode, adaptive colors in varying ambient lighting, etc. For haptics, studies have shown that the change in these contexts can also severely impact the haptic sensations of the user [20, 21]. In order to bring more haptic experiences anywhere, anytime, the systems must be designed to **adapt to mobile contexts**.

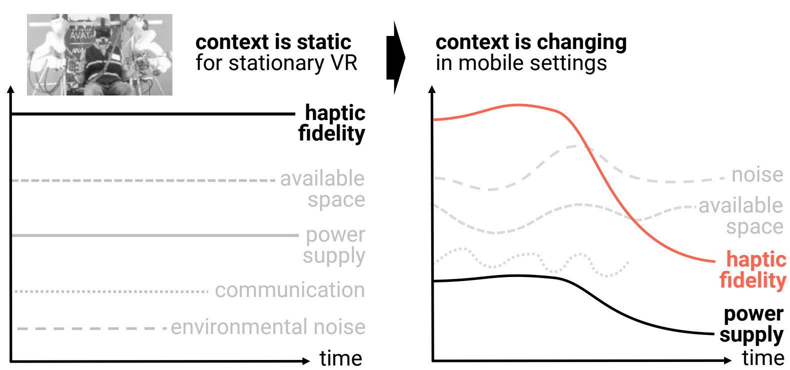

Figure 37: Contrasting context consideration for stationary VR and mobile scenarios.

Power, especially, has a great impact on haptic devices. Providing force feedback to the user (e.g., feeling how much force one should apply while using a tool) is typically realized using mechanical motors. To provide sufficient force, these motors need to be large & power-hungry (large currents convert electricity to mechanical work), which limits their use indoors and tethered to wall power if not having users carrying big batteries and only last for less than a half day (Figure 37).

As such, I explored an extreme approach—a wearable haptic system that is power-aware and can be charged in run-time using energy harvesting when needed, without sacrificing the enjoyment of the interactions [201].

Prolong haptic experiences by harvesting kinetic energy from the user

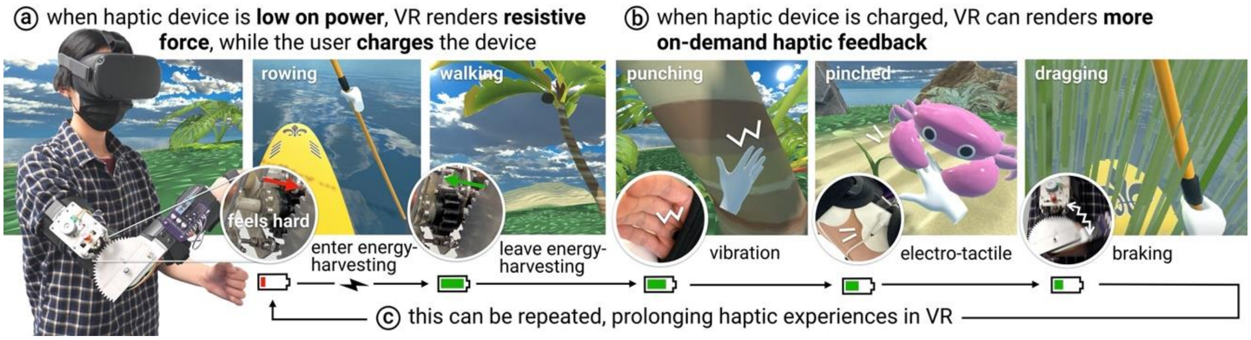

Figure 38: We propose a new technical approach to wearable haptics that requires no battery, yet it provides active haptic feedback.

Motivation for whole day haptics

In the past decades, interactive devices became mobile, moving into user's pockets and body, thanks to power-efficient computation and advances in battery technology. While sensing in devices now can be realized in a power-efficient manner [8, 68, 126, 239], output (e.g., displays or haptics) still remains a power-hungry factor in mobile devices [26, 244:5, 245]. Haptic feedback, specifically strong force-feedback, needs to push against the user to generate its effect, thus demanding even more power [35, 136, 247] (typically orders of magnitude above the power required for a sensor [239]). Therefore, most haptic devices are tethered to the powerline or require large and cumbersome batteries. While researchers have explored alternative actuators (e.g., muscle stimulation instead of mechanical motors; or brake-based actuators) for the sake of power efficiency, even these devices' batteries will likely last far less than a whole day of usage [57, 136].

We propose a new technical approach to implement untethered Virtual Reality (VR) haptic devices that contain no battery, yet can render on-demand & strong haptic feedback. The key is that via our approach, a haptic device charges itself by harvesting the user's kinetic energy (i.e., movement)—even without the user needing to realize this.

Figure 38 depicts how we achieve this: we integrate kinetic energy-harvesting directly into the virtual experience, in a *responsive manner*. For example, in our approach, whenever a batteryless haptic device is about to lose power, it switches to harvesting mode (by engaging its custom electropermanent magnetic clutch to a generator) and, simultaneously, the VR headset renders an alternative version of the current VR experience that depicts resistive forces (e.g., rowing a boat in VR). As a result, the user feels realistic haptics that corresponds to what they should be feeling in VR (i.e., it should "feel hard" to row a boat), while unknowingly charging the device via their movements. Then, once the haptic device's supercapacitors are charged (which charge/discharge much faster than traditional batteries), the device's microcontroller communicates with the VR headset. The VR experience can now use the recently harvested power to request more on-demand haptics, including vibration, electrical or mechanical force-feedback; this process can be repeated, *ad infinitum*.

We instantiated, explored, and validated a version of our concept by implementing an exoskeleton that harvests elbow movements and uses this energy to render on-demand haptic feedback intermittently, e.g., vibration, electrical & mechanical force-feedback.

We validated this via technical evaluation and a user study, in which participants (even without knowing the device was harvesting) rated a VR experience as more realistic and engaging using our device than with a baseline VR setup.

Finally, we believe our technical approach is fundamentally different from devices powered by batteries, as it affords new uses of haptics for prolonged use-cases, which are especially useful in untethered VR setups, since devices capable of haptic feedback are traditionally only reserved for situations with ample power. With our approach, a user who engages in hours-long VR and grew accustomed to finding a battery-dead haptic device that no longer works, will simply resurrect the haptic device with their movement. Moreover, our approach enables new ways to use haptic devices unthinkable for battery-powered devices today: namely, walk-up use. Even if the user forgot to charge the haptic devices or change their batteries, our technique enables these to wake up rapidly after the first interactions.

Our approach: Harvesting the user's kinetic energy to prolong VR haptics

To demonstrate our novel concept of harvesting the user's kinetic energy to prolong the lifetime of VR haptics devices, we engineered an exoskeleton worn on the user's arm that demonstrates one possible instantiation of our technical approach. This exoskeleton, depicted in Figure 38, can be charged by the user during VR even when it loses all its power. Then, it uses this harvested energy to render subsequent haptic effects. The fact that our approach is *cyclical* (the device automatically returns to harvesting *always* before losing power and always informs the VR accordingly) allows any device and VR experience built around our approach to run for *extremely long periods of time*, including being picked up after any arbitrary period of inactivity (the device will *always* switch to harvesting when power is low).

We first summarize the key technical insights that make our approach feasible: **(1) Harvest *kinetic energy* from the user**. While most intermittent-computing interactive devices typically harvest energy from the surrounding environment, such as solar, thermal, or ambient vibrations [167], these harvesting approaches are only suited to systems that operate on very low-power—in fact, most of these are sensing systems since sensors tend to require less power than their actuator counterparts (e.g., sensing a touch via capacitive sensing requires less power than delivering a haptic touch via electro-tactile stimulation or motor-based haptics). In contrast, we focus on a batteryless device designed for *strong haptic sensations* (e.g., vibration, electrical & mechanical force-feedback). Unfortunately, approaches that harvest small amounts of power do not scale to the magnitudes required for strong haptic sensations; thus, we turn to harvesting *kinetic energy from the user* as it provides a suitable power efficiency ratio [36]. **(2) Supercapacitors instead of batteries.** This is the technical insight that enables our approach to quickly charge with sufficient energy to generate strong haptic effects because, supercapacitors charge faster than batteries, and more importantly, balance energy storage with charge and discharge times. While supercapacitors do not hold as much energy as a comparably sized lithium-ion battery, they trade capacity with power density [111], which allows for fast charging/discharging speed (orders of magnitude faster than a battery of similar capacity). **(3) Conceal the harvesting in the VR experience**. Moreover, kinetic harvesting alone would pose a serious problem for VR. Since any time that such a device would try to harvest energy, users would notice the increased force required to move (resistance from moving against the harvester) and feel this as a *distraction*—this increase in resistance does not match their VR experience. Our concept solves this by adjusting the VR world to render a situation in which the user expects to feel resistance—this allows the resistance felt while harvesting to go unnoticed by the user.

Now that we, succinctly, laid out the principles (see *Technical Evaluation* as well as *Implementation* for more details) that allowed our device to render haptic feedback without a battery, we demonstrate its application in a VR example.

Walkthrough: A VR survival experience with *hours* of haptics without batteries

To help readers understand the applicability of our technical approach to achieving batteryless haptics, we demonstrate it in a VR experience that makes use of a range of haptic sensations, including tactile- and force-feedback. This VR user is wearing a device that uses our technical approach to enable non-stop haptics in their arm. The device takes the form of a forearm exoskeleton that pivots around the elbow joint. While our device has no batteries, it can harvest the user's kinetic energy into supercapacitors via a motion harvester engineered from a geared-DC motor paired with a custom-made switching clutch, which powers the VR experience' haptic effects.

At the start of this VR experience, users find themselves washed ashore on an unknown island. Their objective is to find food, water, and batteries to radio call a rescue team, as depicted in Figure 39. Note that many of these interactions could be made more immersive using two of our devices on both arms.

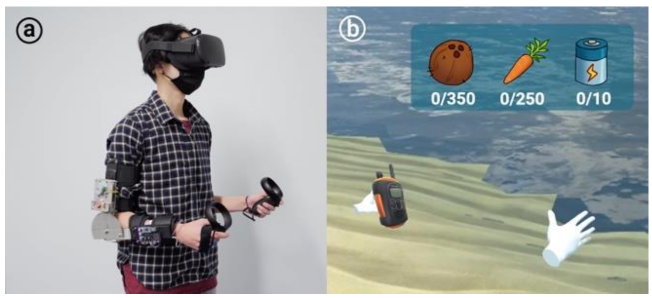

Figure 39: Our VR experience.

Bootstrapping a haptic device without any battery. As the VR experience starts, the user is stranded on a desert island. Upon starting the VR experience, the VR software attempts to contact the haptic device using Bluetooth. However, the haptic device has been idle for an unknown amount of time, potentially days, and therefore has no power. This would be a frustrating situation for existing wearable haptic devices that quickly deplete their batteries [223]. However, our batteryless device can provide non-stop haptics experiences by harvesting the user's kinetic energy on-demand. When the VR software does not receive a response from the haptic device in 300ms, it assumes the device is not charged and it is in harvesting mode, i.e., its clutch is engaged and the user's arm movements are connected to the device's high-transmission gear, which converts kinetic energy into electricity using a DC-motor and our harvesting circuitry. As such, the VR software immediately initiates the pre-programmed "harvesting" sequence depicted in

Figure 40: (a) the tide rises and the user has to swim; (b) as the user moves their arm, they *feel the resistance* of swimming in water. This resistance is caused by our harvester's gears. The user is feeling passive haptics, which is being converted into usable energy, by charging supercapacitors on board of our device. While this might appear simplistic in hindsight, it is a key contribution in our work—*dynamically changing the VR experience to coherently justify why the user is feeling the strong resistive forces* from the harvester's gears. In fact, using this insight, participants in our *User Study* did not notice that the haptic device was harvesting their energy.

Figure 40: When VR fails to connect to our batteryless haptic device, the VR assumes the device needs charging (and is in energy-harvesting mode) and renders a tide rising.

Charging on-demand = charging if haptics is needed. The VR experience can request haptic power on demand depending on events the user might encounter next, or what the designer intended the game narrative to be. For instance, if the user quickly charges the haptic device by swimming fast, the haptic device will harvest sufficient energy to boot its internal micro-controller and circuitry. At this point, the haptic device communicates via Bluetooth to the VR software and transmits its amount of internal power, sending a message with the voltage reading of its supercapacitors. If the VR software deems this to be sufficient, it can stop the harvesting and continue the narrative. Figure 41 depicts how this is achieved in our VR experience by the VR software spawning the next island (from the VR experience's pre-defined narrative) in the vicinity of the user. The user now swims to the island and the VR headset requests the haptic device to stop the resistive force. The haptic device responds by releasing its electro-magnetic clutch, which disconnects the user's arm from the harvesting gear. The user now moves their arm without any resistance and the device is fully charged and ready for delivering on-demand haptic effects.

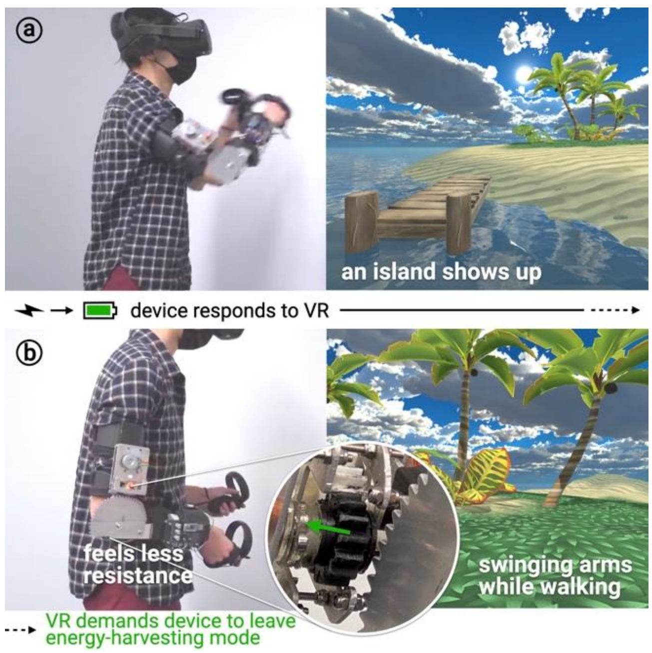

Figure 41: The haptic device is now charged and responds to the VR of its charge capacity.

Spend harvested energy on active haptics. The user now explores the island to find food, water, or batteries to survive. Now, with the charged supercapacitors, different kinds of haptic feedback can be rendered. The user finds coconut trees and bangs their fist against the tree, to make the coconuts fall. Each time they hit the tree they feel a *vibration*. This is achieved by using the energy previously harvested from the user's kinetic movements. Subsequently, the user picks up the coconut and breaks it by smashing it against a spiky rock. When they crack the coconut on the rock, our device provides a force-feedback sensation to render the impact. This is achieved by sending electrical muscle stimulation to the user's forearm muscles, which causes them to involuntarily contract.

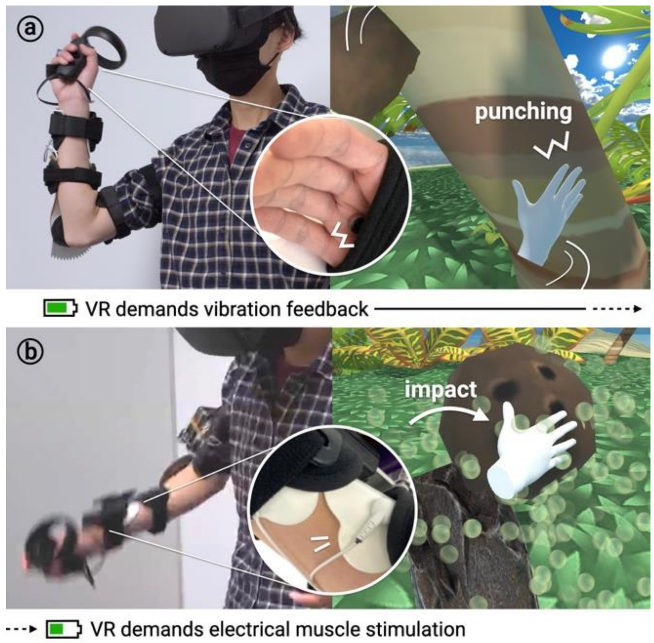

Figure 42: As the user interact with the virtual content, they feel vibrations and electrical muscle stimulation on their hand and the energy required for these haptic sensations were, unknowingly, just harvested by the user as they swam to the island.

Handling the uncertainty of user's behavior = return to charging mode. All the interactions we depicted so far are *dynamic*. In other words, if the user gets lost on the island or remains idle for a long time (or even puts down the game and returns later), the supercapacitors will slowly discharge (see *Technical Evaluation* for measurements). However, this is not a problem for our approach: the key is that VR environments are *computer-generated in real-time*, and thus are easier to alter than physical systems (e.g., less disruptive for the user's sense of immersion than stopping and swapping batteries in a haptic device). As such, if the supercapacitors discharge, our haptic device will *always* engage the clutch (returning itself to charging mode) and *always* notifies the VR software. Upon receiving this message, the VR software immediately instantiates the next available "charging" sequence, such as our "tide raises" example from Figure 40 or "shaking the crab off the user's arm" from Figure 43.

Figure 43: The device senses low power, enters energy-harvesting mode, and informs the VR, which responds by rendering a crab jumping to the user's hand.

Creating variation in harvesting experiences. Previously, when the device was about to run out of power, the VR rendered a tide that washed the user onto the sea (harvesting = swimming). However, the VR designer can incorporate more cyclical VR scenes that justify the felt harvesting resistance with more variety. In Figure 44, after exploring the island for a long time (which mostly involves "spending" energy enjoying haptic effects such as the coconuts breaking), if the device does not urgently need power, VR can instruct the user to walk to the boat where they start rowing—as the user moves their arm to row, they are now harvesting. More power can be used when they explore the next island.

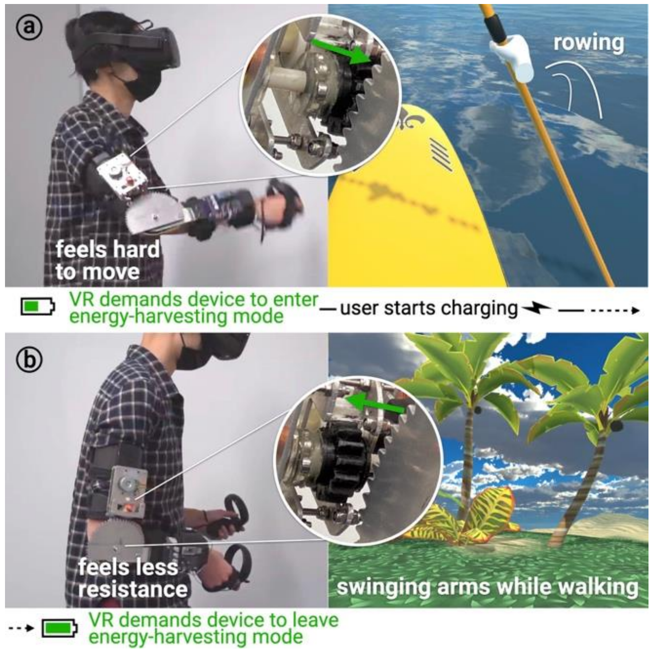

Figure 44: VR demands resistive force (device enters energy-harvesting mode) for this rowing interaction.

