

Touch&Fold: A Foldable Haptic Actuator for Rendering Touch in Mixed Reality

Shan-Yuan Teng
University of Chicago, USA

Pengyu Li
University of Chicago, USA

Romain Nith
University of Chicago, USA

Joshua Fonseca
University of Chicago, USA

Pedro Lopes
University of Chicago, USA



Figure 1: 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. Here, a user follows MR instructions to repair their bicycle. (a) When the user touches the virtual tire, a cover slides down from our nail-device and pushes against their fingerpad to create the *contact & pressure* with this virtual object. To further increase realism, the cover also includes a linear resonant actuator that renders virtual textures using vibrations. This allows, for instance, to feel the roughness of the virtual mountain tire. Then, (b) when the user turns to interact with real objects, the cover folds back, leaving their fingerpads free to feel the texture of their real tire or operate physical tools.

ABSTRACT

We propose a nail-mounted *foldable* haptic device that provides tactile feedback to mixed reality (MR) environments by pressing against the user’s fingerpad when a user touches a virtual object. What is novel in our device is that it quickly tucks away when the user interacts with real-world objects. Its design allows it to fold back on top of the user’s nail when not in use, keeping the user’s fingerpad free to, for instance, manipulate handheld tools and other objects while in MR. To achieve this, we engineered a wireless and self-contained haptic device, which measures 24×24×41 mm and weighs 9.5 g. 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 demonstrate how our device renders contacts with MR surfaces, buttons, low- and high-frequency textures. In our first user study, we found that participants perceived our device to be more realistic

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than a previous haptic device that also leaves the fingerpad free (i.e., fingernail vibration). 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.

KEYWORDS

Haptics, Wearable, Mixed Reality

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1 INTRODUCTION

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 [7–9, 19, 52]) and contacts from interacting with virtual objects (e.g.,

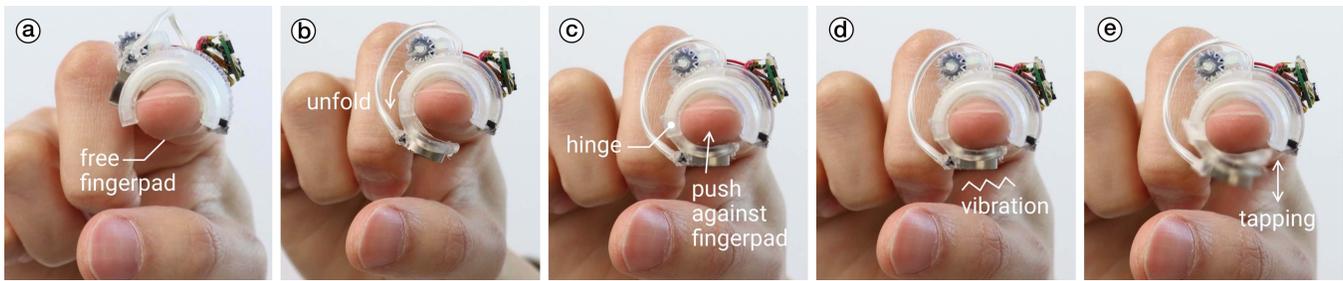


Figure 2: (a) When not in use our device keeps the fingerpad free for feeling the haptics of real-world objects. When activated, it unfolds (b) via a rack and pinion, and (c) a hinge redirects the force against the user’s fingerpad, which allows it to create three types of haptic effects: contact (pressure of the cover), (d) high-frequency textures (using an LRA embedded in its cover), and (e) low-frequency textures (by rocking the cover back and forth).

vibration on the fingerpads [13, 22, 23, 50]). 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 [3, 6, 33, 49, 50].

This is imperative as many powerful uses of MR involve holding tools such as for repairs [17], construction [41], or tangible interactions [18]. 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 [33]. 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 [21, 49, 50] or soft actuators [15]. 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 [34].

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 [2]. 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 1, 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 2

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.

