Altering Perceived Softness of Real Rigid Objects by Restricting Fingerpad Deformation

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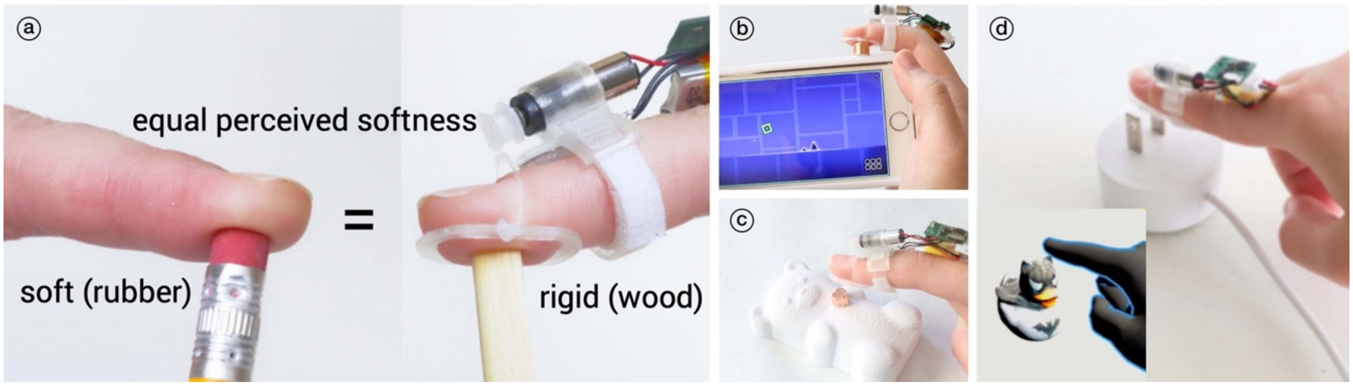

Figure 1: (a) We propose a haptic device that can make *rigid objects feel softe*r. The device works by restricting fingerpad deformation with a motor pulling a hollow frame around the fingerpad. What is unique about our approach is that it leaves the center of the fingerpad free, so the users can still feel the objects they are touching; it is different from typical haptic devices, which cover the fingerpad and only render virtual haptics. We explore our device to alter the softness of (b) rigid protrusions to serve as buttons, (c) part of a rigid 3D printed object, or (d) make the *same* VR prop changes between soft and hard state.

ABSTRACT

We propose a haptic device that alters the perceived softness of real rigid objects without requiring to instrument the objects. Instead, our haptic device works by restricting the user's fingerpad lateral deformation via a hollow frame that squeezes the sides of the fingerpad. This causes the fingerpad to become bulgier than it originally was—when users touch an object's surface with their now-restricted fingerpad, they feel the object to be *softer* than it is. To illustrate the extent of softness illusion induced by our device, touching the tip of a wooden chopstick will feel as soft as a rubber eraser. Our haptic device operates by pulling the hollow frame using a motor. Unlike most wearable haptic devices, which cover up the user's fingerpad to create force sensations, our device creates softness while leaving the center of the fingerpad free, which allows the users to feel most of the object they are interacting with. This makes our device a unique contribution to altering the softness of everyday objects, creating "buttons" by softening protrusions of existing appliances or tangibles, or even, altering the softness of handheld props for VR. Finally, we validated our device through two studies: (1) a psychophysics study showed that the device brings down the perceived softness of any object between 50A-90A to around 40A (on Shore A hardness scale); and (2) a user study demonstrated that participants preferred our device for interactive applications that leverage haptic props, such as making a VR prop feel softer or making a rigid 3D printed remote control feel softer on its button.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interaction devices**; • **Haptic devices**;

KEYWORDS

haptic illusion, compliance, wearable haptics, tactile, VR, props, AR, soft, rigid

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1 INTRODUCTION

Touch is crucial to our interactions with the physical world. As such, many researchers have devoted time to engineering haptic devices to simulate realistic physical effects [2, 3, 25, 26]. One particular

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sensation that many interactive systems try to approximate is the sensation of softness (e.g., pushing a rubber surface), which denotes the material's ability to "easily give way under pressure" due to its mechanical compliance. To interactively simulate the softness sensation, researchers have generally taken two approaches: (1) instrumenting physical objects by adding actuators [23] or, simply using physical props [19, 40]; and, (2) attaching actuators to the user's fingerpad to simulate the softness of virtual objects.