Surplus of harvested energy? More haptics. Our VR experience can leverage a haptic device that is fully charged, despite no immediate need for haptics. While the VR software could simply ignore this, a VR designer could take advantage of this energy surplus and create multiple versions of the same experience that provide more realistic haptic experiences. (Obviously, these scenes could also be required as per the experience's narrative, and thus the player would be required to experience a charging sequence prior to those; but, in this section, we explore the situation where there's a surplus of energy). Figure 45 shows an example, while the user is paddling the boat, the VR experience spends the surplus of energy by rendering dense reeds, in which the user experiences even higher resistance than the harvesting resistance (which is achieved by braking the DC harvester via shortcutting it).

Figure 45: If there is a surplus of energy, the VR software launches one of the pre-made experience that can make use of this extra energy for a more immersive version of the current experiences.

Just-in-time charging for quick haptic sensations. At last, the user explores the final island to find batteries to power their emergency radio. Again, this scene could take advantage of previously harvested power, but we choose to depict a worst-case scenario: the user has been idling and the haptic device has sufficient power for Bluetooth communication, but not enough for any haptic sensations. However, the next VR experience is to feel an electrical tingling as the user's radio comes back alive upon inserting the battery. As such, the VR designer created a short, just-in-time charging experience, that ensures that there is always available power for the user to feel the electrical tingling sensation. When the user approaches the last battery, the VR software checks the available power reported by the haptic device. If it is below the requirement for the electrical tingling (which is rendered via electrical muscle stimulation), a crab appears next to the battery. As the user reaches for the battery, the crab jumps at them and latches to their arm. The VR software instructs the clutch to activate and harvest the user's arm movements in this very short "charging" sequence. The user shakes their arm twice, which generates enough power for the final electrical tingling effect. The VR scene immediately stops the harvesting and causes the crab to be flung off the user's arm. Finally, the user places the battery in their device and experiences the electrical tingling as the radio wakes up and calls for help.

Figure 46: Just-in-time harvesting sequence.

While we depicted only a few key moments in this VR survival experience, this VR experience runs for a long time; Figure 47 depicts the entire VR experience's events, including a cold start (the device has absolutely no power), all harvesting VR sequences (scenes where the user is harvesting), spending sequences (scenes where the user receives on-demand haptics) and their inner loops (that connect harvesting to spending sequences).

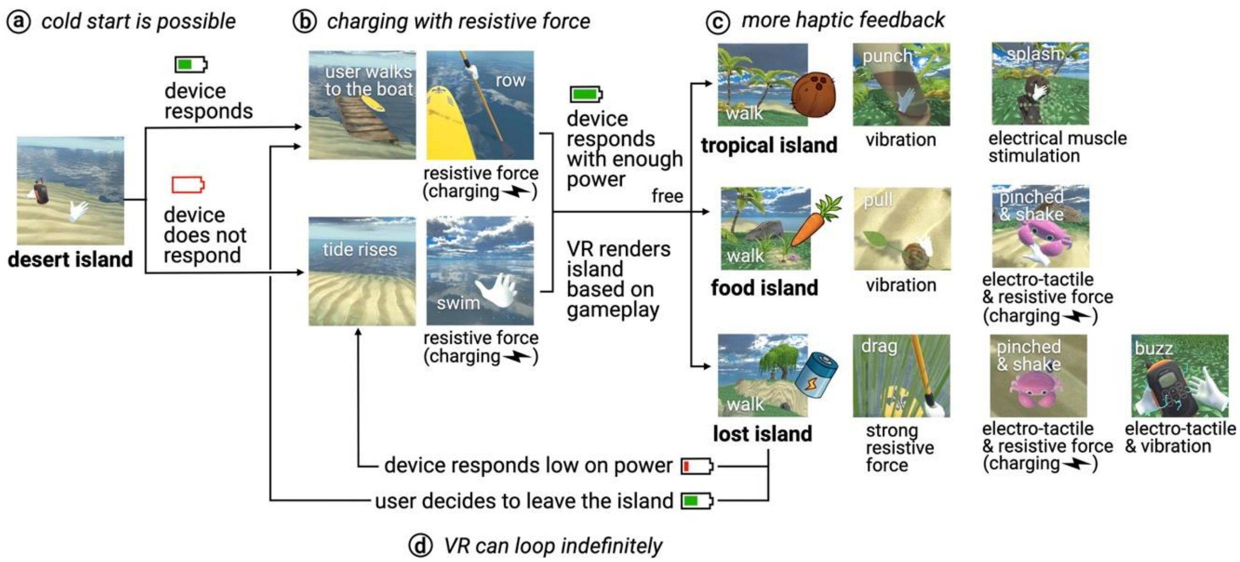

Figure 47: Flow of our exemplary VR experience.

Contribution, benefits & limitations

Our main contribution is a novel technical approach for haptic devices that contains no battery and yet can deliver haptic sensations, even strong active haptics (e.g., vibration, electrical- or force-feedback). Our key technical insight to enable this contribution is our implementation of a kinetic harvester with sufficient power efficiency to render haptic effects longer than the time the user spent harvesting. Secondly, our key conceptual contribution is that, while harvesting alone is not sufficient (as the increased resistance from the harvester would create a distraction to the VR experience), we solve this by adjusting the VR world to render a situation in which the user expects to feel resistance.

The benefits of our approach include: **(1) Technical approach to realize immersive haptics for long VR experiences**—contrast the fact our device can virtually last for days, with the typical lifetime of a wearable haptic device; moreover, in our study, we found that our device was more immersive than today's baseline VR setup; **(2) Technical approach that frees the user from large batteries & power tethers**—contrast this with the abundance of haptic devices connected to large batteries or powerlines; **(3) Users do not need to notice the harvesting**—because we use the VR dynamically to conceal the resistance felt by the harvester, users can use our device unaware of its inner workings; in fact, in our user study participants did not realize our approach was harvesting their movements. **(4) Haptic "walk-up use"**—our device can sit on the shelf for virtually any amount of time and will "wake up" once the user starts the VR experience and starts moving; and, **(5) Re-using power for heterogeneous haptic experiences**—our device harvests kinetic energy, but can deliver power to a wide range of actuators; we demonstrate how our implementation converts this energy into vibrations, electro-tactile, electrical muscle stimulation, and braking-based resistance.

Our approach is not without its limitations: **(1) Content creation for intermittent haptics**—our approach only supports haptic feedback that happens intermittently (up to a few minutes, rather than continuously for hours). This is a consequence of the switching between on-demand haptics and harvesting energy from the user's movements (which in our concept also provides haptics, but typically not on-demand as these are triggered by the haptic device, rather than by the VR content). This necessary switch from on-demand haptics to harvesting haptics, requires VR designers to create harvesting sequences, i.e., alternative moments in the VR experience that can be activated ad-hoc when the haptic device loses all power and returns to harvesting mode. **(2) Longer experiences**—another limitation of our approach is that it leads to longer experiences, since when using our device, the user performs additional actions designed to charge the device if the power is running low. Finally, **(3) Physical exertion**; our approach relies on physical movements, as such it also induces higher physical exertion and might not be suitable for all users or situations.

Implementation

We detail our prototype batteryless haptic device (Figure 48) with its custom energy-harvesting and the VR interactive system. To accelerate researchers interested in reproducing this device, all designs are made available and open-source[2].

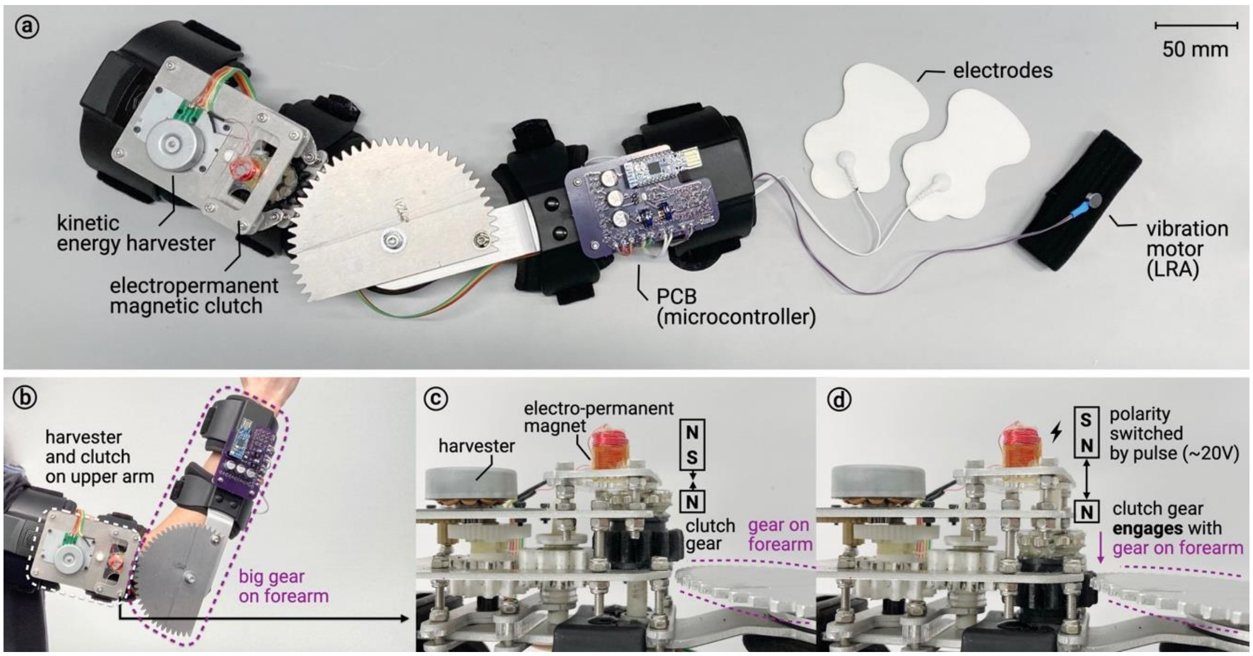

Figure 48: Our wearable haptic device, which is untethered and batteryless.

Arm-worn exoskeleton haptic device

We implemented an exoskeleton that is untethered and batteryless, shown in Figure 48(a). It measures 42 cm in length (adjustable) and weighs 680 g (resistive gears & clutch 325g, exoskeleton 270g, harvester 35g, PCB 30g, electrodes & straps 20g). It harvests kinetic power from elbow movements, since at every triceps/biceps curl, ample mechanical energy is available to be turned

[2] http://lab.plopes.org/#harvesting-haptics

into electricity. Also, the accompanying resistive haptic feedback on the elbow is easy to integrate into VR interactions since the hands are often involved in VR experiences (e.g., rowing a boat, lifting heavy objects, pushing against walls, etc.). We detail each component of our exoskeleton in the following sections.

Harvester mechanics. The core of our kinetic energy harvester is a 3-phase brushless DC motor (ZSFD-F1HD) with gear ratio 1:20.25, which we re-purposed as a power generator with rated output current 700mA. To incorporate a clutch (switching on/off energy-harvesting mode, which we describe later) into the gear set, we added two 12-teeth gear (20 degree-teeth; gear ⌀ 28mm) for transmission, and a 15-teeth clutching gear (20 degree-teeth; gear ⌀ 34mm), fabricated with PLA using FDM 3D printing, 12mm thick, fit into ABS rods (⌀ 8mm). The power generator, transmission gears, and clutching gears are mounted on the upper arm. The lower arm's half-gear (20 degree Metric, 60-teeth, 120 mm Pitch, ⌀ 124mm, fabricated with 3mm-aluminum by water jet cutting) is attached directly to the exoskeleton brace, which increases the torque ratio by a factor of 5 when engaged with the generator. The enclosure of the upper arm gears is fabricated with 2mm aluminum plates (water jet cutting) and secured with M3 screws; finally, these are clamped onto an MOSCARE elbow brace with adjustable upper/lower arm length along with adjustable straps.

Switching harvester on/off using a custom clutch. To enable on-demand kinetic energy harvesting, ideally, the actuation of the clutch should take require harvesting a few arm movements. This is difficult to achieve since most types of clutches (e.g., motorized friction clutch) require actuating large motors to engage/disengage. In the process of designing our clutch, we implemented six different clutch designs (some depicted in Figure 49): a DC-motor horizontal linear-clutch, DC-motor vertical linear-clutch, one-directional ratchet clutch, one-directional spring-clutch, DC motor friction-clutch, but found these would require too much power to actuate compared to a magnetic clutch.

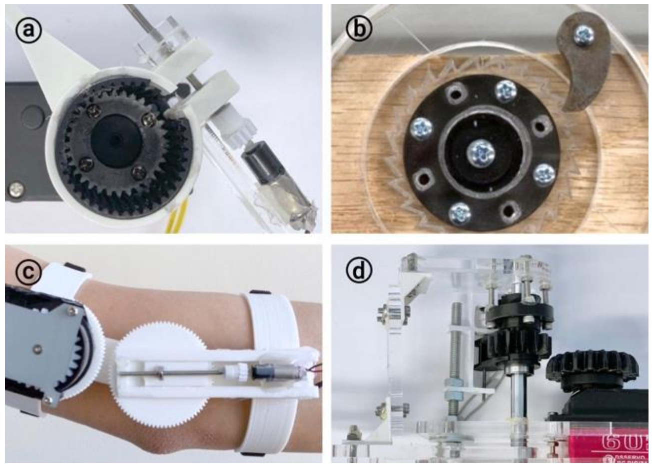

Figure 49: Four (out of six) examples of clutch designs that we implemented.

To clutch in an energy-efficient way, our custom magnetic clutch is based on electro-permanent magnet (EPM). In EPMs, the polarity can be switched by an electric pulse but remains stable for a long time [52, 109, 169] (contrast this with a solenoid, which only pulls when power is supplied). Our Figure 48(b) depicts our EPM clutch, consisting of a clutch gear that has a ring of permanent magnets (neodymium, ⌀ 5mm, 3mm thick, 242 gauss), sliding on a plastic shaft to avoid magnetic materials. To move the clutch, the polarity of EPM is switched to attract (disengage) or repel (engage) the clutch gear on the shaft. Importantly, even if the gear ends up not perfectly aligned (did not slid all the way) the clutch will still slide in to engage when the user moves the arm by just a small amount, since the EPM continues to push the clutch gear. Our EPM (Alnico Grade 5, ⌀ 5mm, 15mm length) was wrapped in a coil with 80 windings (28 AWG). Finally, the magnetic field was measured at 59 gauss in both polarities, after switching.

Microcontroller. The complete circuit is layout in our custom PCB. Refer to the schematics in Figure 50. The control center is NRF52840 Dongle (Nordic Semiconductor), which is a Bluetooth Low Energy (BLE) enabled low-power microcontroller (1.6-3.6V, measuring 1.3mW under 1.8V, while BLE connected). A supercapacitor (0.33F) is used to store the harvested energy. The available power is sensed by the microcontroller through an analog reading pin. To lower the power consumption, we lowered the Bluetooth advertising rate to 100ms. We utilized UART for BLE communication.

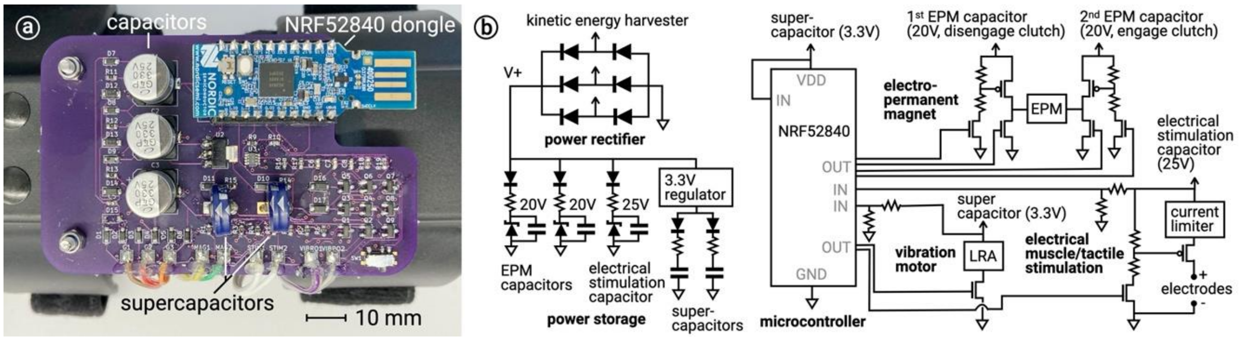

Figure 50: Our custom PCB containing energy harvesting and haptic control circuits.

Harvesting circuitry. We connect the output of the DC-generator to a 3-phase rectifier composed of six Schottky diodes (PD3S0230-7), high-voltage shunt diodes (20V MMSZ5250CT1G and 25V SZMMSZ5253BT1G), and a regulator (3.3V for low-power super-capacitors, NCP1117ST33T3G). This generated power is then fed into five parallel capacitors, each with its capacity and voltage rating, including three electrolytic capacitors (330μF, 25V) and two EDLC (electrostatic double-layer capacitors) supercapacitors (0.1F and 0.33F, 5.5V). Again, we chose supercapacitors rather than traditional batteries (e.g., LiPo, Li-Ion, NiMH) since supercapacitors charge faster than batteries, and more importantly, balance energy storage with charge and discharge times. While supercapacitors do not hold much energy as a comparably sized battery, they trade off capacity with charging/discharging speed [111] —this is the technical insight that enables our approach to quickly charge with sufficient energy to generate strong haptic effects. We will now explain the role of each of our five parallel capacitors, depicted in Figure 51.

Discharging power into haptic effects. Two 330μF 25V electrolytic capacitors are charged/discharged to engage and disengage our EPM-clutch (~20V, with peak current 6 A discharged in 2ms). With just a couple of biceps curls, we can harvest the needed 20V even without requiring a step-up circuit to engage/disengage the clutch. To control the EPM we modified a traditional H-bridge circuit to allow charging up two capacitors at the same time but discharging at different times, ensuring there is power when it needs to disengage/engage the clutch. The H-bridges are manually implemented using 20V N-channel MOSFETs (SQ2310ES-T1_BE3) and 20V P-channel MOSFETs (SQ2351ES-T1_GE3), which can withstand a peak current of 12A. Next, the remainder 25V 330μF electrolytic capacitor stores energy for our simple electrical muscle stimulation (EMS) actuator, which can render either electro-tactile or force-feedback, depending on the stimulation time. For EMS output, we added a current regulator (LT3092) that we configured to limit the output current to 33mA (as most EMS systems that actuate the biceps do not require more than this [136, 139]). The stimulation signal is created by the microcontroller via a P-channel MOSFET (Si2371EDS) and an N-channel MOSFET (SQ2310ES-T1_BE3), at 50Hz with 200 microseconds pulse-width. Moreover, we added two parallel EDLC supercapacitors (0.1F and a 0.33F, 5.5V, PowerStor)—these are the highest storage capacitors in our circuit. The largest (0.33F) constantly discharges onto the microcontroller and the remainder (0.1F) discharges, on-demand, onto the vibration device. We actuate this linear resonant actuator (LRA, C10-100, 65mW at 2V, Precision Microdrives) using an N-channel MOSFET (SQ2310ES-T1_BE3) driven it at its resonant frequency (170Hz) using the microcontroller.