2 SYSTEM WALK-THROUGH

We demonstrate the key qualities of our device with the example of a 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.

2.1 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 3a). The user taps the mid-air “next” button to reveal the instructions for removing the wheel hub nuts (Figure 3b). 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 3c. 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.

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 4a) but also unfolds to creates the textures of different virtual tires.

In fact, our device renders two different textures for two different virtual tires. First, as depicted in Figure 4b, the user strokes their finger across the virtual mountain tire; our device unfolds its cover

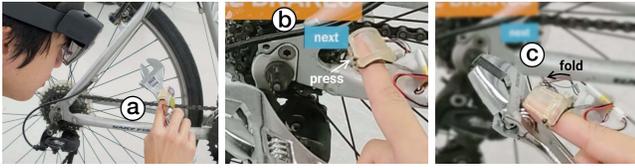


Figure 3: (a) The user holds a wrench while wearing our device. (b) When the user reaches out to touch the virtual button, our device unfolds and renders the contact with the MR button; then (c) as soon as the user’s finger leaves the MR interface, our device folds back, allowing the user to feel and manipulate the wrench with their bare fingerpad.

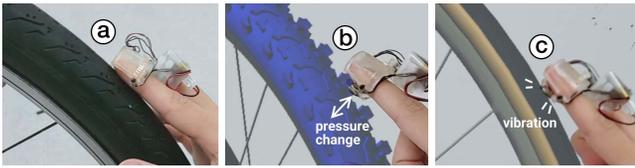


Figure 4: (a) The user feels the texture of their real tire. (b) Our device moves its cover back and forth to render the bumps of a rough, virtual mountain tire. (c) Our device vibrates its LRA to render the fine texture of a virtual racing tire.

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 4c, 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.

2.2 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 5a 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 5b). 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 5c).

3 RELATED WORK

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

3.1 VR and MR Demand Wearable Haptics

As real-walking VR increases in popularity (e.g., VIVE’s light-house [53]), most recent advances in haptic feedback have focused on wearables. These are devices mounted onto the user’s body,



Figure 5: (a) User grips the bike handle while wearing our device. (b) As they type the address, our device renders the clicking of the keys. (c) When they drag the slider, our device renders haptic detents that depict the magnification levels.

delivering haptic sensations anywhere. In the case of MR, this wearability requirement is paramount since most of AR devices are untethered, such as HoloLens [54], MagicLeap [55], or even smartphones [38].

3.2 Force Feedback & Tactile Feedback in VR

Haptics devices can be categorized into two main streams: force feedback and tactile feedback [28]. While force feedback devices render the forces that arise with contacting a virtual object (e.g., feeling the weight of a virtual object [20, 37]), tactile feedback devices render the contact with the object’s surface (e.g., texture [40, 47], temperature [56]). To maximize realism, researchers seek combinations of tactile and force feedback (e.g., [26, 45]).

3.2.1 Wearable Force Feedback. Wearable force feedback, especially in VR, is often provided through the means of motor-based exoskeletons [52] or ferromagnetic fluids [48]. More recently, researchers have explored alternative avenues to miniaturize these exoskeletons using smaller semi-passive actuators, such as brake mechanisms [8, 9, 14, 19], or pulley mechanisms that provide force feedback to the arm [44] or fingertips [12, 46]. Pseudo-force feedback was proposed as an alternative [1]. On the other hand, electrical muscle stimulation (EMS), which bypasses motors entirely and directly stimulates the user’s muscles [30], has been used to enable a smaller hardware footprint for force feedback in both VR [32] and AR [33].

3.2.2 Wearable Tactile Feedback. Wearable tactile feedback is typically achieved by attaching vibration motors to the user’s body, most commonly on the fingerpads [57]. Vibration was used to emulate textures [42], compliance [24], or even to create force illusions [36]. 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 [57].