The advantage of physical props is that they are realistic because they are truly compliant. However, modifying the feeling of an existing physical object is not trivial. Prior work has explored instrumenting the object's material (e.g., texture, compliance, and thermal properties) and geometry properties (e.g., size and shape) to provide physical objects a sense of changing compliance/softness. For instance, Kildal et al. [23] altered the users' softness perception toward a rigid box by providing a subtle vibration when users squeeze the box. Other approaches such as *PneUI* [49], used shape-changing interfaces to create soft tangibles materials. While physical props offer realistic sensations, this approach requires us to instrument every single object the users might interact with to achieve ubiquitous interactive softness.

On the other end of the spectrum, researchers engineer haptic actuators that cover the user's fingerpad and allow them to feel "virtual" softness sensations, i.e., touching virtual objects that feel soft (but the objects are not physically present). For example, Quek et. al. [34] created a skin stretch stylus that leverages artificial skin stretch together with augmented force feedback to increase the perceived stiffness of a virtual surface. Many other works rendered the illusion of softness using vibrations [10, 11, 46], stretching fabrics [17], or electrical muscle stimulation [51]. These approaches tend to be either hand-held (users grab onto handles) or wearables, but in both cases, their actuators are directly attached to the fingerpad. As such, with these haptic devices, users cannot feel the texture of *real* objects. In other words, these devices are typically limited to simulating virtual softness.

Thus, the open challenge we try to address is: can we alter the softness of *everyday rigid objects*, without instrumenting them? To tackle this, we propose a haptic device that alters the perceived softness of rigid objects by restricting the user's fingerpad deformation via a hollow frame that squeezes the sides of the fingerpad. In particular, because the fingerpad is restricted by our devices' frame, it is not allowed to deform laterally as it normally would. This causes the fingerpad to bulge outward from its initial position (described in full in Section 3)—thus, when users touch an object's surface with their now-restricted fingerpad, the spread of the contact area between their finger and the object changes. As a result, **users feel the object to be softer than it is**. Figure 1 illustrates the extent of experiencing the softness illusion induced by our device, where touching the tip of a wooden chopstick will feel as soft as a rubber eraser.

To render the softness illusion interactively (i.e., to turn softness on/off for certain parts of a rigid object), we engineered a haptic device that restricts the fingerpad's deformation by pulling the hollow frame against it using a motor. Unlike most wearable haptic devices, which cover up the user's fingerpad to create sensations, our device creates softness while *leaving the center of the user's fingerpad free*, allowing users to feel most of the object they are interacting with. This makes our device a unique contribution to altering the softness of everyday objects. For instance, we demonstrate a range of its applications, such as: creating "buttons" by softening protrusions of 3D printed materials (Figure 1(b)), or even, altering the softness of props for VR (Figure 1(d)).

Finally, we validated our device through two studies: (1) a psychophysics study showed that the device reduces the perceived softness of rigid materials between 50A-90A to around 40A (on Shore A hardness scale); and (2) a user study demonstrated that participants preferred our device for interactive applications that leverage haptic props, such as making a VR prop feel softer or making a rigid 3D printed gamepad feel softer on its button.

2 RELATED WORK

Our work builds upon wearable haptic devices for haptic augmented reality [21], softness perception, and softness rendering techniques.

2.1 Perception of softness

"Softness" and "hardness" are subjective concepts that arise from our evoked perceptions while handling compliant materials [43]. Discriminating a material's compliance allows us to better manipulate and classify objects [43]; thus it is seen as a critical sensation that many interactive systems seek to emulate.

The most common way we assess an object's softness is by squeezing it with our fingerpads. During this, two types of haptic information are sensed, which assist in discriminating the object's softness: kinesthetic and cutaneous cues [43]. Kinesthetic cues arise from the ratio between the force applied by the user and the displacement experienced by the finger as it penetrates the soft object. Simultaneously, the contact between the object and the user's skin also stimulates our skin's mechanoreceptors, arising as cutaneous (or tactile) cues [22]. It is using these cutaneous cues that we sense the object's surface properties, such as its texture and, more importantly for our case, its contact area, which prior work has established as critical for judging softness [1, 7, 14].