Finally, any capacitors' voltage drops gradually over long-time frames; thus. the voltage of supercapacitors and the EMS capacitor is sensed, by using a voltage divider circuit and the microcontroller. We estimate the voltage of the EPM capacitor by reading the EMS capacitor as a workaround for limited analog reading pins available on this microcontroller dongle.

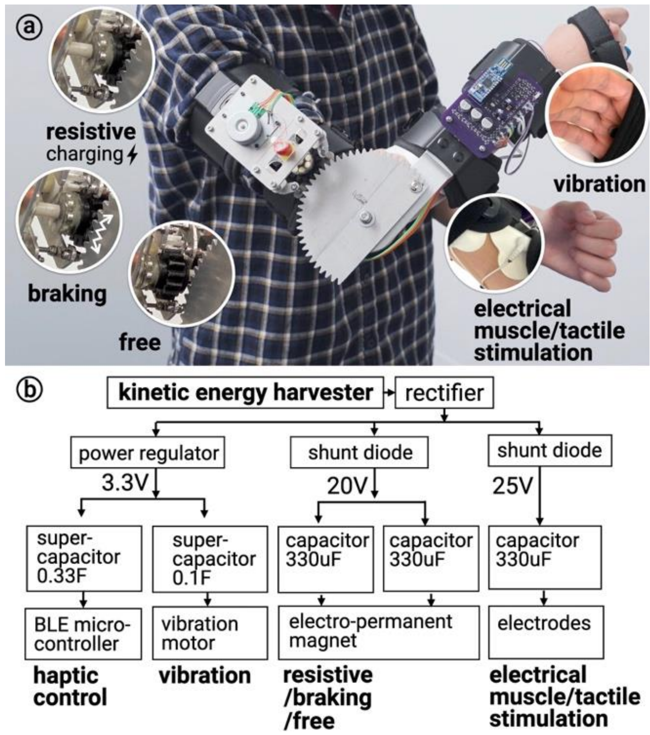

Figure 51: The various available haptic output provided by our device.

Available haptic feedback modes

We wanted our prototype device to be representative of the wide variety of haptics that our approach can enable. In our prototype, four actuators can be driven (motor braking, magnetic clutch, electrical stimulation & vibration motor) enabling six different haptic sensations, which we present in ascending energy-consumption order:

1. Resistive force feedback (energy-harvesting). This is when the clutch is engaged with the kinetic harvester and makes the user feel resistance in their movements. We measured the torque to be 1.29 N·m. Since this is the default state of our device (i.e., left alone it will eventually lose power and switch to this mode) it consumes the least power.

2. **Stronger resistive force-feedback (braking)**. This is when the clutch is engaged and we brake the motor by shortcutting it, which we achieve by discharging the EPM engage-capacitor into the motor terminals. We measured torque of 1.61 N·m, higher than in harvesting—this allows users to feel force-feedback sensations of higher resistance [15].

3. **Free (disengaged)**. Upon disengaging the clutch from the kinetic harvester, the user experiences virtually no resistance from the device (0.05 N·m).

4. **Electro-tactile (using EMS)**. By actuating our simple electrical muscle stimulation circuit for very short periods, such as 10ms, we render an electrical tingling sensation similar to electro-tactile sensations [93]. In our main VR experience, we delivered these impulses via two electrodes on dorsal side of user's forearm.

5. **Force feedback (using EMS)**. By actuating our simple electrical muscle stimulation circuit for longer periods, such as 100 ms or longer, we render involuntary muscle contractions sensation similar to force-feedback [135]. In our main VR experience we deliver this stimulation via the same electrodes as for electro-tactile (same circuit) close to the wrist extensor muscles. These can be attached to other parts of the body for different applications. Note that our EMS implementation is simplistic. First, the difference between our electro-tactile and EMS is how long the actuation is (long induces muscle twitches; very short feels like electro-tactile). Second, our EMS approach induces only small movements since it uses only 25V. However, this still depicts the range of haptics that can be easily added to our harvesting-based approach. Obviously, our simple EMS sub-circuit can be swapped for more powerful EMS circuits, such as *bioSync* [156].

6. **Vibration**. We create vibrations using a linear resonant actuator (LRA) attached to a strap on the user's palm. It can be attached to other parts of the body for different applications.

VR-side implementation

We developed our VR experiences using Unity 3D and render these via an Oculus Quest 1. The VR experiences are rendered in a laptop but displayed in the VR headset via *Oculus Link* connection over Wi-Fi. The haptic device sends all its messages over Bluetooth (BLE), which arrive at the laptop. We capture these *Bleak* (handles the low-level BLE connection) and we convert them messages to Open Sound Control (OSC), which are delivered via TCP to Unity3D. While typical OSC implementations utilize UDP, we switched to the TCP protocol to ensure the delivery of messages.

VR searching for haptics device. At the start of our VR, our Unity3D class (that can be added to any Unity3D project that wishes to extend or use our approach), automatically starts searching for the haptic device via BLE. If the device does not respond within 300ms, it assumes the device is out of power and in harvesting mode. Thus, the VR experience triggers the next available "charging scene", which in our *Walkthrough*, was the swimming scene.

Anatomy of a "charging" VR scene. The idea behind these VR scenes that justify the presence of the resistive force from the harvester is that they are cyclical, i.e., they can be looped or instantiated in sequence until the VR receives confirmation that the amount of power is sufficient. We implemented such scenes in Unity3D using two design strategies: (1) *transport-to-charging-area*; and (2) *in-place-charging*. For *transport-to-charging-areas*, these are scenes that take place in a specific place (literally a software scene as determined by Unity3D). We transport the user to this scene by, for instance, fading the previous scene (e.g., we use a thick fog to transport them from "swimming" from the island to swimming in the open ocean). Now that the user is in this scene, the scene can loop itself (or be infinite/procedurally generated) while it constantly is charging the device. Examples of this scene included also our "rowing the boat", which even includes procedurally generated clouds and rocks on the water, to ensure the user feels there is a lot of variety—while, strictly speaking, they are caught in the charging loop (again, users in our *User Study* did not realize this at all). As for *in-place-charging* scenes, these are events that happen in place where the user is currently at. We recommend these, especially, when needing to harvest smaller amounts of power for the next haptic effect. Examples of this scene include our "shake-the-crab" scene, which we simply trigger on-demand when needed by toggling its visibility.

Power thresholds for each scene. Each scene or haptic effect in our VR experiences extends from our "spending" or "charging" Unity3D classes. Any VR event that extends from a "spending" class will behave dynamically and will require the designer to indicate what type of feedback (from our six possible types, at fixed durations). Using this information, our Unity3D class automatically estimates the required power from our measurements (see *Technical Evaluation*). If the power threshold is not satisfied (under voltage) this will cause the next "charging scene" to appear. For example, in our *Walkthrough* application, the threshold is set to 2.4V, which we measured to last for about 5 minutes (on idle). We also determined a low power threshold in our program to trigger energy-harvesting mode in the device and render the respective scene (e.g., "tide rises" scene). We set the threshold of the supercapacitor for the microcontroller to be 1.85V as the microcontroller will shut off with 1.7V remaining in supercapacitor.

Communicating available power. Unity requests voltage readings from our device every 100ms. Since supercapacitors consist of two-layers, the voltage sensed by the microcontroller can be higher than what is charged, especially in a relatively quick charging in kinetic harvesting; thus, to obtain a reliable reading of the current voltage, our Unity3D class employs a 20-sample moving average.

Technical evaluation

When engineering energy-harvesting devices it is paramount to characterize their behavior with respect to how long they take to charge and for how long they operate (discharge) under different conditions (idle vs. delivering haptics).

Apparatus. Measurements were performed using our prototype (described in *Implementation*) connected to a factory-calibrated precision-multimeter (0.01 mV resolution, accuracy of 0.02%, 4 ½ digits of precision and USB logging). For the technical evaluation, unless where noted, all the movements were performed using biceps/triceps curls at a period of 2 seconds by a participant with no arm injuries but a relatively low muscle mass (biceps diameter 22 cm, much below the average of 34.3 cm [47]).

Kinetic harvester's electrical output. Figure 52 depicts the voltage of our harvester in two exemplary situations: (a) a ~30V peak from a slow biceps curl (~1.4 seconds per complete flexion/extension) and the ~35V peaks from a faster biceps curl (~1 second per complete flexion/extension). Moreover, we measured a current of 70mA averaged across one complete elbow movement (one elbow flexion followed by one elbow extension) at the slower pace, and 65mA at the faster pace—this minimal difference illustrates how we tuned the gear ratio to be effective at slower movements.

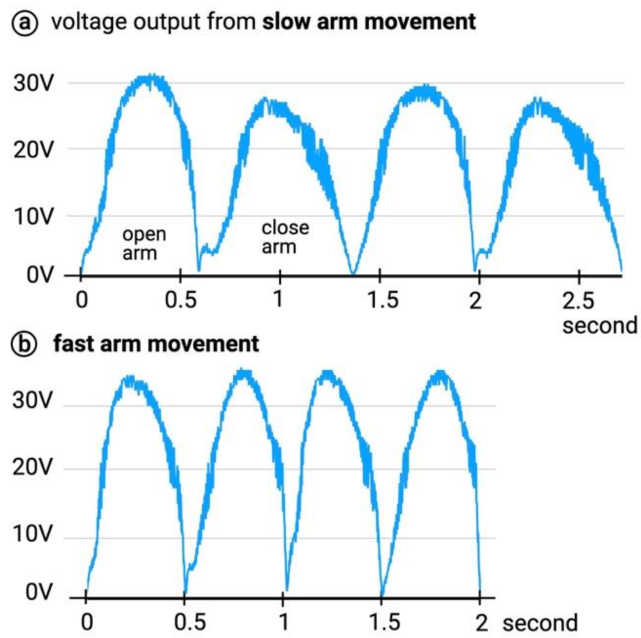

Figure 52: Voltage (rectifier output) of our harvester for two consecutive elbow movements (flex/extend for each movement).

Measuring harvesting for the microcontroller. Microcontrollers require a stable power source to remain operational. In Figure 53(a), we depict a *cold-start* of our haptic device. In this exemplary run, it took ~30 seconds to charge the 0.33F supercapacitor to 1.8V, which wakes up the NRF52840 microcontroller (including Bluetooth). However, this 1.8V region is close to the shutdown voltage (around 1.7V), as such, our device remains in harvesting mode (clutch engaged) until the voltage is at least 2.4V at this supercapacitor. As depicted in Figure 53(a), it took ~1 minute of harvesting to reach this point, at which microcontroller clutches off to leave harvesting mode. Left alone, this stable mode would last for ~5 minutes; thus, the idle efficiency is 1:5 (1 minute of harvesting provides 5 minutes of idling).

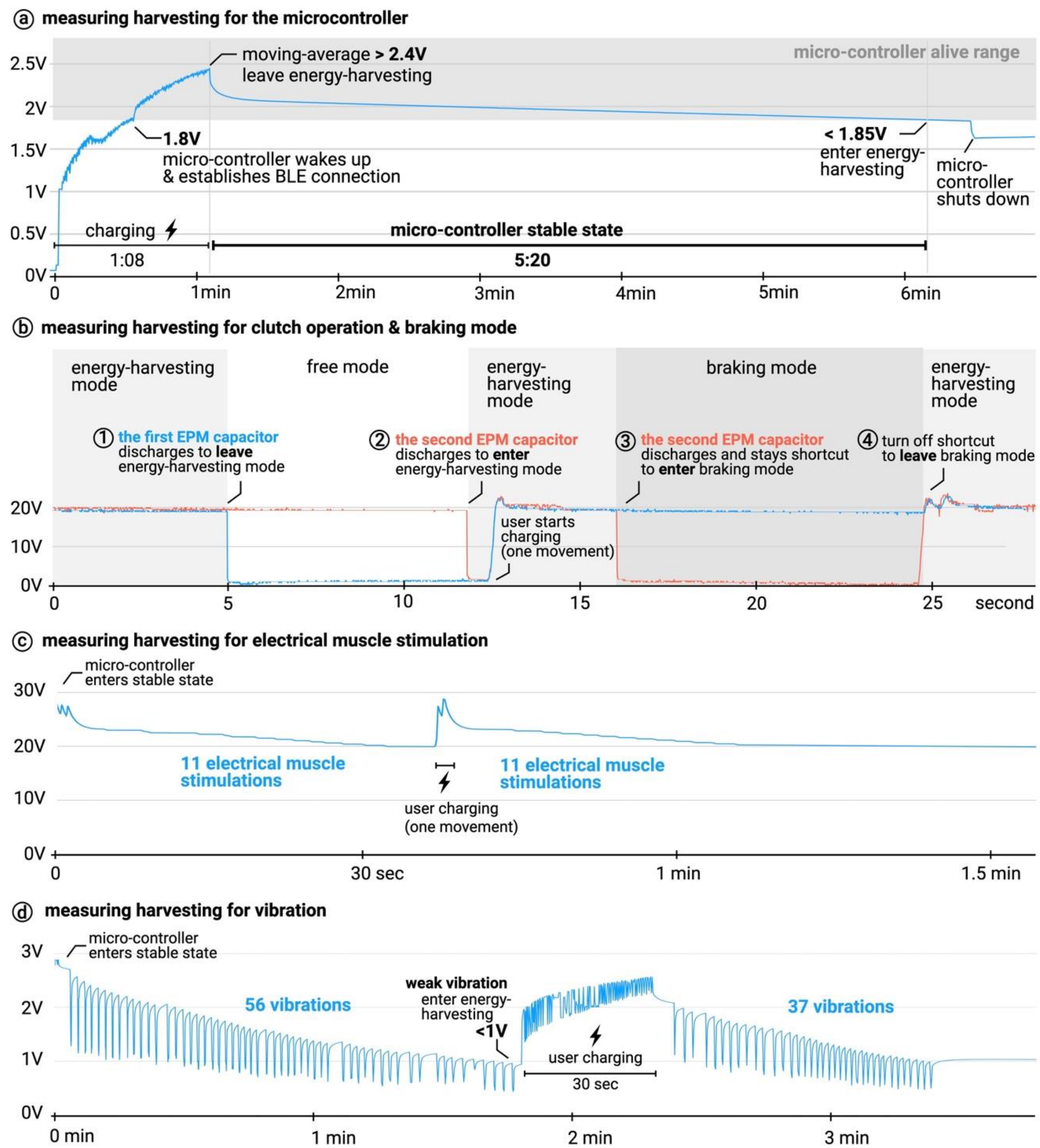

Figure 53: Charging and discharging profile of capacitors.

Measuring harvesting for clutch operation & braking mode. While the previous measurements evaluated how fast our implementation can wake up the microcontroller (~30 seconds), we now turn to measuring how long it takes to harvest sufficient energy to engage/disengage the clutch. Since the microcontroller is already charged, the two clutch capacitors are also charged. As depicted in Figure 53(b)(1), at the 5s mark, we discharge the first EPM capacitor, which clutches off (leaving harvesting mode). The device is now in free mode and the user feels no resistance. Note that our second EPM capacitor is also charged, which we trigger to re-enter the energy-harvesting mode at the 12s mark, in Figure 53(b)(2). Now, both capacitors are discharged, and the system does not have sufficient energy to move the clutch; however, the system is in harvesting. As shown at the 13s mark, the user starts charging by moving their arm: a single elbow movement charges both capacitors immediately; it is already ready to leave the energy harvesting or deliver haptics on-demand. This depicts a fast turn-taking efficiency (i.e., 1 movement charges the clutch switching). In Figure 53(b)(3) depicts a later case in which the device activates the braking mode (which feels harder to move than in harvesting mode). Because the clutch capacitors are already charged after a single movement, our device can render the braking mode by discharging the second EPM capacitor to shortcut the DC motor. The capacitor is charged again when the shortcut is off, as shown in Figure 53(b)(4). Finally, we found that, while in idle mode, the capacitors conserve adequate charge for clutch operations for ~5 minutes.

Measuring harvesting for electrical muscle stimulation. In Figure 53(c) depicts the efficiency of harvesting power to drive our simple electrical muscle stimulation subcircuit. We found that a single arm movement can charge its capacitors sufficiently for 11 electrical stimuli (300 ms each) to be delivered to the user. Since our electro-tactile circuit is the same, its performance is similar. The VR experience can request another arm movement when more EMS-based effects are needed. This depicts also a quick turn-taking from our system (1 arm movement, 11 EMS impulses). Moreover, we found that while in idle mode, the EMS capacitors conserve adequate charge for EMS stimulation for ~5 minutes.

Measuring harvesting for vibration. in Figure 53(d) depicts the efficiency of harvesting power to drive our vibration subcircuit. We found that from the microcontroller's stable mode, we can deliver 56 vibrations on our LRA (300ms each) before these become too weak, which happens when the LRA voltage drops below 1V. We also found that harvesting for vibrations takes longer when compared to clutch, braking, or EMS. We found that ~30s of harvesting are required to charge up to ~2.1V, which allows delivering ~37 vibrations. Note this was to be expected, since we used a large supercapacitor for vibration (0.1F) but not for EMS (330μF). Yet, this still results in an efficiency of 30s of harvesting to ~1 minute of vibration. Finally, we found it to conserve adequate charge for their vibration operations for ~24 hours.

Limitations. The operation of any force-based device (including kinetic-based harvesters) depends on the operators' force. As such, we advise to take our results as illustrative of a typical performance of our device rather than a lower (e.g., users with less muscle force) or higher (e.g., users with more muscle force) bound for its performance.

Summary. We characterized the efficiency of our device. We found that for all haptic modes, users will tend to spend less time in harvesting mode (where they provide energy by means of their movement) than in enjoying on-demand haptics. In fact, we found that our microcontroller requires ~30s-1min of charging for 5 minutes of operation; our vibration circuit can be charged in ~30s and lasts for one minute of vibration; and, finally, our clutch's operation, as well as the EMS stimulator, can be charged in a few seconds (i.e., these are charged in a single arm movement). Moreover, if left alone, our device tends to discharge in ~5 minutes; however, it will always return to its harvesting mode (sending a message to the VR and clutching), so it is always ready to be picked up by a user and will always wake-up on charge.