However, feeling a vibration is different from feeling pressure [27, 31]. Pressure triggers the Merkel cells, while vibrations mainly activate Pacinian corpuscles [27]. 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 [39]; *HapCube*, a finger mounted device that renders stiffness, friction, and pressure by deforming

the skin surface [23]; *FinGAR*, a finger glove device that renders pressure, low- and high- frequency vibration, and shear forces using mechanical actuation and electrical stimulation [50]; 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 [22]. A more general and thorough review of wearable tactile haptics can be found in [35].

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.

3.2.3 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 [43]. 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 [25]. 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.

3.3 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. [2]. 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 [4]; *Tacttoo*, a device comprised of a thin electrode sheet on the fingerpad and a stimulator at the wrist, which electrically stimulates the fingerpad [49]; or *HydroRing*, a finger-worn liquid chamber and a wearable pump, which creates pressure, vibration, and temperature on the finger using hydraulics [15].

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 [34]. Furthermore, with thin actuators, the resulting haptic

feedback is mostly limited to vibrations (e.g., [49]) or small contact areas (e.g., [4]). 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.

4 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 remain 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 [10], 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.

5 IMPLEMENTATION

To help readers replicate our design, we now provide the necessary technical details. Furthermore, to accelerate replication, we provide all the source code, 3D files, firmware, and schematics of our implementation¹.

Figure 6 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.

5.1 Folding Mechanism

At the core of our contribution is our folding mechanism, depicted in Figure 7. Its key design feature is a hemispheric rail from which our "cover" unfolds. Once extended, the cover presses against the user's fingerpad.

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 7a depicts the initial configuration, in which the cover's front segment stays in the case. Figure 7b depicts the cover's front segment is pushed as it is driven by the pinion

¹<http://lab.plopes.org/#touchfold>

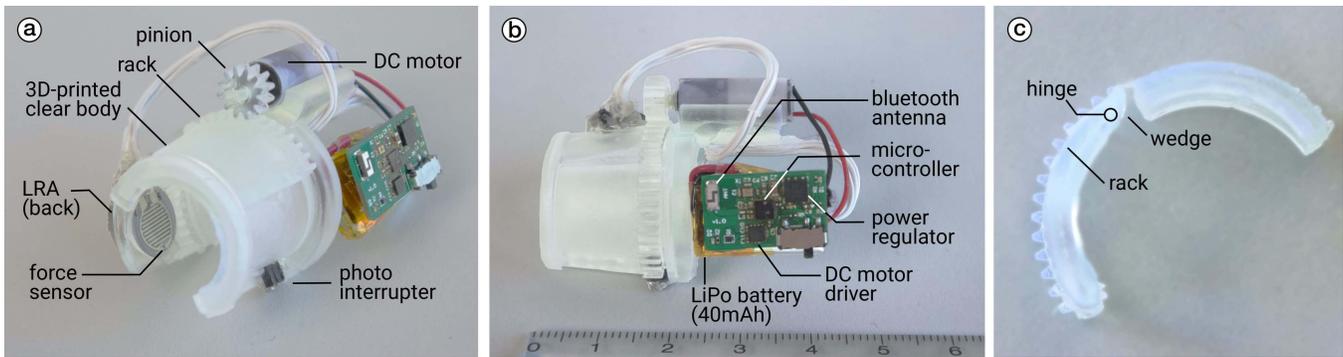


Figure 6: (a) Our self-contained haptic device; (b) detail of its cover; (c) top view of our device with ruler unit in cm.



Figure 7: The key to our mechanism's unfolding is that (a) its cover is comprised of two segments; (b) our hinge is based on two detents that create a stopper and (c) force the cover to pivot and be pushed by the wedge against the fingerpad.

to the point where the front segment is fully extended and hits a hinge stopper at the end of the rail. Figure 7c 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.

5.2 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.

5.2.1 *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.

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.

5.2.2 *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 9a. 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. [16]. Then, we actuated our device so that it contacts the artificial finger and leaves an ink imprint, which we depict in Figure 9b. 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.