Haptic devices have used both these cues to alter the perceived softness, such as creating force feedback, tactile feedback, and even pseudo-haptic feedback. We will now describe how researchers leveraged these cues to emulate softness while touching both virtual and real objects.

2.2 Rendering softness while touching virtual objects

To create an illusion of touching a soft virtual object, researchers in virtual reality (VR) typically construct haptic devices that feature actuators attached to handheld controllers or directly to the user's fingerpad.

One way to achieve this is to leverage the kinesthetic cues is by using force-feedback actuators that push against the user's finger or body. This effectively alters the force-displacement relationship when the user squeezes or stretches an object. For instance, CLAW [12] is a haptic VR controller with a rotating arm that moved the user's index finger according to the amount of object penetration and rendered normal forces based on the stiffness of the object. Similarly, CapstanCrunch [41] is a VR controller that utilized brake mechanisms to render compliance between thumb and index finger.

Beyond finger-level softness/compliance, some researchers also explored stiffness rendering between hands, such as by connecting and dynamically braking to lock two controllers [45].

While the force feedback technique creates softness sensations, these kinesthetic cues alone are not sufficient for providing discriminable softness levels [5]. To improve softness discrimination, researchers also leveraged cutaneous cues by applying tactile feedback. Prior work attached vibrotactile motors to fingertip wearable devices [10] as well as VR controllers [24] to simulate the compliance of virtual objects. Beyond finger touching, the vibration was also used to generate a feeling of compliance from the floor, as we walk on it [46, 48]. While vibration-based actuators are promising for softness illusions, they also do not provide all the tactile cues. In particular, they do not provide a directional compliance feeling. To compensate for the missing directional information, researchers investigated adding skin stretch [34, 35] and skin deformation [38, 39] to improve stiffness discrimination. Many other techniques have also been explored to render softness for virtual objects, including modulating fabrics stiffness state [6, 9, 17], tilting plates [50], and even electrical muscle stimulation [51].

While these haptic devices render virtual softness, they are not suitable for interactions with physical objects (e.g., in augmented reality, with tangibles, or with everyday objects). Unfortunately, to realize these tactile and kinesthetic fingerpad cues, researchers apply the actuators on the user's fingerpad, thereby limiting users' ability to feel real objects. In other words, these haptic devices are only for virtual haptic interactions.

2.3 Rendering softness while touching *real* objects

On the other side of the spectrum, researchers have explored ways to alter the perception of softness on real objects. While one can consider shape displays or other soft-actuators a way to manipulate softness [44], and these certainly have their value in achieving this, we focus on techniques that manipulate softness on *everyday* rigid objects.

One popular way that researchers have explored to change the softness of a rigid object is by means of pseudo-haptics illusions (i.e., illusions that trick the tactile senses without using tactile actuators). These create a sense of softness by leveraging the multisensory integration between visual and tactile sensations that happens in the human brain [16]. For instance, using mixed reality, Hirano et al. [20], superimposed a computer-generated image of a deformation (an indentation on the object) onto real objects. This illusion tricks the user into feeling that the object is deforming by mere visual suggestion. Similarly, Punpongsanon et al. [33] used a projection-based method to add a visual deformation effect around the contact area between the user's finger and the object surface to visually suggest more softness than the object exhibits. Beyond visual cues, researchers have also demonstrated that audio cues as indicators of softness [4, 8]. We take inspiration from the principles behind these illusions but, instead, explore an illusion that works without the need for projectors or mixed reality equipment.

Since pseudo-haptics does not provide any actual tactile experience, researchers also explored combining tactile cues with visuo-haptic illusions. Choi et al. [11] devised a hand-held device, with a voice coil actuator transmitting active transient vibrations to the index fingertip, to alter the perceived softness of passive haptic proxy.