User study

In our study, we evaluated whether wearing our haptic harvesting device impacted actual VR experiences. To do this, we created a long VR experience (the island survival experience shown in our *Walkthrough*), in which players could be immersed for longer periods. This is the type of experience that would deplete existing haptic devices, and, at some point, the user would find themselves with just input but not enough power for haptics. As such, in this study, we compared our harvesting approach to a baseline condition where the participants use only input controllers. Moreover, this study was conducted with *incomplete-disclosure*, i.e., our participants consented that "something about this study" was not told until the complete study was done. In fact, **we did not inform our participants that our device had no battery nor that it was harvesting their movements**. This study was approved by our institutional ethics committee (IRB22-0467).

Hypotheses. Our hypotheses were as follows: **(H1) our approach would lead to more realism than the baseline condition**, since we hypothesized that the addition of haptics would be felt as more realistic because—even though our participants would be required to exert more force to harvest the haptics' power—our harvesting technique charges while simultaneously rendering passive haptics that are, in themselves, also realistic. Moreover, we hypothesized that, with our approach, participants would **(H2) feel their senses are more engaged**, which is a key feature in immersion [183]. Furthermore, we expected that **(H3) our approach would lead to more fatigue than the baseline condition** since the harvesting of our haptics comes at the expense of the user's physical exertion. Because of the latter, we also hypothesized that the **(H4) experience duration would increase with our approach**. Still, despite this expected physical exertion and longer gameplay, we further hypothesized that **(H5) participants would find this exertion more enjoyable with haptics than in the baseline condition**.

Preview of study results. We found that our device increased the realism and sensory engagement, which suggests it is useful for increasing the immersion of VR experiences, especially for very long VR experiences that could not easily befit from wearable haptics. Moreover, we also confirmed two expected limitations of our device, i.e., it makes the experiences longer and more physically demanding (since the charging is via physical movement).

Interface conditions and apparatus

Conditions. Participants were asked to play our island survival VR in two conditions: (1) **harvesting-device**, in which they wore our harvesting device on the arm and held input controllers to navigate and interact with objects; and (2) **controllers-only**, in which where they did not wear our device and used controllers to navigate and interact with objects. Note that we only use controllers for sensing purposes in both conditions and we did not use the built-in vibration motor in controllers, since we were interested in rendering all haptics using the power harvested by the participant without the need for batteries. Interface condition order was counterbalanced across participants.

Apparatus. An inside-out 9DOF tracking VR headset (Oculus Quest 1) with controllers in both hands, and our device. In the harvesting condition, the experimenter discharged all the capacitors so that the **device started with zero power**.

Participants

We recruited ten right-handed participants (M=22 years old, SD=2; five self-identified as female and five as male). Four of them had prior experience with VR, but none had experience with our device or haptics beyond vibration in controllers. It is important to note that, all participants did not have prior knowledge about the device in terms of its harvesting capability—

as aforementioned, this information was withheld from participants until the end of the study (Incomplete Disclosure).

Tasks

We utilized our island survival VR experience (see *Walkthrough*). The experience was configured to be shorter than our walkthrough by requesting participants to find three coconuts, three carrots, and three batteries. Pilot tests were used to inform how long the task should last. We designed it to last ~10 minutes in baseline condition. To prevent a sequence effect in which participants memorize the location of the objects and puzzles, we changed the order of the first two islands and locations of the objects; moreover, we also counterbalanced the condition order. With participants' consent, we recorded their VR screen for later labeling of events and time duration. After each condition, participants were asked to rate the perceived realism, enjoyment, sensory engagement, and physical fatigue on a 7-point Likert scale. The experimenter conducted semi-structured interviews with the participants to collect subjective feedback. Breaks were given in between the conditions.

Finally, **only at the end of the interview**, **we disclosed that our device charged by harvesting kinetic energy**.

Results

Figure 54 depicts our main findings, which were analyzed using paired t-tests.

H1 (realism). First, we found that participants rated significantly higher ($F(9)=5.6$, $p<.0005$) realism in harvesting device ($M=5.3$, $SD=0.7$) than controllers only ($M=3.8$, $SD=0.9$). This finding suggests that our **H1 was confirmed (our approach led to more realism)**.

H2 (sensory engagement). We found the participants rated significantly higher ($F(9)=7.7$, $p<.0005$) in sensory engagement with harvesting device ($M=5.7$, $SD=0.8$) than with controllers only (M=3.7, SD=0.9). This finding suggests that our **H2 was confirmed (our approach led to more sensory engagement)**, which is a key factor in immersion [183]. Taken together, our H1 and H2 suggest that our approach to generating haptic feedback from power harvested from the user, improved the realism of VR experiences.

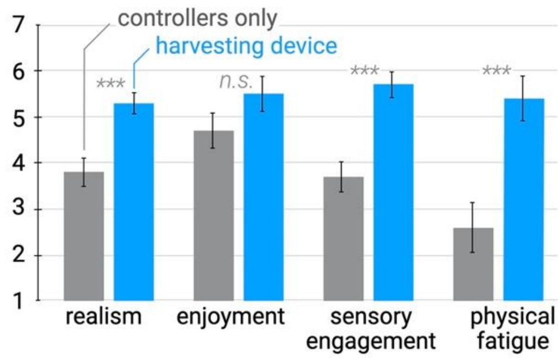

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Figure 54: Study results, error bars show standard errors.

H3 (fatigue). We found the participants rated significantly higher (F(9)=5.7, p<.0005) in physical fatigue with harvesting device (M=5.4, SD=1.5) than with controllers only (M=2.6, SD=1.6). This confirmed our **H3 (a harvesting approach leads to more fatigue)**, and confirms this as a limitation of our approach.

H4 (duration). We found that participants took significantly longer (F(9)=4.9, p<.0005) to complete the experience with the harvesting-device (M=18.3 min, SD=4.41) than with the controller-only (M=11.3 min, SD=2.75). This was to be expected since when using our device, the user performs several additional actions (e.g., more rowing, swimming, etc.) while they charge the device in case the power is running low. This supports our **H4 (harvesting increases the duration of the VR experiences)** and confirms this as a limitation of our approach.

H5 (enjoyment). We did not find a significant difference (F(9)=1.6, p=0.14) in enjoyment even though harvesting device (M=5.5, SD=1.2) was rated higher than controllers only (M=4.7, SD=1.2). As such, our H5 was not supported.

Subjective feedback

Disclosure of harvesting. No participant realized our device was harvesting their movements. After disclosure of the working principle of the harvesting device, all participants found it unexpected and felt the integration was well executed. For example, P2 realized why "[I] had to row more to reach the islands!", P4 commented "makes sense now that I think about it"; P6 commented "wow, that is unexpected"; and P8 expressed "definitely it [the integration] works".

Harvesting-device. All participants mentioned that they felt the resistive force from our device when rowing the boat, and that this also contributed to the realism of VR. Regarding this, participants stated, for instance, that "it felt heavy" (P2) and "heavy when I moved my arm" (P3) and "the fact that you have to work your arm for it to go increased the realism" (P7). Some limitations were also brought up: P5 added that our device did not replicate the exact "physical experience of paddling since resistance in other joints is missing", and P8 mentioned it was "less fatigued than rowing in real life". However, most participants felt it to be enjoyable, e.g., "the rowing made it more enjoyable" (P9). The rising tide on the island happened at least once to seven (out of 10) participants—in fact, one participant experienced it twice because they wandered for a longer time exploring the island. The remaining two participants did not experience flooding because they found items quickly and immediately left the current island in search of the next one.

On-demand haptics. As for the remainder, on-demand, haptic sensations, most participants had a vivid impression of their experience with the electro-tactile feedback. Participants stated the crab felt like "I was pinched" (P4, P10), "a shock" (P2, P10), and "kinda sharp" (P3). In fact, P2 and P4 subsequently tried to avoid the next crabs to prevent them from getting pinched. Inserting batteries felt “some electricity” (P2) and "tingly" (P3) and, similarly, participants recalled the coconut’s EMS impact as "crashing” (P9) and "tingly” (P3). Participants also positively recalled their vibration experience. All participants felt it when hitting the palm trees; one participant stated that “vibration pulled me into the world, especially the thunking on the tree” (P8).

Baseline. Compared to the baseline, without haptic feedback, all participants mentioned it felt less real and less engaging to their senses. For instance, they said, “I did find myself missing the stimuli even though it hurt” (P8), “without the thing on my arm rowing was easier” (P10), or “I was just looking around [instead of feeling] for this condition” (P6).

Study conclusion. Our qualitative and quantitative findings suggest that our approach can prolong VR haptic experiences that lend themselves well to intermittent haptics. Furthermore, we found that our harvesting approach

might go unnoticed by unknowing participants, which are likely to feel the passive haptics from the harvesting as a source of realism and sensory engagement, leading to immersion even during harvesting periods. Naturally, we also found that our approach to prolonging haptics leads to more physical exertion and to longer experiences.

Expanding our concept to more form-factors and applications

To further expand our approach, we explored additional applications, form factors, and other actuators in this section.

Fire-training simulator. To use our approach in a VR experience, the key is to design *harvesting sequences* that are adequate for the user’s expected experiences and can be triggered seamlessly. Figure 55 depicts another illustration of using our approach in VR, with the example of a fire-training simulator, in which users must put out a fire in a building with an unknown room layout: (a) shows the start of this experience. (b) The user yields a heavy ax to break down a door of the building on fire. As the user moves the heavy ax, they feel resistance; while, at the same time, they are charging our device from a cold-start (no power). Once the microcontroller wakes up, the haptic device communicates to the VR experience. (c) The VR experience responds and breaks the door into pieces, instructing the clutch's release—the user now moves freely into the first room, they are no longer harvesting. Then, the user puts out fires in this room, and the VR experience requests on-demand haptics: such as (d) the feeling of flames (electro-tactile) or (e) the vibration from a fire extinguisher. Anytime that the haptic device is about to lose power, it extinguishes the fires in the current room and shows another locked door, which the user will have to ax down (harvesting) to reach the next room on fire.

Figure 55: This VR experience immerses the user in a simple fire-fighting exercise, complete with haptic sensations.

Endless VR running. Different usage of our haptic device by attaching it to the knee joint is depicted in Figure 56. In this VR experience, users play a running VR game, akin to endless VR runners where users *walk in place*. However, our VR endless runner is complete with haptic feedback, even for hour-long game runs.

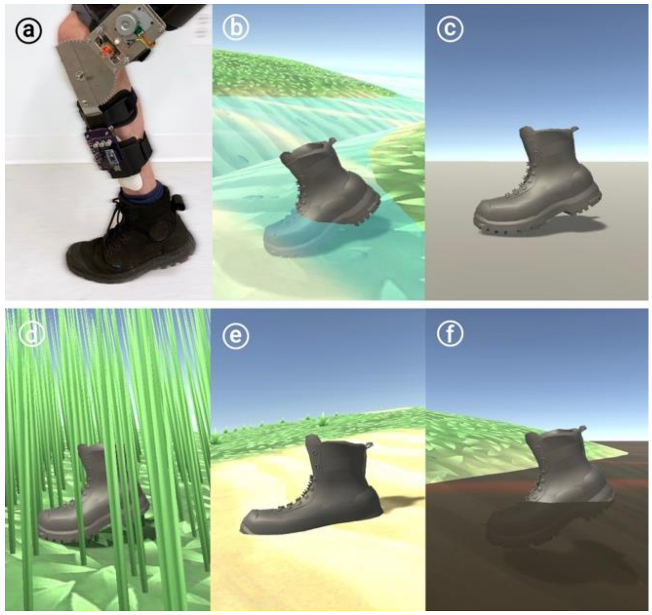

Figure 56: Our batteryless haptic device is worn on the foot in a VR running experience with haptic feedback.

Figure 56 depicts: (a) The user wearing our device runs in place. (b) As they run inside water through a shallow stream, they feel an added resistance from our harvester. (c) As always, once the microcontroller wakes up and reads a stable power, the haptic device communicates to the VR experience, which responds and stops rendering the shallow water and instructs the crutch to be released—the user now moves freely and runs on solid ground; they are no longer harvesting. Then, as users run through different sections of the terrain, the VR experience requests on-demand haptics, such as (d) grass brushing the user's legs (electro-tactile on legs), (e) a sandy terrain (vibration), or (f) running on mud (braking-mode, high resistance). Anytime that the haptic device is about to lose power, it informs the VR experience, which renders another section of the shallow water, so that the device can harvest energy from the user's leg movements.

Other haptic actuators. We believe our approach is not limited by the actuators used in our current prototype. One can envision a plethora of haptic actuators to provide richer haptic experiences, such as pressure, temperature, wind/airflow/fluid. In our preliminary explorations, we found that our device could successfully drive: (1) a small DC motor (26:1 Gearmotor Polulu) for ~5 seconds, which can be used for pressure or skin stretch feedback; (2) a solenoid (ZMF-1632d) for 100ms, which can be used to create impact; and finally, (3) a small Peltier element (CP081030-M) for ~5 seconds, which can be used for thermal feedback; the latter required an additional capacitance of 0.2F due to its high power consumption.

Prior work on batteryless powering techniques and adaptive systems

The work presented in this paper builds primarily on the field of haptics, with particular emphasis on sensations that require high-energy devices, such as force-feedback (motor-based exoskeletons, friction-based haptics, etc.). Moreover, we take inspiration from recent approaches to batteryless computing, which have predominantly focused on harvesting energy from the user or the environment for sensing applications. Finally, as our technical approach requires not only a hardware component (our clutch & kinetic harvester) but also a dynamic VR environment, we also review prior work on adaptive VR systems that render scenes to users in real-time depending on different constraints (e.g., space).

Batteryless computing devices

The growth of ubiquitous computing devices, internet of things (IoT) and wearable devices, has brought attention to the problem of powering devices that cannot reach a powerline or include a large battery. As such, many researchers across HCI and electrical engineering have been exploring new ways to power devices without the need for batteries.

Wireless transfer & RF backscattering. While power can be transferred wirelessly using Tesla coils, the power required can be dramatically high (i.e., this approach's efficiency is low) and the coils tend to be very large even at close distances (also removing the heat from the coils is nontrivial). As such, to power up small devices, radio frequency (RF) *backscattering* is a popular technique, in which the batteryless device's antennas pick up RF and convert it into power [8, 146]. In this way, multiple devices can be powered using one RF transmitter, making the receiving devices easier to set up around users [240]. One widespread usage of this is RFID technology, which leverages the same concept for powering ID badges and transit cards. For interactive devices, researchers utilized RFID for sensing gestures on surfaces [124] and tangible props [73]. In fact, we take inspiration from a recent endeavor to push batteryless devices to the tactile domain, such as an NFC-powered tactile device [233]. Overall, these devices based on wireless-transfer/RF are promising and popular for sensors using small amounts of current, but these require installation of a transmitter with a large battery or tethered to wall power—these are not ideal for mobile haptics applications such as free-walking VR.

Energy harvesting. Without instrumenting the device with a power supply or without instrumenting the environment with power transmitters, the energy must be *harvested* directly from the *environment* or its *user*. Next, we overview the most common techniques to realize this and their application area (for a comprehensive review of energy harvesting, see [225]). For powering small devices, solar ambient light or heat can be harvested. However, using small solar panels (the kind that would fit in a user or haptic device) requires constant and ample sunlight, but lighting conditions vary throughout the day. Therefore, harvesting using small solar panels is mostly suitable for sensors that operate at low power and in an intermittent manner [55]. As for harvesting energy from the human body, body heat and kinetic energy from movements can be used [242]. Body heat can be harvested using Peltier elements, which are exciting in that they harvest passively (the user does not need to engage in a harvesting behavior). However, their efficiency is low in the small sizes that are wearable, e.g., even very large skin areas covered can only generate μW of power [101]— not sufficient for driving large haptic devices. A source of larger energy efficiency is body movement. On a smaller scale, even micro-movements can be harvested via MEMS energy harvesting devices, e.g., piezoelectric [53, 125] and triboelectric [212] harvesters—again, these are promising but outside the range needed for driving strong haptics. Finally, to harvest more power from the body, large body movement from the joints can be harvested using electromagnetic generator (e.g., a DC motor)—the most powerful way to harvest kinetic energy from the body [36].

As our goal is to harvest energy for haptic feedback, where the power ranges from mW to W [35, 136, 245], and considering the mobility of the device (i.e., untethered), we see *kinetic energy* as the most promising power source.

Energy harvesting for interactive applications

HCI researchers have been exploring concepts to blend energy harvesting in our everyday appliances and devices [17, 163]. Here, we specifically overview energy harvesting applications for interactive devices.

For example, *Peppermill* [208] is a handheld input knob that is powered by the user's motions. *Paper Generator* [98] harvests power from the user rubbing an electret harvester on paper for lighting LEDs or driving an e-ink display. *Battery-free Gameboy* [218] integrates energy harvesting into an interactive system, utilizing solar panels and button clicks to power an interactive game, even bootstrapping between power losses—we take conceptual inspiration in this as well, since we engineered our device to be able to bootstrap itself from absolutely no battery (by ensuring the default state is harvesting mode). *Interactive Generator* [15] is a handheld knob that harvests energy when the user turns the knob, which it uses for RF communication to the interactive application. Moreover, while it does not provide a wide range of haptic feedback (e.g., vibration or others), it does provide on-demand resistance changes, by shortcutting the terminals of its DC motor—we take inspiration in this to realize our braking force. Furthermore, *SPIN* [28] integrates triboelectric nanogenerators into wearables that power LEDs and a buzzer. In fact, more recently, a similar approach has even been used to generate electro-tactile feedback [179]. However, the output power is still low at the µA level, while stronger stimulations tend to require mA level intensities. As such, with these previous harvesting approaches, electrical muscle stimulation or vibration has not been demonstrated and might not be readily achievable.

Generally, these previous devices incorporated energy harvesting by harvesting for a *short duration of time* (e.g., a button push [218], or a twist of a knob [15, 208]), which limits the amount of harvested energy (i.e., short harvesting = small energy). As such, this small amount of energy limits applications of these techniques to devices using relatively low power when compared to more power-hungry haptic actuators (e.g., vibrations, EMS, etc.). While we take inspiration from all these approaches, we take two conceptual turns: (1) *harvesting large movements for much longer*—thus harvesting larger output currents that are sufficient to power stronger haptic devices; and (2) *concealing the harvester's side-effects* (i.e., resistance that users would feel as distracting) as part of the VR experience & interactions.

Adaptive VR systems

Our system adapts the user's VR experiences in real-time to properly integrate the energy harvesting in the experience. This is inspired by works that utilize VR to adjust to different constraints (e.g., space), while preserving immersion. For instance, *Scenograph* [144] adjusts the VR experience dynamically according to the empty space available in the room, while preserving the same VR narrative. *VirtualSpace* [145] takes this further by enabling multiple users to overload the same limited physical space; to achieve this, the system generates *alternative VR* *scenes* in run-time (such as rendering an effect in a particular location, or making a new "power up" to appear), which causes users to move, even without needing to realize that there are sharing the space with other users. Moreover, motivated by the high power demand for haptic feedback, a series of research works have been exploring the idea of using humans as actuators in VR systems [29–32]. Specifically, in *Mutual Turk*, VR users, without even knowing other users are present, trade haptic forces with one another. Again, in this system, the VR experience also dynamically renders the content according to the motion of the other person to render realistic haptic feedback. Like these approaches, we take inspiration from VR experience's ability to be dynamically generated in real-time and use it to justify the resistive force felt while wearing our harvesting device.