5.3 Electronics: Printed Circuit Board And Schematics

Figure 10 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

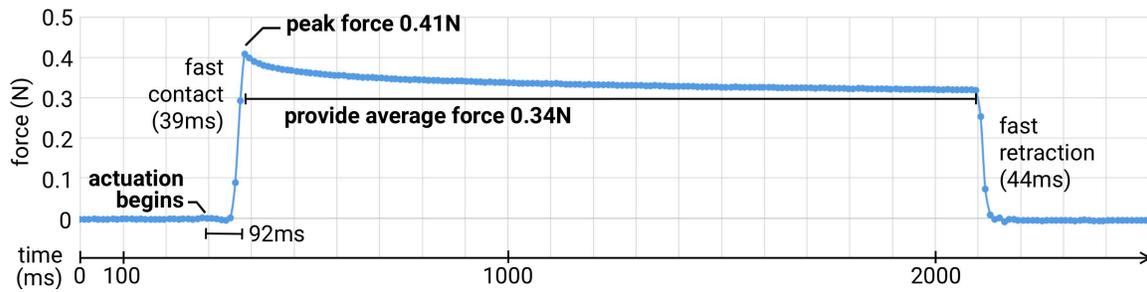


Figure 8: Our device produces a constant pushing force around 0.34N against the user’s fingerpad. Furthermore, it folds and unfolds very fast, taking only around 92 ms.

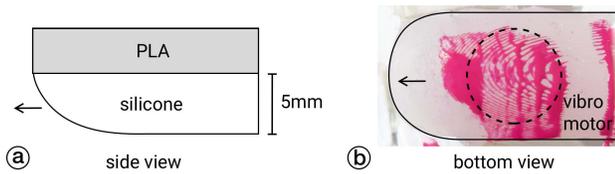


Figure 9: (a) To measure the contact area of our folding mechanism with the user’s finger pad we utilized an ink contact test between our device and an artificial (yet realistic) finger. (b) result from a contact test. (Arrows point to the fingertip).

its footprint, we used a ceramic chip antenna (W3008C, Pulse Larsen), instead of the traditional zig-zag PCB antennas.

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.

5.4 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.

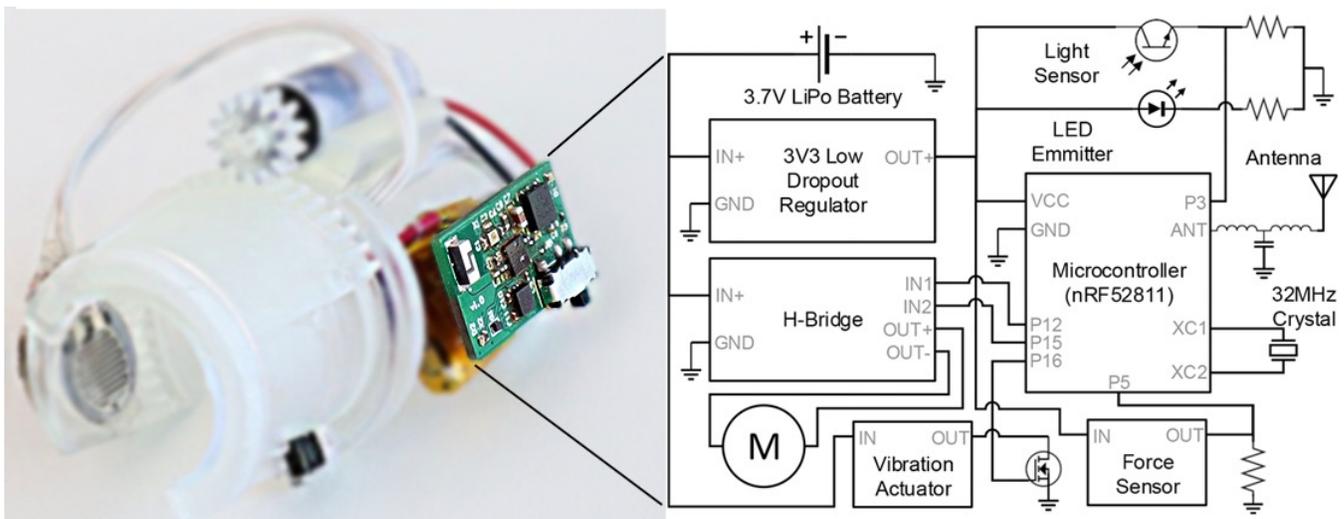


Figure 10: Electronics schematic of our PCB.

- 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.

5.5 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.

6 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.

6.1 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 11 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 [5] or HoverUI [51]. 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.

6.2 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 [29, 33]. Figure 12 depicts a user transitioning between *feeling their real table* to feeling the texture and contact of the table's virtual extension.

6.3 Application #3: Enabling Multi-Finger Haptic Feedback That Does Not Occlude Fingers

To render the feeling of contacting with more complex objects, which typically requires multiple fingers, the user can *wear two*

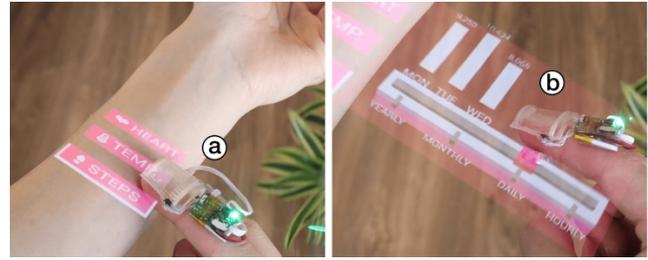


Figure 11: Our quantified-self MR application uses a menu anchored to the user's arm. (a) As our device tucks away when not in use, the user's fingerpad can touch their own arm. (b) When the user touches a mid-air slider, our device then creates the feeling of contact and renders the slider's haptic detents.



Figure 12: In our interior design application, (a) users can feel both the real table but also, (b) the virtually-extended table.

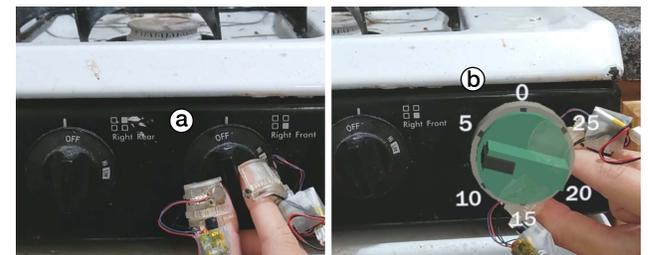


Figure 13: A user wearing two of our foldable haptic actuators to interact with a MR kitchen-timer. (a) Users can grasp the physical knob on the stove as our device leaves their fingerpads free, but also, (b) as they turn the virtual timer knob, they feel the contact and detents (vibration) generated by the two devices they wear on their index and thumb).

(or more) of our devices. Figure 13a 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 13b, 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.