Discussion on batteryless haptic devices

Even though there exists plenty of research on haptic devices, they are rarely mobile. One prominent issue is their high power consumption [247], leading them to be often tethered; or to have short battery lives if not having cumbersome batteries (e.g., *CLAW* [35] estimates the use of 1000mAh LiPo to yield only ~1 hour). This happens because devices generating haptic feedback require more power, typically orders of magnitude above, than a sensor.

While researchers have explored alternative actuators for the sake of power efficiency (e.g., using muscle stimulation instead of mechanical motors; or using brake-based actuators instead of motor-based actuators), even these alternative devices still feature batteries that will likely last far less than a whole day of usage. For example, *Dexmo* [57] uses a 800mAh LiPo battery, which allows it to provide haptic feedback for 4h, but only provides resistive force. Similarly, *Impacto* [136] uses a 1050mAh LiPo battery, which allows it to provide haptic sensations for ~200 seconds. In fact, as devices attempt to simulate richer sensations, they require adding more haptic modalities, which implies even more power consumption and shorter uptime. We see an urge of seeking alternative solutions to batteries in haptic devices.

We demonstrate that integrating intermittent energy harvesting is a viable approach for VR. While the aforementioned battery-powered *Impacto* [136] provides ~2000 haptic sensations (each 100ms), we estimate, with our approach, these sensations can be replicated with 3 seconds of charging prior to each stimulation (during runtime, i.e., after the process of bootstrapping the microcontroller and communications). Our device can provide ~2000 of these sensations within 100 minutes, and it can continue doing this for as long as the user intends, 10 hours, etc. For *Impacto* to match this, it would need more than its current battery (1050mA LiPo). For example, to prolong its usage to 2.5h, it would require a 3150mA LiPo, weighing ~0.5kg (three times heavier than the original battery). Naturally, adding more weight to wearables is undesirable as it creates fatigue, hinders movement, and creates unwanted haptic sensations. Moreover, to make matters worse, even this now heavier battery (lasting 2.5h) would still need to be charged at some point—the bigger the battery, the longer the charging time.

We believe that without batteries, haptic devices can be more mobile and more readily available, without users needing to worry about having enough charge. Finally, while we focused on the extreme case of having *no batteries at all*, one can also integrate batteries in our approach—in this way, the device can provide continuous haptic feedback when its batteries have charged, or switch to our intermittent harvesting approach when its batteries are depleted.

Summary

We propose a new technical approach to implement untethered VR haptic devices that contain no battery, yet can render on-demand haptic feedback. The key is that via our approach, a haptic device charges itself by harvesting the user's kinetic energy (i.e., movement)—even without the user needing to realize this. This is achieved by integrating the energy-harvesting with the virtual experience, in a responsive manner. We instantiated a version of our concept by implementing an exoskeleton (with vibration, electrical & mechanical force-feedback) that harvests the user's arm movements to power haptics intermittently. We validated this device by means of a user study, in which participants (even without knowing the device was harvesting their movement) rated a VR experience as more realistic & engaging using our device than with a baseline VR setup. We believe our technical approach affords new uses of haptics for prolonged use-cases, especially useful in untethered VR setups, since devices capable of haptic feedback are traditionally only reserved for situations with ample power. Instead, with our approach, a user who engages in hours-long VR and grew accustomed to finding a battery-dead haptic device that no longer works, will simply resurrect the haptic device with their movement. Moreover, our approach enables new ways to use haptic devices unthinkable for battery-powered devices today: namely, walk-up use. Even if the user forgot to charge the haptic devices or change the batteries, our technique enables these to work rapidly during the interaction.

I show this as an approach to tackle the challenge of unstable power in mobile and wearable scenarios (Figure 57). As for future work, we envision how researchers might expand our approach to integrate different haptic actuators (e.g., Peltier elements) or create new renditions of our approach for other body parts (e.g., neck, shoulder, and so forth). On the software level, one can explore various algorithms that optimize for interaction longevity, sensory immersiveness, or user preferences.

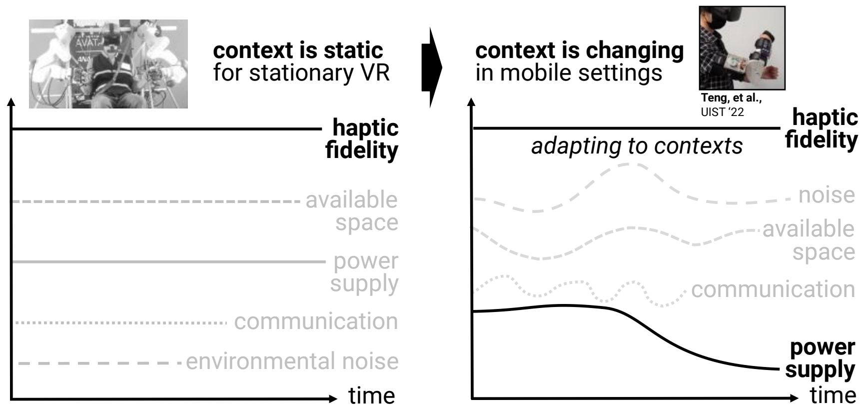

Figure 57: Adaptive haptic feedback enables consistent haptic fidelity for mobile experiences.

After addressing the two fundamental challenges, in Part III, I demonstrate that how a haptic device that is **unobstructive for physical interactions** and used in a **mobile scenario** can be valuable in assisting daily tasks.

Part III - Opportunities: Haptic assistance in everyday life

Through the work I propose, I want to depict that new possibilities that become available once we prioritize mobility, rather than aiming for maximum haptic fidelity. I posit that this will move haptics into new territories, such as haptics that support daily activities, mixed reality, and even sports. Haptic devices would be integrated into devices that are not only be used in labs, in arcades, at homes, but follow us to anywhere in almost every of our activities (just like smartwatches and earphones). To demostrate the benefits, in the following section, I show a new wearable sensory substitution that supports Blind users to feel and grasp objects in their everyday life, *Seeing with the hands* [198].

Seeing with the hands: a sensory substitution that supports manual interactions

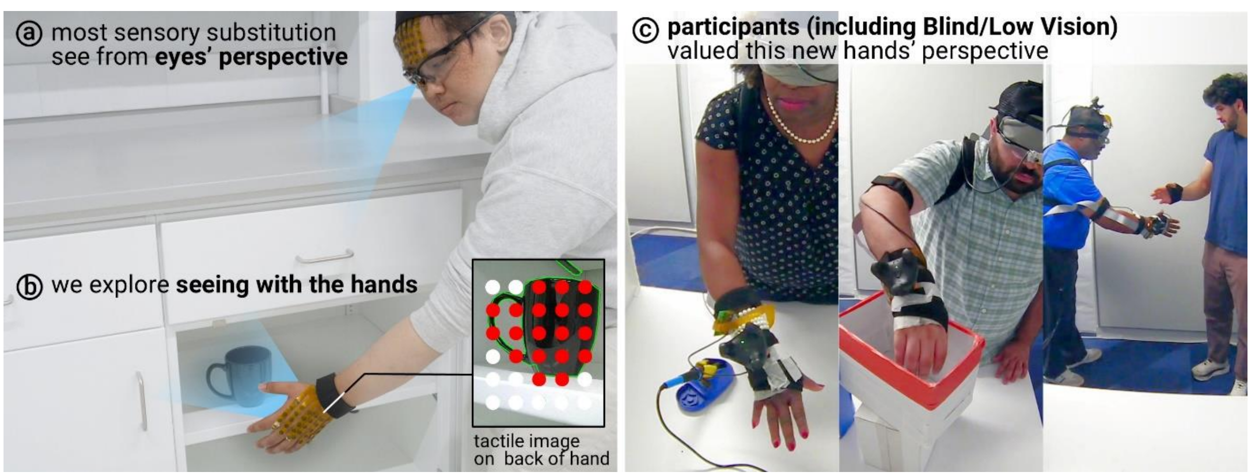

Figure 58: We propose *seeing from the hand's perspective*—camera mounted on the hand, which gets rendered as an electrotactile image on the back of the hand. In our user study, we found that this enables flexible manual interactions, and supports ergonomic interactions, e.g., less crouching, leaning, craning, etc. (Photos with consent from participants)

Motivation for enable seeing with haptics

Perceiving the characteristics of objects (e.g., shape) at a distance is advantageous for preempting interactions (e.g., preparing grasp while reaching for an object), identifying parts of the environment (e.g., avoiding obstacles), and building spatial understanding. Neuroscientists have long established that during the reach phase of a hand grasping movement, humans (as well as other primates) "pre-shape the hand" [78, 216, 217] to best fit the object they intend to manipulate—these types of preemptive adjustments of one's grasp also led some to denote this phenomenon as anticipatory planning of reach-to-grasp movements [191]. Particularly, it has been understood that the target object's shape, size, and orientation influence the activity of hand muscles [49]. In fact, "vision appears to be more relevant for the final phases of the movement" [18], as one's hand approaches an object, real-time visual feedback becomes more critical to prepare their grasp accordingly [18, 54]. However, this is extremely difficult for Blind or Low-Vision individuals who cannot rely on sight for these adjustments during object manipulation.

Sensory substitution devices, while initially proposed to study brain plasticity, became powerful interfaces allowing users, especially those that cannot rely on vision, to *distally* perceive objects by translating information from one modality (e.g., visual) to another (e.g., tactile). Canonical examples of the many sensory substitutions in prior work include the *BrainPort* [255] and a forehead device developed by Kajimoto, et al. [97], which stem from research in visual-to-tactile interfaces dating as early as the 1960s [12]. These interfaces, like others, utilize a camera for input and a tactile array for output. The camera is typically worn on the forehead and captures visual information from the *eyes' perspective.* Images are processed to extract features (e.g., contours of objects) and displayed to the user by means of a haptic device. Most commonly, the device renders the camera's view as a "tactile-image" using electrotactile [89, 97, 255] or vibrotactile [12, 133] feedback. Over the past decades, this type of sensory substitution has successfully enabled Blind, Low Vision, or blindfolded users to tactilely perceive many features of their surroundings from a distance [27, 180]. In fact, *BrainPort* has become a commercially available assistive technology. Given the success of sensory substitution, much research effort has been dedicated to design variations on these systems, especially focused on exploring which areas of the body to use for the haptic output. While the forehead [97, 181] and tongue [11, 89] are two of the most well-known candidates, other devices render their tactile-images to the user's abdomen [133], back [12], and even thigh [37].

Yet, while many have explored where to place the haptic-output, *the camera's location has remained largely unexplored*—with many sensory substitution devices using tactile-images from the *eyes' perspective*. Moreover, to match the viewing perspective, most devices utilize a haptic-output location with a similar frame of reference (e.g., similar viewing angle or even fully parallel) to that of the eyes, such as the case of the forehead (parallel to the eyes), tongue (same heading as eyes), and back/torso (mostly parallel, usually same heading). Intuitively, there are excellent design reasons to use this eyes-perspective and render tactile images to a body location with a similar frame of reference (e.g., forehead), namely the naturalness of the placement (i.e., head rotates, and the view rotates accordingly) as well as the view it affords (i.e., facing forward). These might explain why these devices are typically used for rendering surroundings (e.g., walking [133], avoiding objects [27], and so forth), but *rarely for assisting with interactions that involve object manipulation,* e.g., perceiving the affordance of the object (e.g., shape) in order to adjust hand shape for successful grasping [78, 216].

Hence, we explore **adding a new perspective for assisting with object manipulation**, distinct from the one afforded by the eyes, that might enhance flexibility of sensory substitution.

To this end, we engineer & study a wearable device enabling users to **see with their hands** when hovering over objects. Figure 1 depicts users feeling tactile-images rendered on their hands from a camera mounted on the palmar side of their hands. This new perspective allows users of sensory substitution to leverage the hands' flexibility—hands move rapidly, reaching from multiple angles, exploring tight spaces, circling occluded objects, etc. To realize this, we implemented a novel sensory substitution device consisting of a wrist-worn camera, whose image is displayed as through a 5×6 electrotactile array on the *back* of the user's hand—moving the electrotactile array to the back of the hand prioritizes the ability to interact with physical objects with the palmar side of the hand.

To understand the benefits of "seeing with the hands," we conducted a study on Blind and Low Vision participants, as well as blindfolded sighted participants, who used the eyes' & hands' tactile-perspective, one at a time, to perform challenging manual tasks. We found that while both perspectives provided comparable performance, "seeing with the hands" resulted in more ergonomic interactions, especially when reaching for objects.

At this point, the reader might expect we are proposing replacement of the traditional (eye-view) sensory substitution with one that views from the hand's perspective. However, *this is not the case*. Our goal is to explore and understand the unique advantages afforded by "seeing with the hands" towards the goal of combining both approaches. In fact, we also had participants try out all interface combinations. We found that when given the option to use either or both devices, *all* participants chose to use *both*. We believe that this novel combination will unleash new modes of interaction and new benefits for users of future sensory substitution devices.

Contributions & positionality statement

Our contribution is the exploration of a novel interface concept for sensory substitution, in which users *see with their hands*, by feeling tactile patterns on the back of their hands captured from wrist-mounted cameras.

Benefits. Our approach has several key benefits: (1) it provides a fresh perspective to sensory substitution, by exploring a new location to place the visual & tactile components of the interface (camera on palmar side & tactile image on dorsal side); (2) the hands-perspective was found, in our study, to be suited for ergonomic reaching; (3) it enables new applications for sensory substitution, which we drew from participants feedback; (4) relocating the electrotactile array to the back of the hand provides a new design strategy for sensory substitution devices that wish to prioritize the user's dexterity; and, finally, (5) it is not a competitive approach to sensory substitution, we found that the hands-perspective can be easily combined with the traditional eyes-perspective, and, in fact, all our participants opted to do so in phase 2 of the study.

Positionality statement. Our device & study was co-designed and piloted by a blind lead co-author. This author was born legally blind and has no functional vision now (only light perception and color contrast). We acknowledge that this does not represent the lived experiences of congenitally blind (i.e., no visual memory) and low vision individuals. Moreover, as with our blind participants, our blind author has no prior experiences with sensory substitution, so design decisions were also made from a wish to improve the initial experience with these devices.

Prior work on sensory substitution

The work presented in this paper builds on the field of haptic devices for sensory substitution. Since our goal is to support users wishing to non-visually explore and interact with anything in their surroundings by means of tactile sensations, we primarily focus our related work on tactile-visual *sensory substitution devices*. We also succinctly overview devices for haptic guidance, especially, those also exploring a hand-perspective. Finally, given that our implementation is based on electrotactile, we succinctly review this haptic technique.

Sensory substitution

In 1969, Paul Bach-Y-Rita developed the first sensory substitution device, *Tactile Television*, which converted images captured by a stationary camera into tactile feedback on the person's back [12]. After extensive training, blind individuals were able to understand the movements of people and objects in the environment, etc. Since this pioneering work, many sensory substitution devices have been developed. While the original device enabled a visual-to-tactile translation, others have explored translating to other senses (e.g., visual-to-auditory substitution [39, 150, 256]). Given the extensive range of this field, readers can refer to the reviews on the subject [14, 44, 117, 131, 209].

When focusing on visual-to-tactile substitution, tactile images have been rendered to the forehead [97, 181], tongue [11, 27, 89], abdomen [100, 133], back [12, 76], and thigh [37]. These devices often capture visual information from the *eyes' perspective* or similar references (e.g., torso) and render it to a tactile array using vibrotactile [12, 133] or electrotactile [11, 97]. A modern example is the *BrainPort* [255], a commercialized product featuring an electrotactile display on the tongue. In most cases, the image is processed to extract features—typically, contours—that are rendered as tactile sensations. For instance, if a person using *BrainPort* or the forehead device proposed by Kajimoto, et al. [97] "looks" at a door, they will feel a rectangle of tactile bumps on their tongue or forehead.

Others explored capturing information from the perspective of body parts other than the eyes or the torso. In audio-visual substitution, Brown, et al. [24] found it was easier to recognize objects via a handheld camera (like a flashlight), compared to using a head-mounted camera. In tactile-visual substitution, *FingerSight* [72] proposed a finger-mounted camera that captured edges to be perceived on the finger via two vibromotors. Krishna, et al. [116] used 14 vibromotors on the back of fingers to present facial expressions. *ThroughHand* [88] engineered a tabletop device for visually impaired users comprised of an overhead camera and a shape-changing display; by resting their palms on the surface, users are able to feel the content (e.g., 2D video games) as the pins of the shape display update—while designed for a purpose very different from our approach, this interface shares one common goal with ours, i.e., rendering multiple stimulation points on the user's hands. Kilian, et al. [102] translated the depth image of a camera mounted on the back of the hand to a tactile pattern on a 3×3 vibrotactile array, enabling blind participants to navigate an obstacle course. Lobo, et al. [132] used a line of vibromotors on the legs to represent the height of upcoming obstacles. *SpiderSense* [147] explored tactile perspectives from multiple parts of the body, by translating distal information to servo motors that push against the user's skin.

Hands have been shown to be effective locations for perceiving tactile images. Yet the aforementioned sensory-substitution systems mostly focus on *perceiving virtual images* (e.g., *ThroughHand* [88] renders a game screen, wearable gloves [116] render emoji icons) or *navigating the environments* (e.g., *Unfolding Space Glove* [102] assists only with avoiding obstacles, of identical shapes, while walking). As such, existing sensory-substitution systems rarely consider *interactions with physical objects* (e.g., prepare grasp for object's affordance [78, 216]). In contrast, hand-worn haptic interfaces have been explored extensively to guide the users' hand to interact with objects, which we discuss next.

Haptic guidance from the hands' perspective

Researchers have explored haptic cues to guide the user's hand closer to a target object. Such haptic patterns are typically designed to be perceived from the *hands' perspective*—the spatial information of the target is *relative* to the hand. This has been shown to be an intuitive strategy, e.g., if the target is on the left to the user's hand, the left vibromotor on the hand [23, 59] or on the wrist [164, 213] will vibrate to guide the user to move to the left.

While many works were realized in virtual environments, a follow-up work of *FingerSight* [172] contains a miniature camera with four vibromotors worn around the index finger to indicate the direction to a target. *PalmSight* [235] used a depth camera placed on the palm and five vibrotactile motors on the back of the hand. The direction and distance of a target object (from the depth camera) relative to the hand were translated to activate corresponding vibromotors. While the authors described their work as sensory substitution, they emphasized that *PalmSight* "relies on the computer to make high-level judgement, e.g. whether the target object is identified and what its relative location is to the hand" [235]. This highlights the core difference between *haptic-guidance* and typical *sensory-substitution* systems—haptic-guidance systems must be able to *track the object of interest* which relies on the assumption that (1) the user has indicated an object (they assume it exists in the scene); and, (2) the system will track this object for the user. With these assumptions in place, the system then resorts to different haptic cues to steer the user closer to the tracked object. Compared to haptic guidance, tactile sensory substitution foregoes these assumptions and lets users non-visually parse the scene by themselves—users do not indicate objects of interest or ask the system to track objects. Instead, they receive information about their surroundings and make judgements by themselves (decisions happen in the user's brain, not in the computer).