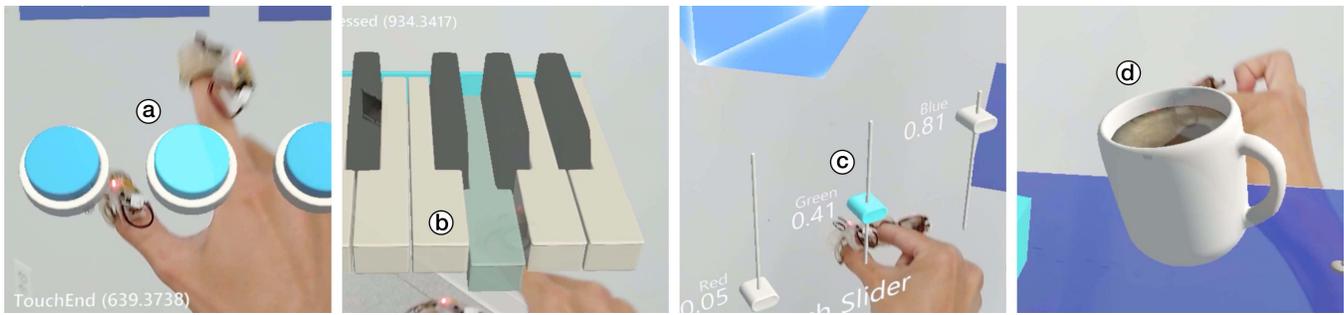


Figure 14: Adding contact haptic feedback to GUI widgets in existing Microsoft HoloLens Mixed Reality Toolkit (MRTK): (a) buttons (b) piano (c) sliders, (d) grabbing objects, a coffee mug in this case.

6.4 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 14, we add the missing haptics to MRTK demos (from the Hand Interaction package [58]). Here, contact haptic feedback is rendered when the user presses any widget, such as buttons (Figure 14a) or even piano keys (Figure 14b). Furthermore, by wearing two of our devices, we also render contact haptic feedback for pinching (Figure 14c) or grabbing virtual objects (Figure 14d).

7 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 [2]), 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).

7.1 Apparatus

Participants wore a North Star headset [59]. 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.

7.2 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.

7.3 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 15). For

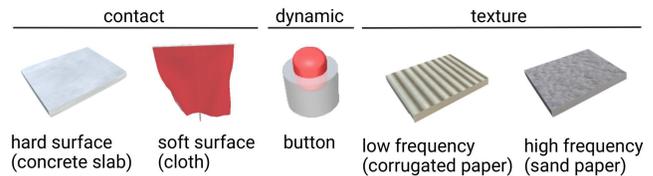


Figure 15: The five MR objects presented in our study: a hard surface (slab of concrete), a soft surface (cloth), a button with a spring mechanism, a low-frequency texture (corrugated paper), and a high-frequency texture (sandpaper).

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.

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 \times 5 objects \times 2 conditions. Trials were presented in randomized order. At the end of the study, we asked participants which interface condition they preferred.

7.4 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.

7.5 Results

Our main findings are depicted in Figure 16. 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.

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

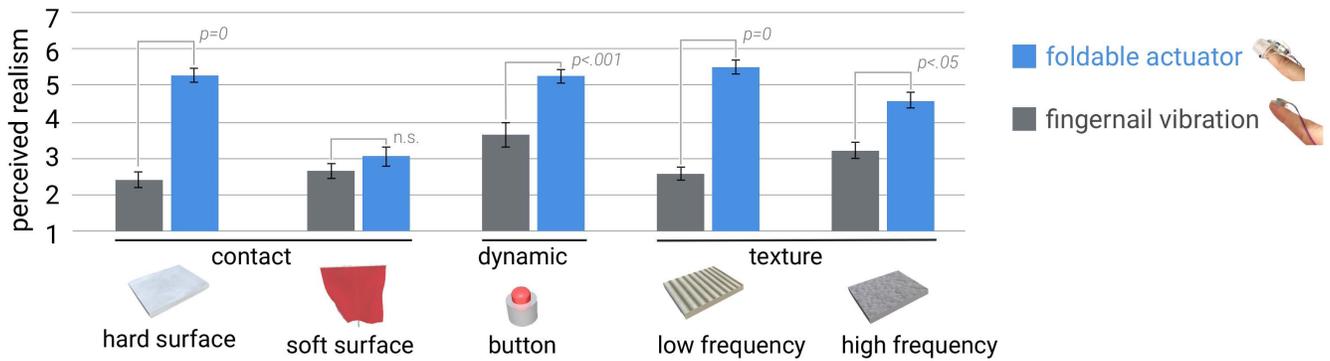


Figure 16: Participants' perceived realism in both conditions.