Bringing the hands' perspective to sensory substitution for manual interaction

Instead of guiding to objects, De Paz, et al. [41] explored a sensory-substitution device that allows free exploration from the hands' perspective to assist non-visual grasping. The device consists of two vibromotors worn on the index finger and thumb. The intensity of the vibromotors increase as fingers approach objects (akin to a game of "hot cold"). The study shows that blindfolded participants were able to locate, identify, and grasp cylinders on a table in a fully-tracked environment using motion-capture system. Yet, since their device only featured two haptic stimulation points (two motors), the authors reported that the device fell short on presenting the shapes of objects [41].

We see a missed opportunity here— how can we leverage the *hands' perspective* to support the complete interactions involved in object manipulation (e.g., including shape recognition)? We believe that by bringing more expressive sensory substitution to the hand (i.e., 2D tactile display allowing to feel tactile images), we can uncover the unique benefits offered by the hands' flexibility and mobility to assist object manipulation.

Electrotactile stimulation

Electrotactile stimulation is a technique that creates tactile sensations by means of electrical impulses, delivered across electrodes at user's skin [94, 190]. Electrotactile has been shown to generate various sensations on the skin (touch, pressure, textures) [51, 195], and offers several advantages over canonical vibrotactile feedback. First, since electrodes can be made thinner (just 0.1 mm thick) than mechanical actuators (physical displacement requires space), electrotactile arrays can be made slimmer and more conformable than a vibrotactile arrays and therefore suitable to be worn on various parts of the body. Second, electrotactile feedback has been shown to be felt more localized than vibrotactile feedback [186, 205], which makes electrotactile a suitable method for high-resolution tactile arrays. As such, besides sensory substitution [91], there is growing interest in electrotactile for many interfaces, such as—touch feedback in virtual environments [192, 197, 222, 227], guidance displays on the user's wrist [186] and foot [205], and prosthetics [187]. We invite the reader to refer to [112] for a thorough review of electrotactile and its applications.

A new perspective for sensory substitution to assist with manual interactions

Typical sensory substitution interfaces are used for assisting with perceiving one's surroundings (e.g., navigation, avoiding obstacles, etc.), which has led to the camera's most common position at the eyes (and in some work, also at torso, waist-level). While prior work explored placing camera on the back of the hand as to avoid obstacles [102], this leaves us to wonder: *could a more flexible perspective, i.e., facing the direction of a possible hand grasp, be useful?*

"Seeing with the hands" for manual interactions with physical objects

We explore a new tactile-perspective by which users of sensory substitution devices "see with their hands"— feel tactile-images rendered onto their hands, which are captured from hand-mounted cameras *on the palmar side*—This is the side of the hand facing towards objects to grasp for hand manipulation (as opposed to [102]). Figure 59 illustrates our concept by contrasting it with the more traditional eyes' perspective: (a) rather than having a camera seeing from the eyes' perspective and a tactile interface to feel via the eyes' frame of reference, we explore (b) *seeing with the hands* via a tactile interface attached to the back-side of the hands—this allows users to preserve tactile sensitivity on the palmar side to grab and manipulate objects with dexterity. This perspective is unique in that it enables users of sensory substitution to leverage the hands' affordances—namely their flexibility & speed as hands can move rapidly around the body, skirting objects, reaching from multiple angles, getting into tight spaces, circling behind occluded objects, etc. As depicted in this example (from our user study), users can use the "hands view" to perceive the shape of the object and adjust their grasp during reaching, even when manipulating a risky object (e.g., a soldering iron).

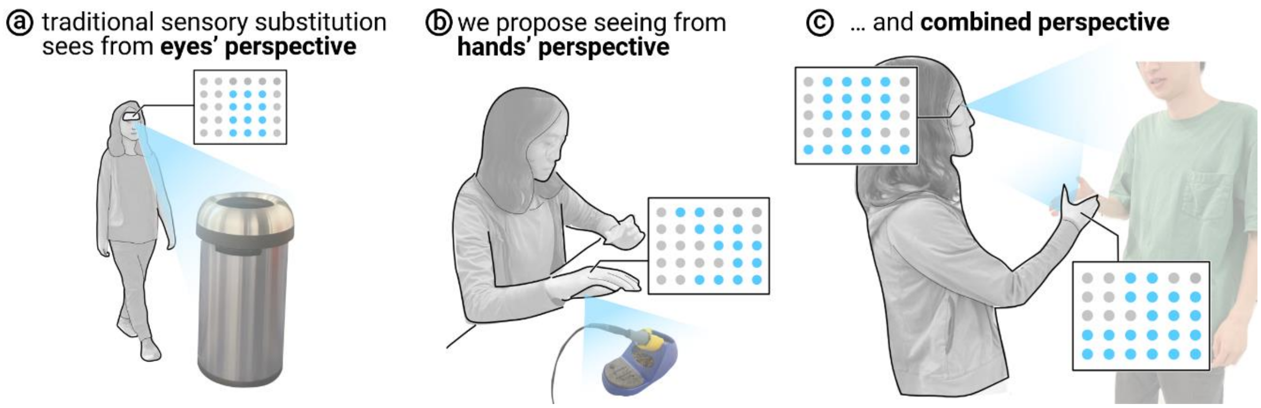

Figure 59: Contrasting three different tactile-perspectives for sensory substitution.

Besides contrasting our approach with the traditional (eyes) perspective, Figure 59 (c) highlights an important aspect of our concept: we are *not* proposing to replace the eyes' perspective with that of the hands'; instead, we believe the advantages afforded by each way of seeing allows these approaches to *combine*. i.e., by seeing from eyes, hands, or both. In fact, we found in our study that when given the option to use either or both devices freely, *all* participants used *both*.

Implementation

To instantiate our concept, we implemented a wearable prototype. To help readers replicate our prototype, we provide the necessary technical details. Additionally, all source code & materials will be made publicly available[3].

Figure 60 (a) depicts our prototype worn at the hands' perspective. For the purpose of our study, we also adapted this prototype to the eyes' perspective, by moving the camera to the forehead (on a glasses' frame) and the electrotactile to the forehead (mounted on a headband as in [97, 181]). Regardless of the type of perspective, our prototype is comprised of two main modules (vision & tactile) connected to a PC where the processing is performed.

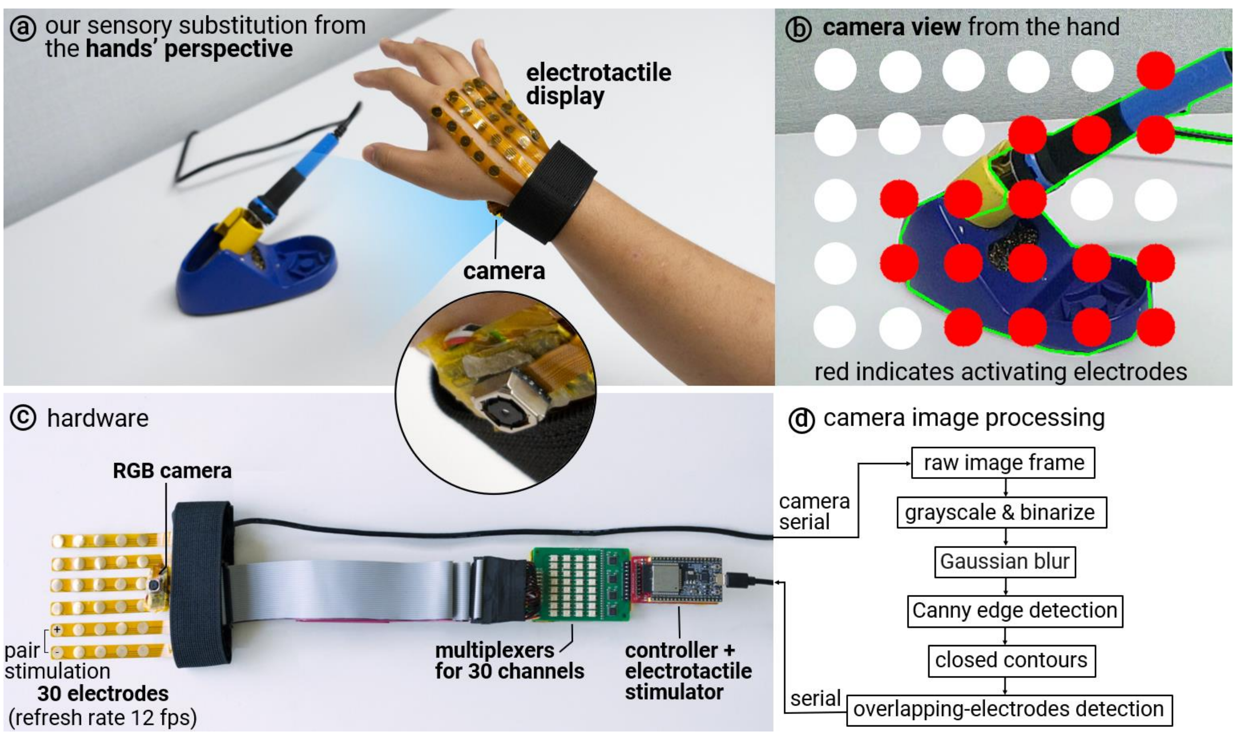

Figure 60: Implementation.

[3] https://lab.plopes.org/#seeing-with-the-hands

Vision module. We utilize a miniature camera (10×10×5 mm) with 60° field of view, to minimize obstruction, especially when mounted on the hand. The camera sends its data over USB (15 FPS). A Python program uses OpenCV to process images, using the simple pipeline in Figure 60 (d). First, we threshold the raw RGB image to grayscale and binarize (at a threshold of 90, adjustable for lighting conditions, albeit not automatically in our implementation). To reduce noise, we apply a Gaussian blur (5×5 kernel). Then, contours are detected with the Canny edge detector [257] and filtered based on their area, retaining only those greater than 1,000 pixels. A final polygonal approximation [258] is used for contour refinement. Finally, a grid of circles (5×6) is projected on top of the processed image, each circular-cell depicting an electrode on the user's skin. An electrode on this grid is considered activated if a contour passes inside, as depicted in Figure 60 (b). The list of activated electrodes is transmitted via serial communication to a microcontroller.

Tactile module. Our implementation makes use of electrotactile stimulation. The hardware is depicted in Figure 60 (c). An electrotactile stimulator [96] and our multiplexer are controlled with an ESP32 microcontroller board. Our multiplexer (similar architecture as [205]) routes which electrodes outputs the stimulator's signals to the user's skin. It can route one signal to a maximum of 32 electrodes. The tactile arrays were fabricated using flexible PCBs (flexPCB), since their polyimide substrate is strong (e.g., hard to rip), while still being relatively thin (0.1 mm). 30 electrodes (⌀8mm) are used to cover the back of hand or the forehead placed in a 5×6 grid with equal spacing (15mm), which is larger than the two-point discrimination on the back of hand (9mm [174]) and forehead (3mm [97]).

Stimulation parameters. We use a pulse generator with programmable current output (circuit design from [96]). For each tactile pixel, we program the circuit to form an electrode pair (we found in pilot experiments that the sensation was robustly felt at the ground electrode, despite the location of the positive electrode; thus we chose to stimulate a horizontal pair of electrodes as depicted in Figure 60c). We stimulate with a square-waveform with a pulse width of 360 µs at 200 Hz. These values were determined through pilot tests as they produced localized and comfortable sensations on the back of the hand. The current (1-5mA) is calibrated for each user (see *User Study* for calibration details). We utilize time division for stimulating multiple tactile pixels. The refresh rate of the entire tactile array is 12 frames per second.

User study: Understanding the contribution of the hands' perspective

The goal of our study is to understand whether there is a unique contribution of seeing with the hands for tactile-visual sensory substitution. Therefore, we designed a study with two phases: **(1) single-perspective phase**: where participants completed tasks using either the hands- or eyes-perspective, but not both simultaneously. This was purposefully designed to collect data (quantitative, qualitative, and observational/behavioral) that captured where they succeeded or struggled with the affordances of each device **(2) combined-perspective phase**: where participants completed a final task in which they could freely choose which perspective they use (eyes', hands' or both at the same time).

Since our goal is to gain insights that might one day impact users of future substitution devices, most of whom are Blind or Low Vision, our study was co-designed and piloted iteratively by one of our blind lead authors.

This study was approved by our institutional ethics committee (IRB21-1229).

Tactile perspectives (sensory substitution interfaces for our study)

Hand's perspective (*hand-device*): This is our proposed new perspective. This was implemented by means of the device described in *Implementation*. Participants wore the *hand-*

device on their dominant hand alongside its back-of-hand electrotactile display that renders tactile image from the wrist mounted camera.

Eyes' perspective (*eye-device*): This is a baseline condition that we chose to represent the traditional approach, with the camera mounted at eyes' level (between the eyes on the frame of an empty glasses). We chose the forehead from prior work (e.g., [97]), as the forehead was shown also be suitable for electrotactile display.

Apparatus. Besides the location of the camera/tactile-array, both devices were identical in their implementation (same hardware & algorithm). Participants also wore both (eye- & hand-) devices at all times. The study was conducted in a room with white walls. A table was used to place objects. For data collection, a fisheye camera was mounted in front of the table. HTC VIVE Trackers were attached to the participants' dominant hand and head for tracking trajectories.

Minimizing bias. Importantly, all participants had no prior knowledge about sensory substitution devices and were not told which was our interface condition (*hand-device*) and which was the traditional sensory substitution device (*eyes-device*), instead they were neutrally asked to try both.

Participants

Eight participants were recruited, five were male and three were female (average age=36 years, SD=15.23). Four were sighted (PS1-4) while four were Blind or Low-Vision (PB5-8). Participants were offered the option not to have their videos recorded, and two participants preferred to not be recorded. Participants were compensated with 50 USD.

Calibration of electrotactile interfaces & tutorial

Before the trials, we calibrated both electrotactile displays and provided an explanation on sensory substitution.

Calibration. An iterative calibration of all 60 electrodes (forehead & hand arrays) was performed to ensure that each of the electrotactile sensations generated by the array could be felt clearly and localized. During calibration: (1) each tactile pixel (an electrode pair) was stimulated; (2) participants then verbally assisted the experimenter with adjusting the intensity of the stimulation (starting from 0mA and increasing by 0.5mA steps), until; (3) the stimulation at the target location was felt clearly and without causing pain; (4) finally, if the sensation was not collocated with the electrode pair (e.g., causing referred sensation at the fingers), the electrode pair was skipped to avoid confusion (at most we only allowed to skip five pairs out of 30 per participant, to ensure at least 25 active and well-calibrated electrodes)—this calibration process is typical in electrical stimulation devices (e.g., similar to [85, 192]).

Tutorial. Most studies on sensory substitution use long training phases, sometimes up to several hours [14]; however, we wanted to explore how participants might make use of natural affordances of each interface so we limited this to 10 minutes per condition (order counter-balanced). In these tutorials, participants had a chance to try sensory substitution for the first time (even our Blind and Low-Vision participants had never experienced such devices) and also experience how electrotactile feels. Participants were asked to: (1) use the device to feel a sponge ball without touching it—this allowed participants to get familiar with field of view of the camera; (2) trace the outline of a plastic frame—get familiar with feeling a bigger object containing line and corner features; (3) explore a PET bottle—get familiar with objects that have a significant third (height) dimension; (4) find & grasp the sponge ball three times—this allowed them to get familiar with the mechanics of the upcoming trials.

Study Phases

Phase 1: single-perspective phase (comparison of eyes' vs. hands'). After training, participants were asked to use each perspective (eyes or hands condition) *one at a time* to complete four tasks while blindfolded (regardless of visual acuity). The tasks were designed by our lead blind author so as to involve a diverse set of everyday manual interactions (extending prior visual-tactile sensory substitution which studied on simple objects [41] or navigation [102]). The tasks as depicted in Figure 61, are: **(1) object identification task**: finding and picking up a pen among three objects on the table (similar to [9] studying daily objects); **(2) object orientation task**: picking up a "hot" soldering iron by its handle (the iron was not actually hot to ensure their safety), which represents a safety task with similar concepts in [122]; **(3) hand-eye coordination task**: find and pick up a bottle lid from the table, and subsequently find a bottle on the table (without touching the bottle, align the two, and aim the lid at the bottle's opening, screw the lid on the opening (this task is similar to a lid-aiming task in [119]); and, **(4) obstacles & occlusion task**: find a small notebook inside one of the three boxes that are placed unknowingly beforehand, without picking up the wrong object (a pen is placed inside another box). The final task represents a scenario with obstacles which were shown to affect reaching [152].

Figure 61: Study tasks.

Trial design. We limited each trial (i.e., a task done using one condition) to a maximum of five minutes—if by the end of the time participants were not able to complete it, we moved to the next. To ensure that participants solved the tasks *using the actual sensory substitution* *interfaces* and not just by touch alone, we instructed them that if they touch an incorrect object, this counted as a mistake. This encouraged that they explored objects via the sensory substitution prior to attempting to grab them. For instance, if a participant in task 1 (picking up a pen among other objects) grabbed the wrong object, a mistake was counted, and the objects were reshuffled to new locations (the completion time was paused while experimenters reshuffled). The participants were given time for breaks in between tasks.

Questionnaire & metrics. During each trial (a task, performed once per device), we collected videos of their movements, completion time, hand and head trajectories, and number of mistakes. Finally, once they completed a trial, they were asked to rate physical and cognitive load (these two items were taken from the NASA TLX [63]) as well as provide comments on what they experienced, which were transcribed by an experimenter. Observed behaviors were transcribed from videos; two of the authors annotated each recorded video using a sequences of codes [123] which included (1) descriptions of hand & head movements and locomotion, and (2) the occurrences of un-ergonomic postures, e.g., neck inclination, trunk inclination, and crouching according to ISO 11226 and EN 1005-4 [42].

Condition order. Within each task, the condition order was counter-balanced across participants (i.e., if a participant used the hands-perspective first for task 1, they would use the eyes-perspective first for task 2).

Phase 2: combined-perspective phase: Finally, participants completed a task in which they could choose any of three perspectives: **(1) eyes-only**, **(2) hand-only**, **or (3) both** at the same time. To toggle between the three different perspectives, they simply said the desired perspective out loud ("hand", "eyes", "both") and an experimenter switched them at a press of a button. **The task was to find a person and shake their hand** (extending a task similar to [133] with additional manual interaction). They were told that the person could be standing at any location of the room with their hand extended, including higher or lower than a normal handshake position. While at first glance this task seems easier than our previous ones (e.g., than finding an object in boxes), pilots with our Blind author confirmed this task is challenging. First, this task is less spatially constrained, i.e., while the objects were on an unmovable table (acts as a frame of reference), a person can stand anywhere in a room (larger frame of reference). Secondly, moving and exploring the room in search of a person is harder than finding objects on an empty table (clear signals), since a person can stand behind camera tripods, in corners, etc. This heightened difficulty was intentional since we wanted to see what participants used each perspective for. At the end of this task, experimenters asked the participants to explain their rationale when choosing the perspective(s) they used.

Results from interactions using a single tactile perspective at a time (eye or hand phase)

We first report findings from the first phase in which participants used one device at a time for each task. The quantitative results including cognitive & physical loads, mistakes, and task durations are reported in Figure 62.

Comparable performances and loads for *hand*- and *eye-device*. We observed a comparable average number of mistakes for both devices, with the *hand-device* at 0.7 (SD=1.0) and the *eye-device* at 0.7 (SD=1.0). Across both perspectives, five (out of a total of 32) tasks were not completed within the limited time. The task durations for the hand-device is in average 148 seconds (SD=102), and the eye device was 139 seconds (SD=97).

The average physical load was lower with *hand-device*. While we did not find a statistical difference in cognitive load (hand: AVG=4.2, SD=1.7; eye=4.4, SD=1.7), we found that the average physical load with hand-device was significantly lower than of the eye-device (AVG=2.1, SD=1.2; eye: AVG=3.0, SD=1.9; paired t-test; p<.001, F(31)= 3.69).

		cognitive load (7-point)			physical load (7-point)			mistakes			task duration (sec)		
	tactile device	sighted	BLV	all	sighted	BLV	all	sighted	BLV	all	sighted	BLV	all
task 1	eye	5.8 (1.0)	5.0 (1.4)	**5.4 (1.2)**	4.3 (2.1)	2.0 (1.4)	**3.1 (2.0)**	0.8 (0.1)	1.5 (1.3)	**1.1 (1.1)**	233 (114)	118 (75)	**175 (109)**
	hand	4.0 (0.8)	4.5 (1.7)	**4.3 (1.3)**	2.5 (1.3)	1.8 (1.0)	**2.1 (1.1)**	1.0 (0.8)	1.8 (1.5)	**1.4 (1.2)**	160 (103)	179 (140)	**170 (114)**
task 2	eye	4.8 (0.5)	3.5 (2.1)	**4.1 (1.6)**	3.5 (1.7)	2.3 (1.9)	**1.9 (1.8)**	0.3 (0.5)	0.3 (0.5)	**0.3 (0.5)**	114 (44)	57 (52)	**86 (54)**
	hand	4.5 (1.7)	4.3 (2.8)	**4.4 (2.1)**	2.5 (1.0)	2.0 (2.0)	**2.3 (1.5)**	0.3 (0.5)	0.5 (1.0)	**0.4 (0.7)**	165 (101)	100 (134)	**132 (115)**
task 3	eye	3.8 (1.0)	2.8 (2.2)	**3.3 (1.7)**	4.3 (2.2)	1.8 (1.0)	**3.0 (2.1)**	0.8 (1.5)	0.8 (1.0)	**0.8 (1.2)**	158 (101)	99 (114)	**128 (105)**
	hand	3.8 (1.0)	4.0 (2.4)	**3.9 (1.7)**	2.8 (1.7)	1.3 (0.5)	**2.0 (1.4)**	0.8 (1.5)	0.8 (0.5)	**0.8 (1.0)**	152 (101)	114 (119)	**133 (104)**
task 4	eye	5.0 (0.8)	4.5 (2.6)	**4.8 (1.8)**	4.3 (2.1)	1.8 (1.0)	**3.0 (2.0)**	0.3 (0.5)	1.0 (1.4)	**0.6 (1.1)**	178 (103)	158 (115)	**168 (102)**
	hand	4.5 (1.7)	4.0 (2.2)	**4.3 (1.8)**	2.8 (1.0)	1.5 (0.6)	**2.1 (1.0)**	0.5 (1.0)	0.3 (0.5)	**0.4 (0.7)**	138 (73)	172 (108)	**155 (87)**
all	eye	4.8 (1.0)	3.9 (2.1)	**4.4 (1.7)**	4.1 (1.8)	1.9 (1.2)	**3.0 (1.9)**	0.5 (0.9)	0.9 (1.1)	**0.7 (1.0)**	170.6 (95.5)	108 (91)	**139 (97)**
	hand	4.2 (1.3)	4.2 (2.1)	**4.2 (1.7)**	2.6 (1.1)	1.6 (1.1)	**2.1 (1.2)**	0.6 (1.0)	0.8 (1.0)	**0.7 (1.0)**	153.8 (85.6)	141 (118)	**148 (102)**

Blind & Low Vision (BLV) participants rated **lower physical loads** for both devices

overall, ***hand-device*** was rated **lower physical load** than *eye-device*, with **comparable performance**

Figure 62: Phase 1 study results (Numbers are average with SD in parentheses).

Blind & Low Vision (BLV) rated lower physical load. We found a significant difference between BLV and sighted participants in physical load with eye-device (BLV: AVG=1.9, SD=1.2; sighted: AVG=4.1, SD=1.8; paired t-test; p<.001, F(15)=5.03), and with hand-device (BLV: AVG=1.6, SD=1.1; sighted: AVG=2.6, SD=1.1, paired t-test; p<.05, F(15)= 2.47). We did not find a significant difference regarding cognitive load. Moreover, we observed comparable mistakes and duration.

Emergent scanning behavior for exploring objects. We observed that participants adopted scanning movements (despite never being told about this)—move their eyes-device or *hand-device* back and forth to "scan" objects. Also, they often reoriented the devices to scan objects from different angles —by rotating their hand when using the *hand-device*, or rotating the whole head/torso/body when using the *eye-device*. This scanning behavior was confirmed by our trajectory data. We found that the average trajectory length showed more movement of the body part where the device was placed. When using the *hand-device*, the hand moved an average of 11.8 m (SD=3.4) while the head moved 5.6 m (SD=1.3). When using the *eye-device*, the hand moved an average of 7.7 m (SD=2.1) and the head moved 9.1 m (SD=2.4). As we will see next in the video observations of participants' behaviors, the length of the head movements (almost comparable to those of the hands) were felt as less ergonomic than hand movements.

***Eye-device* led to more unergonomic behaviors than *hand-device*.** When using the *eye-device*, crouching was more commonly observed to perceive the object from a different angle or to avoid occlusion (e.g., see inside of boxes). Across all 32 trials, 17 crouches were observed with the *eye-device*, compared to only six when using the *hand-device* (an example shown in Figure 63b in thumbnails #3 and #4, which is considered an awkward posture [42]). This observation was corroborated in participants' recounts of their experience. For instance, PS2 stated "[with *eye-device*] I need to bend down, and it was hurting a bit". Similarly, PS3 stated "[with *eye-device*] you can't scan it the same way as using your eyes (...) having to crouch and squat to find these objects". Other unergonomic behaviors [42] while using the *eye-device* were observed for all participants, such as craning the neck (i.e., neck flexion). Furthermore, across all trials, we observed 18 trunk forward inclinations (an example shown in Figure 63b in thumbnail #2) while leaning when using the *eye-device*, compared to only six with the *hand-device*. To this end, PB6 stated: "I don't think [eyes-device] is practical because it's a pain in the butt to always crane your neck to figure out what it is". In contrast, some participants commented on the *hand-device* to feel freer. Namely, PS4 stated "hand[-device] is freer and easier to search". Similarly, PS3 stated "I feel like I really prefer the hand[-device] for scanning and the head[-device] for trying to tell like the shape of the object". Exemplar behaviors in the study are depicted in Figure 63.

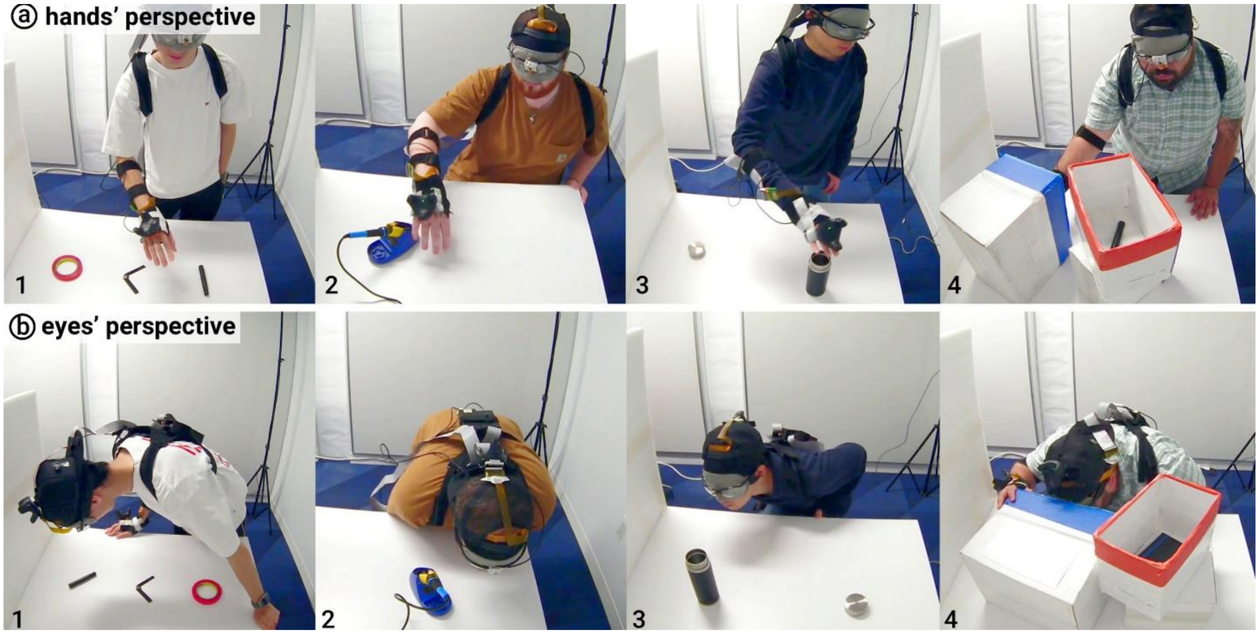

Figure 63: Comparison of hand and eye devices. (Photos with consent from participants)

***Hand-device* felt easier**. Namely, across all their feedback, we found 15 trials where, without being prompted, participants specifically stated that the *hand-device* was easier to use, and only 2 trials where they specifically stated the *eye-device* was easier (for the remainder trials, no specific device was stated to be easier). While there was a high degree of inter-task agreement (i.e., PS1, PS2, PS4, PB6, and PB7 always specifically stated that *hand-device* felt easier regardless of the task they commented on), there was one preference that was task dependent (i.e., PS3 specifically stated they preferred the *eye-device* for task 2, but the *hand-device* for task 1).

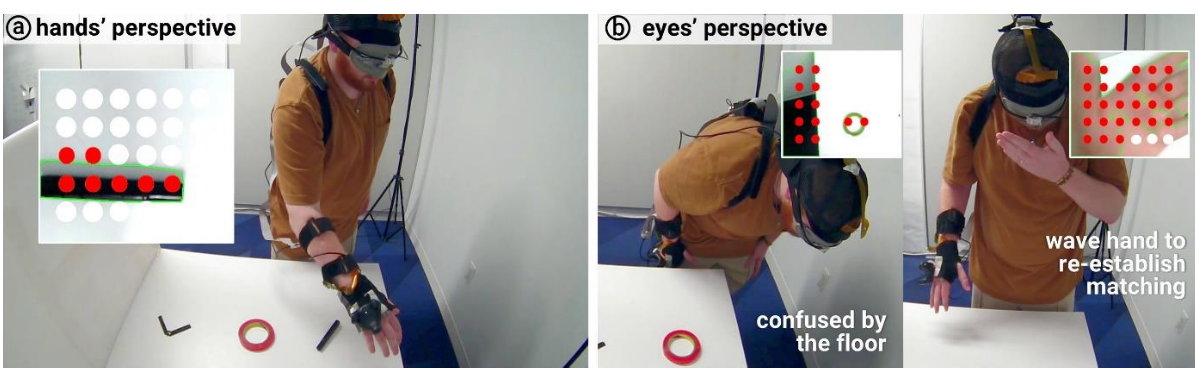

Figure 64: Contrasting the frame of reference for hand and eye devices. (Photos with consent from participants)

***Eye-device* requires spatial reference**. We observed cases in which participants momentarily were lost with their exploration, i.e., not knowing where they were with their device. While this happened for both devices, participants exhibited different behaviors for each device. Figure 64 (b) depicts one example of this, in which PS3 is momentarily lost when using the *eye-device*. They searched for the edge of the table, but confused by their spatial understanding, they waved their hand in front of the eye-camera to re-establish the matching between the tactile image and the physical world. PS3 stated: "I kept finding the floor because of the color contrast". Three participants directly commented on this difficulty in finding their frame of reference. To this end, PS1 stated: "It was easier to figure out where the [hand] camera is intuitively, all I had to do was imagine a camera on the wrist, like, when I think about touching things it needs to go to my palm like having eyes on my wrist it made it a lot easier." Later, they contrasted this with their experience with the *eye-device*, stating: "I map out range that I can see, I used [the] side of the table and feeling of continuous [stimulation] as a reference for where table started [and] ended" (by physically moving their head along the edges of the table). Finally, PS2 stated: "I actually had really hard time [locating] where it is, so I tried to [zoom to] table and maybe it was just near the edge. It was very confusing. I felt like maybe it would be an edge but maybe it would be object also".

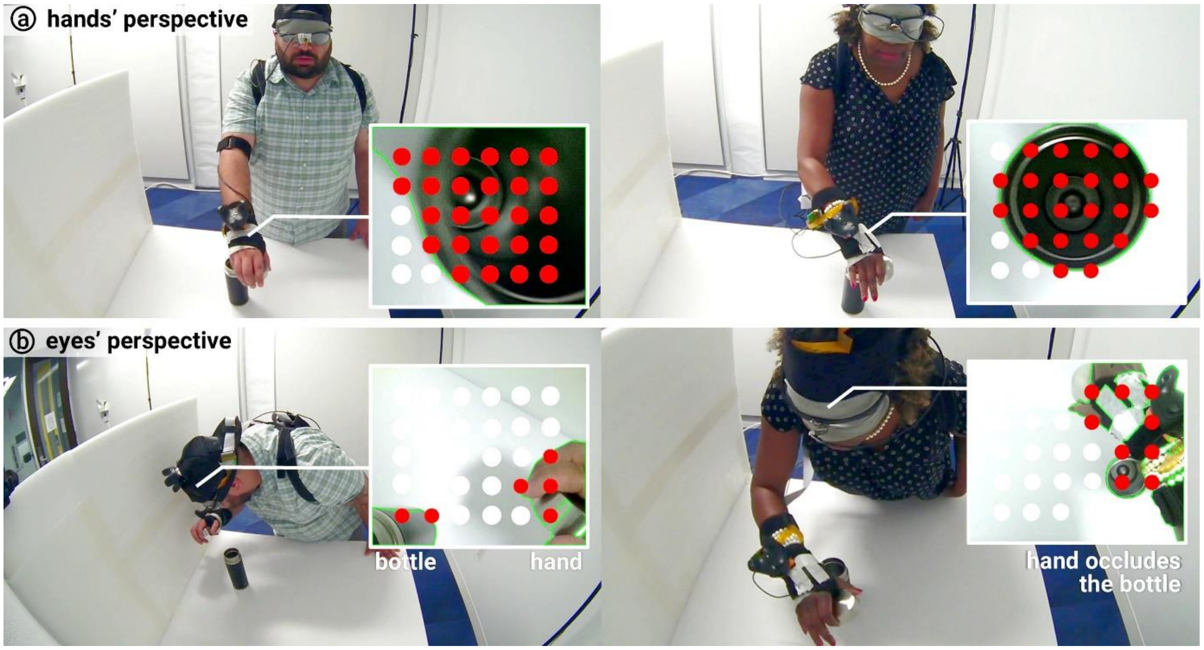

Figure 65: Contrasting using hand and eye device to align the lid and the bottle. (Photos with consent from participants)

Reaching for objects. Generally, we observed that the *hand-device* allowed for a smoother pursuit when reaching objects, while reaching for objects with the *eye-device* required additional matching and was subject to occasional occlusions from the hand during reaching. Figure 65 illustrates some of these observed behaviors: (a) when using the *hand-device*, we observed how participants performed their reaching gestures, often by keeping the object in the center of the tactile array and then pursuing it; in contrast, (b) when using the *eye-device*, participants fixed their head orientation and then moved their hand into the view, checking once it overlapped with the object which indicated the hand was aligned with the object. While this behavior often ran into hand occlusions and can cause confusion (e.g., PB3 overshot their hand to target), it can also be beneficial, for instance, for alignment tasks, such as putting the lid on the bottle as shown; in fact, PB5 stated they found this easier for the bottle task and we observed PS4 using a similar strategy for the soldering iron. From their behaviors we also observed that both PS4 and PB5 were at times confused by their own hand occluding the view, despite the fact they were able to create a compensatory strategy and make it work. Specifically, regarding reaching and alignment with objects, PS1 stated: "[with eye-device] I could feel where the bottle cap was and match where my hand was on the head, [it] helped me pinpoint where I should be moving". Similarly, PS4 stated: "I changed strategy for putting on the lid [after a mistake]. I placed my head so that the bottle is on the left side of the forehead. I tried to approach it with my hand, and it worked".

Results from allowing participants to choose any tactile perspective (eye, hand, both—phase 2)

Finally, we report the results for the second phase of the study, where participants were allowed to choose any combination of tactile perspectives (eye, hand, or both at the same time) to complete the handshaking task. The quantitative results are reported in Figure 66, particularly a per-participant timeline of device usage in this final phase.

Task difficulty. One participant was not able to find the extending hand within the allocated five minutes. The average cognitive load was 4.3 (SD=2.6) and physical load was 2.9 (SD=2.2), both slightly higher than in the average of all the individual tasks from phase 1, which was expected since this task was less constrained than that of phase 1.