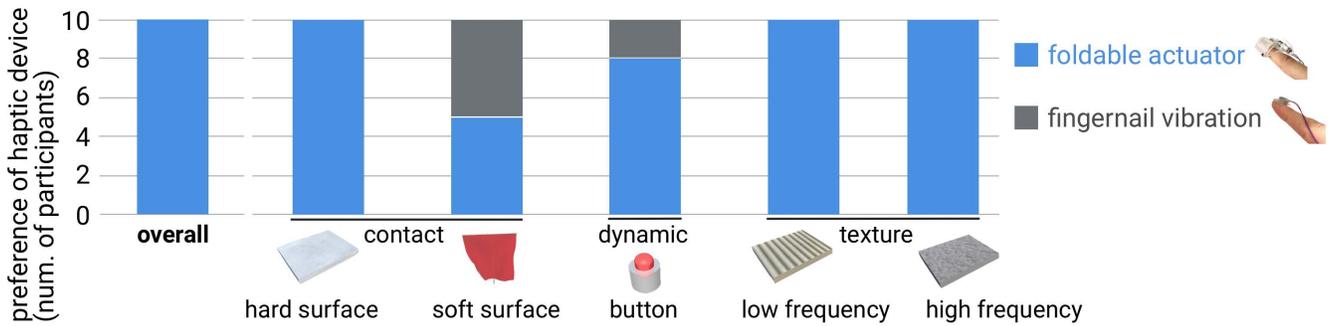


Figure 17: Participants' preferred interface for each MR object.

- 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** ($M=2.4$, $SE=0.21$).
- 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** ($M=2.63$, $SE=0.21$).
- 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** ($M=3.63$, $SE=0.33$).
- 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** ($M=2.57$, $SE=0.18$).
- 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 17 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.

7.6 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".