All participants used both devices. For this task, participants were able to freely choose which device to use (task started with none selected). Overall, we found that all participants used both devices at least once to solve the task. Specifically, two participants chose to use both devices at all times (PB5, PB8). Three participants switched back-and-forth between the *eye-* and *hand-device,* but only one at a time (PS1, PS2, PB6). Finally, the three remainder participants chose to use all devices either individually, or at the same time (PS3, PS4, PB7). The aggregated timelines of device use are shown in Figure 66.

cognitive load (7-point)			physical load (7-point)			mistakes			task duration (sec)		
sighted	BLV	**all**	sighted	BLV	**all**	sighted	BLV	**all**	sighted	BLV	**all**
5.5 (1.7)	3.8 (1.8)	**4.6 (2.6)**	4.0 (2.3)	1.8 (1.0)	**2.9 (2.0)**	0.3 (0.5)	0.3 (0.5)	**0.3 (0.5)**	208 (93)	91 (43)	**150 (92)**

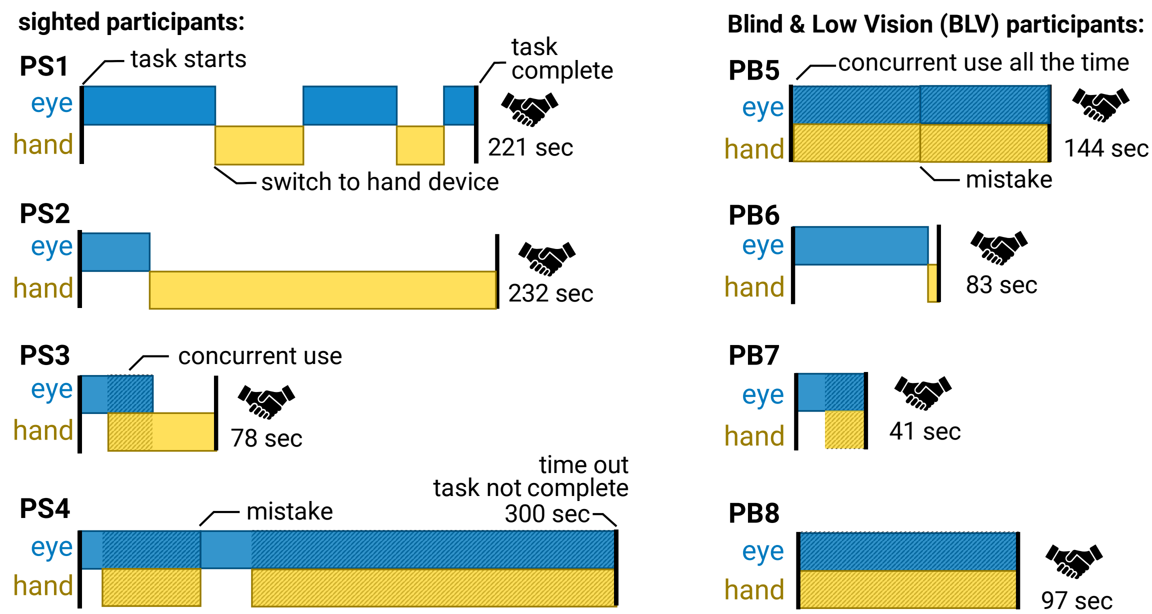

Figure 66: Results from phase 2.

Comparing Blind & Low Vision (BLV) with sighted participants. We found that BLV participants took, on average, less time to finish the task when compared to sighted participants. In terms of cognitive and physical loads, we did not find a significant difference. Interestingly, the two participants who chose to use both devices at the same time were BLV participants (PB5, PB8). Specifically, two sighted participants (PS1, PS2) mentioned it felt overwhelming to use both devices concurrently; conversely, this type of comment was absent with BLV participants.

Switching & concurrent perspectives. As aforementioned, the majority explored all combinations to solve this task, including both trying the devices individually or concurrently. Some participants stated the rationale behind the strategy naturally occurred to them while using the devices in combination. To this end, PS4 stated they used a switching strategy as it helped with attention: "I was not using both, I was focused to either one (...) it was really switching, I used my head[-device] to detect a big object and hand[-device] to detect the arm [of the person to handshake] (...) switching the focus to one [device] was not too hard." To this, but using the devices concurrently rather than switching, PB8 stated: "I was using both equally. I like confirmation from both of them".

***Eye-device* to find the person vs. *hand-device* to find extended hand**. We found that for participants who used a single device at the start of the task (PS1, PS2, PS3, PS4, PB6, PB7) chose to use *eye-device first*, and switch to the *hand-device later*, suggesting a strategic use of devices (as shown in Figure 66). We observed, as exemplified in Figure 67, that participants naturally used the devices for different purposes. The *eye-device* was employed for finding the person in the room (in the words of PS4, "[the] big thing"). Conversely, once they located the person, they focused/switched to the *hand-device* to find the person's extended hand (in the words of PS4, "[the] detailed part"). All but one participant used this strategy, which suggests they naturally found the *eye-device* to provide a sort of overview, while the *hand-device* to provide a sort of pan & zoom—their feedback further corroborated this. For instance, PB6 stated: "I was focused on the [eyes-device] giving me direction on where he is and I was focused on hand[-device] to find his extended hand (...) once the head started really tingling then I immediately started looking for his hand (...) it [was] easier to find his hand with my hand". Moreover, PS4 (and similarly PS3) stated: "I could use hand[-device] to detect more freely, I can use head to detect big thing and used the hand to detect detailed part". PB6 also added to this "[with hands-device] you're working with a smaller space, but with the forehead is a bigger space." Nevertheless, one participant who tried both devices (PS1) used a different strategy from the rest to solve this task: "I ended going up and down with the head[-device] to see where his hand was and where it ended."

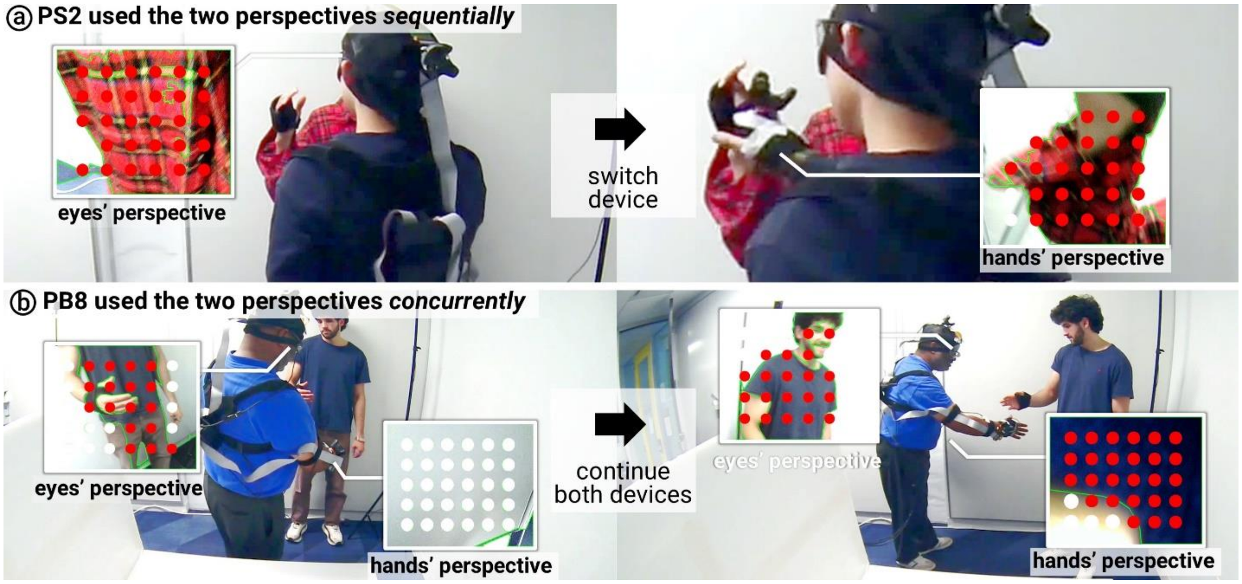

Figure 67: Study phase 2 examples. (Photos with consent from participants)

When combined, only the *hand-device* moved extensively. While in our previous set of tasks (phase 1, where devices were used in isolation) we observed almost as much movement of the *eye-device* as of the *hand-device*, this was no longer the case when devices were combined (here we relied on video observation since it is not trivial to decouple walking from moving head and hand). During combined usage, only one participant performed significant scanning with the head (PS1), while all others only moved significantly the *hand-device*.

Envisioned applications from our study participants

Finally, we asked our study participants what they would envision using either the combined- or hand-device for. We present their feedback, and additionally, in Figure 68, propose envisioned applications drawing from their experiences.

Figure 68: Envisioned applications drawn from participants' feedback.

Situational impairments. Sighted participants envisioned situations where they momentarily could not use their eyes and would rely on the substitutional devices. To this end, PS1 envisioned using the hands-device while cooking with both hands—we depict this envisioned application in Figure 68 (a)—or while walking in the dark and trying to feel where the light switches are (if the camera afforded night vision). PS2 envisioned the hands-device while trying to find objects inside of holes (e.g., pipes or even "in the water"). PS3 envisioned to see "colors" with their hand. Finally, PS4 envisioned the device for "when I'm walking (…) to be more aware of your surroundings".

Blind or Low Vision participants envisioned new combinations (e.g., cane). Our Blind or Low Vision participants also drew extensively from their lived experience as non-visual. For instance, PB5 envisioned a novel use for the combined-device: "the [eyes-]device will (…) know there's something coming, and I will know to move to the left or to the right to navigate around it (…) and the [hand-device] would work well for finding a banister to walk downstairs (…) subway stairs. Because with low vision it's sometimes difficult to find the banister, so me personally I have to hold on to walk down the stairs down"—we depict this envisioned application in Figure 68 (c). PB6 envisioned using the combined-device to "know someone's there and next to you in the airplane or train and I'm not saying it's taking the place of your cane but it's just nice to know". PB6 also envisioned using the hand-device to "reach for things on the shelf, without breaking the glasses"—we depict this envisioned application in Figure 68 (a). PB6 also envisioned using the hands-device for "if I drop earrings on the floor the hand[-device] could be really great for that"—we depict this envisioned application in Figure 68 (b). PB7 envisioned not a specific application but areas in which they could feel that sensory substitution would be advantageous, such as for when working in tight spaces (e.g., for "plumbing or surgery"). Finally, PB8 envisioned many possible use cases for the device, stating: "Earlier today I dropped my cane, and I had to crawl on the floor. But if I had one of these [combined-device] I could follow the [electrotactile]". Then specifically about the hand-device they envisioned: "if I dropped something on the floor (...) under the table I'd try the hand[-device] because if I used the head, I'd have to avoid [hitting] the kitchen table." —we depict this envisioned application in Figure 68 (b).

Discussion & limitations

Limitations of our study: (1) While our study was already several hours long, it only covered a limited number of tasks. (2) The first phase of our study involved tasks that are not perfectly representative of everyday tasks, since we purposefully restricted users to solving these tasks using sensory substitution devices and did not allow them to solve by touch alone. (3) For simplicity, we only tested unimanual tasks. (4) Our results are limited to the number of recruited participants. (5) The computer vision was limited to contour segmentation, while our tactile resolution was limited by the available channels on our multiplexers (30 electrodes on the hand and 30 on the forehead). Therefore, we warrant caution when generalizing our findings to other contexts, which would require validation from future researchers.

Discussion of our findings with respect to future directions. Importantly, despite the aforementioned study limitations, we see a number of key findings that might illuminate future directions. **(1) Core benefits of our device for manual interactions**: We found that, when compared to traditional eyes' perspective, the hand's perspective afforded more ergonomic ways to identify and grasp objects. Moreover, when given the option to use both devices, we found that participants tended to use the eye-device for *overview* and the hand-device for *details*—some even mentioned this was motivated by the extra mobility of the hands, which made it easier for some participants to focus on a certain region of interest (by moving one's hands instead of needing to move the neck or entire torso/body). These benefits arose even with our fixed setup, one can envision future directions in which users can tweak the camera's angle or field of view (e.g., zoom, tilt, pan)—potentially enabling new flexible interactions for sensory substitution devices. **(2) Combination of multiple "ways of seeing"**. It is worth pausing on the fact that our participants, without much training, were able to use the hand-device, since this interaction is completely novel to the brain—humans only see from their eyes. Being able to switch between two kinds of "seeing" with little training illustrates the flexibility of humans in incorporate new sensory signals [13] (e.g., as it is also the case when learning to use a cane). Based on this result, one might speculate it could be possible to explore parallel perspectives (e.g., "bimanual seeing"), fine-grained perspectives, (e.g., "finger seeing", akin to [172]) or even "seeing through other limbs" (e.g., "seeing with foot"). **(3) Perspective switching UI**: In our study, the participants verbally told the experimenters when they wanted to switch between the substitution devices. It is worth exploring the design of interaction techniques for switching perspectives, e.g., automatically based on inferring attention or intention, or manual using direct manipulation interfaces. **(4) More elaborate tactile-images**: Researchers might want to test new vision algorithms (e.g., depth rather than contours), camera placements (e.g., fingertips), or other visual-tactile mappings beyond binary stimulations (e.g., feeling depth, colors, and so forth). **(5) Impact on spatial understanding**: Participants in our study mentioned they memorized where objects were by scanning with our hand-device. It might be worth investigating how this might impact their spatial mental model. **(6) Social acceptance & privacy**: Lastly, as with any device based on cameras, it may also raise concerns regarding the privacy of users, which is fertile ground for future variations that build on privacy-focused/preserving camera approaches [75].

Summary

Most vision-to-tactile sensory-substitution interfaces focus on translating images captured from the eye's perspective to tactile patterns. We argue that this focus on the eyes' perspective is excellent understanding one's surroundings (e.g., navigation and avoiding obstacles), but misses new interactive opportunities that arise from exploring other vantage points for both the camera and for the tactile output device. As such, we proposed & studied a sensory-substitution device that allows users to *see & feel information from the hands' perspective.* We found that this could enhance flexibility & expressivity of sensory-substitution devices to further support *manual interactions* with physical objects. Our device was engineered as a back-of-the-hand electrotactile-display that renders tactile images from a wrist-mounted camera, allowing the user's hand to feel objects while reaching & hovering. Through our user study with sighted/Blind-or-Low-Vision participants, we found unique benefits of sensory substitution from the hand's perspective-participants felt the hands' perspective was suitable for detailed-oriented work and more ergonomic during object reaching. Nevertheless, in the last phase of the study, we saw how the combination of hands and eyes perspectives was also perceived as beneficial by all participants.

We believe these insights extend the landscape of sensory substitution and demonstrate more possibilities of haptic devices beyond VR but for the real world.

Conclusion & outlook

In this dissertation, I envision more haptics, beyond single vibration, to be integrated into **mobile and wearable interactions**, including Augmented Reality (AR). This is a stark contrast compared to the traditional field of haptics, which focuses on the performance for canonical applications such as teleoperation and training in Virtual Reality. I examined and tackled the fundamental challenges for this new generation of haptic devices, including (1) balancing virtual and real haptics and (2) adapting to mobile contexts. Through a series of explorations involving developing a series of novel software and hardware prototypes, I demonstrate the vision and new applications for having haptics in everyday life (e.g., assisting repairing, grasping for Blind users).

Within a few years after the publishing of my work [200], more haptic researchers have focused their attention to the challenge of preserving more haptics from the real world, and proposed new haptic devices through a variety of exciting new techniques [25, 83, 143, 148, 154, 192, 193, 202, 226]. Many of these departed from the traditional approaches such as making devices thin or simply avoiding haptic feedback on the target. Some exemplar efforts include: Tanaka, et al. [192] explored leveraging tactile sensitivity to perceptually render tactile feedback on the fingerpad from relocated electrodes on the back of the finger, which can preserve even more haptics from the real world compared to foldable actuators, since no mechanical parts could block the fingers; Nakayama, et al. [154] further explored using a similar technique but to render lateral forces on the fingerpad, without blocking the fingerpad at all. Tsai, et al. [202] created retractable finger-mounted devices to provide haptics that combine with real-world objects. These works show that this direction has started to become well valued in the community and opens even wider space to explore, involving mechanical, electrical, and interface design aspects.

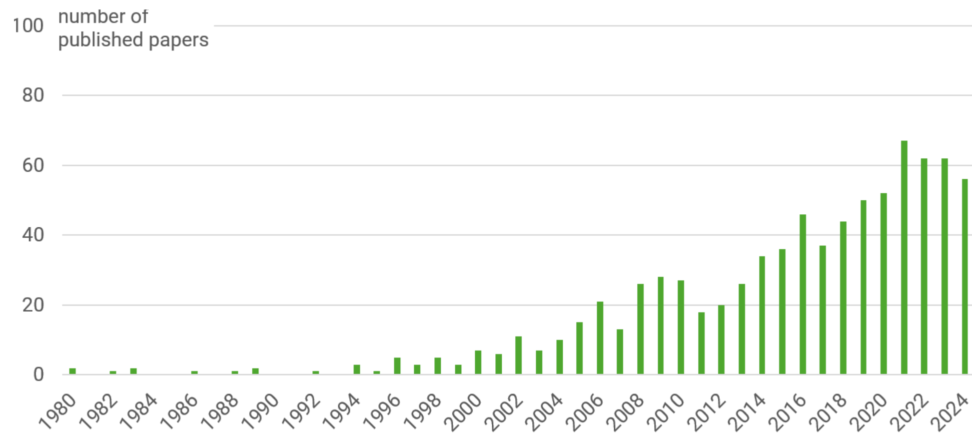

Figure 69: Published haptic papers that include “hands free”, “unobtrusive”, “preserving”, “real world”, etc, queried from Scopus.

Besides new hardware approaches, I see the emerging interest in haptic research that considers less obstructive form factors. Figure 69 shows the numbers of published papers on haptic that contain descriptions of preserving real-world haptics (queried with words “hands free”, “fingerpad free”, “unobtrusive”, “preserving”, “real world”, etc, and filtered out irrelevant papers manually). While this is a relatively small, focused area compared to the field of haptics, it is an exciting start. As we expect more wearable devices including Augmented Reality glasses advance and integrate into everyday life (e.g., Meta Ray Ban), I can project the need for haptics that respect the real world only to grow.

To bring these efforts together, it is worth analyzing various haptic design and engineering approaches for their advantages and inherent limitations. Furthermore, even though individual evaluations were conducted in these works, they are often scattered and not standardized, a new framework for evaluation may be needed as well to understand the perceptual and behavioral effects across these devices under different interactions, e.g., comparison of haptic perception (e.g., sub-modalities, bandwidth, resolution, integration of virtual and real world haptics), performances under different haptic exploration (e.g., passive and active, range of motion [121]), impact on applications (e.g., spatial or temporal sensitive tasks), rendering design and algorithm (e.g., realistic rendering vs. symbolic information [142]).

How far are we until being able to enjoy more haptics anywhere, anytime? This dissertation attempts to discover and tackle the fundamental challenges, especially affecting haptic perceptions. Down the line, developers and researchers should consider other factors such as comfort, environments, maintenance, customization, social acceptability, sense of agency, safety, etc. (one can extend the challenges for vibrotactile devices [20]), along with marketing considerations when translating research prototypes to commercial products.

In the future, if this vision is achieved, haptics, the sense of touch, forces and more, will become common modalities that can be programmed, generated, and presented anywhere, anytime. Augmented Reality will feel seamless as the user dexterously interacts between real and virtual worlds (e.g., multitasking). Learning will become more tangible as the user can feel the shape and textures of any object (e.g., biological tissues). Remote communication will feel more realistic and effective as the user can share haptic sensations with each other (e.g., handshake). Assistance will become more embodied as the user can be directly guided with haptic feedback (e.g., manipulating tools). Haptics can be more intuitive, intimate, but also more invasive. It will be up to us how to use these new capabilities wisely.

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