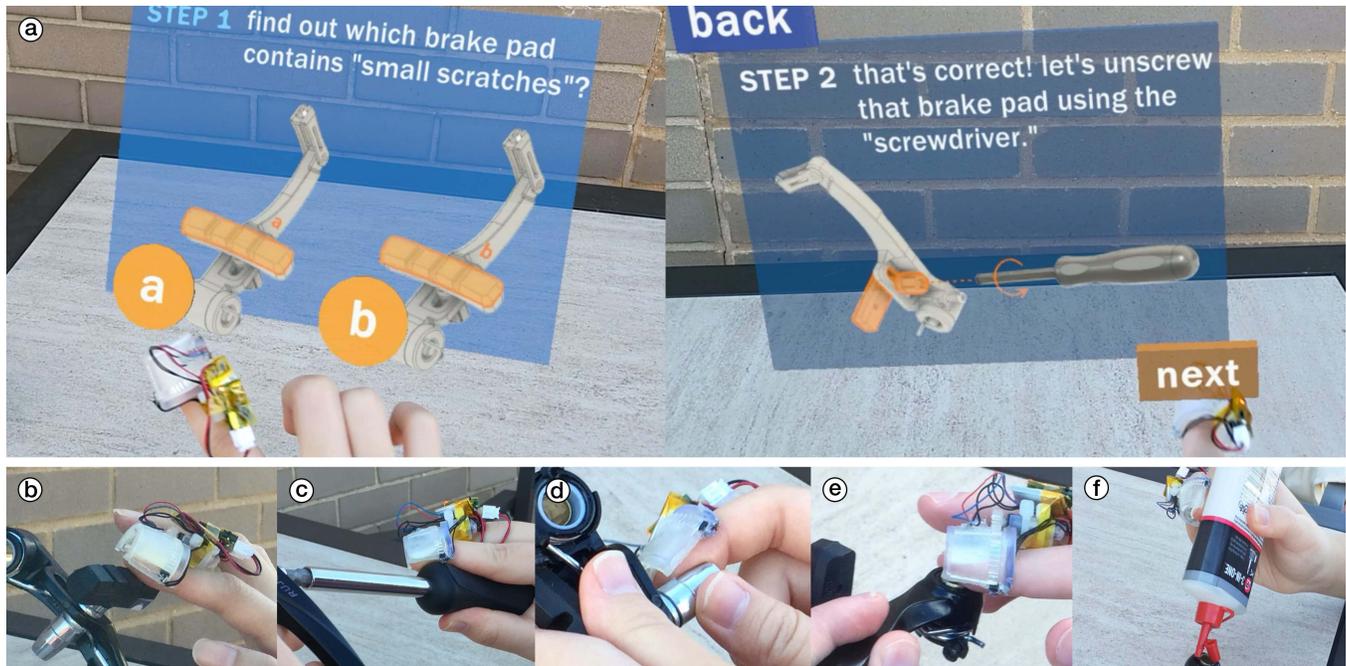


Figure 18: (a) The participants tapped on MR interfaces, in which our foldable actuator provided touch feedback. The participants then followed the instructions shown in MR to: (b) find out which brake pad contains small scratches, (c) unscrew the brake pad using the screwdriver and screw a new one, (d) screw a new brake pad using fingers, (e) feel which part of the v-brake is oily, and finally (f) apply more lubricant onto it. All shots were taken during the task in user study.

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”.

8 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.

8.1 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.

8.2 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 18a. 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).

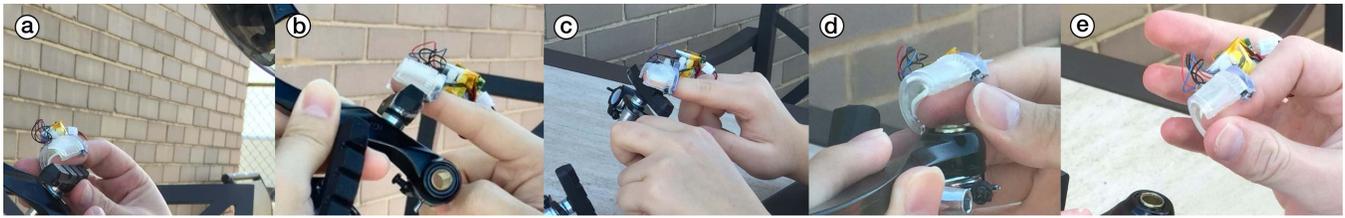


Figure 19: (a) Participant visually examined the brake pad by holding it using the finger that our device sits on. (b,c) Participants used their index finger to touch the surface of the brake pad. (d) Participant used multiple fingers, including the index finger, to feel the oily part. (e) Participant rubbed their index finger and thumb to test if it felt oily.

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.

8.3 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.

8.4 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.

8.4.1 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]”.

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 19e).

8.4.2 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 20c.

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 20d,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]”.

8.4.3 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



Figure 20: (a) Participant held the screwdriver ready to turn it. (b) Participant exerted force on the screwdriver using index finger when turning it. (c) Participant unconsciously raised their index finger while holding the screwdriver, they put down after noticed it. (d) Participant held the oil bottle. (e) Participant slightly squeeze the bottle using all fingers.

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".

8.4.4 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).

8.4.5 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.

9 DISCUSSION

9.1 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 8, 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.



Figure 21: Example of integrating a Peltier element onto our foldable actuator: (a) The Peltier element attached to the cover; and, (b) as the user touches the virtual coffee cup they feel not only contact but also actual heat.

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.

9.2 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 21, 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 [49] can be integrated into our device as well.

10 CONCLUSION & FUTURE WORK

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 $24 \times 24 \times 41$ mm 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.

We believe that our device might inspire researchers to explore new types of foldable haptic designs that optimize their form-factor and are therefore more suited for MR. Future research might consider how small heating/cooling elements [15] or electrodes [49] could be included in our foldable cover, and how sensing and actuation can be integrated in one single LRA [11]. Lastly, while our device creates pressure against the fingerpad, it does not explore skin-stretch [39] or force illusions (by using asymmetric vibration of its LRA [36]).

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