Another approach is to develop rigid objects that might approximate everyday objects (such as generic tangible blocks) that can also display softness sensations. For instance, Kildal proposed Kooboh [23], a rigid tangible user interface that is able to display compliance when squeezed. Its key principle is to use a pressure sensor that measures the user's pressing force and a vibrotactile actuator that responds with vibrations typical of compliant objects. This technique has also been adapted for stylus interactions, in which it enables the user to feel that the writing surface becomes softer [22]. Moreover, also using vibrations, PseudoBend [18] creates a sense of object deformation during bending of an instrumented proxy.

While all of the aforementioned techniques are promising, they are, unfortunately, also dramatically limited: (1) some require instrumenting the objects; (2) others require instrumenting the user's fingerpads, preventing users from any natural haptic exploration of their surroundings; and (3) some rely on custom-engineered generic tangibles, which have their benefits but are not everyday objects.

2.4 Rendering softness for real objects without object-side instrumentations

We drew inspiration from the work of de Tinguy et al. [47], who engineered a haptic device that simulates stiffness on everyday objects. Their device is based on a different principle: it pulls a fabric belt against the finger, not on the fingerpad but on the proximal finger phalanx, which generates pressure and gives the user the impression that the object is pushing harder. As a result, a soft object will appear stiffer than it is. Moreover, in a follow-up work [36], these authors found that releasing the fabric belt at the moment of touch can also make an object feel softer than it is. Our device offers a different take on this, which is based on *restricting the deformation of the user's fingerpad*, rather than applying pressure to the user's proximal finger phalanx. One difference between our device and their approach is that [36] and [47] require pressure changes to signal a change in stiffness, while our technique works as long as the fingerpad is restricted (no changes needed, even if the restriction force is statically applied, which we validated in our first study). Finally, it is worth noting that our approach is currently one-way (softness), while the fabric belt approach works in both directions.

3 WORKING PRINCIPLE OF ALTERING SOFTNESS BY RESTRICTING FINGERPAD DEFORMATION

Our work builds upon prior findings in softness perception and contact area. Haptic discrimination of softness is determined by both kinesthetic and cutaneous cues. Tiest et.al. [5] specifically quantified that the cutaneous cues, produced by the contact between the object and the user's skin, provide the majority (nearly 90%) of information regarding an object's compliance. Other researchers [1, 7, 14] also validated the role of the contact area, which is the key factor we leverage in our device to induce softness. Moreover, Moscatelli et.al [31] found that contact area modulation is even able to induce illusory displacement. In this section, we will illustrate

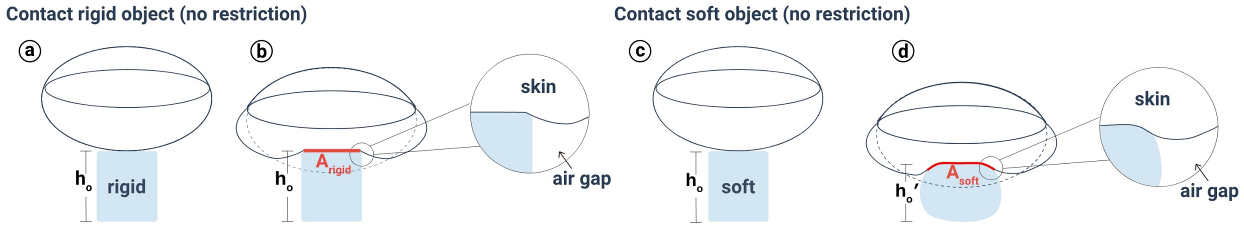

Figure 2: Depiction of contact area when interacting with a rigid object: (a) the finger in its natural shape prior to contacting a hard object; (b) the finger deforms laterally as it pushes against the object; the object does not conform to the fingerpad, leaving the contact area as A_{rigid}. Depiction of contact area when interacting with a soft object: (c) the finger in its natural shape prior to contacting a soft object; (d) the finger also deforms laterally as it pushes against the object; however, since the object is soft, it conforms to the fingerpad, adding more contact area between the finger and object ($A_{soft} > A_{rigid}$).

how our technique modulates the contact area between finger and object, which leads to a change in softness sensation.

First, as depicted in Figure 2 (a) and (b), we examine what happens when a finger comes in contact with a rigid object: the fingerpad experiences pressure on a *small area* [15] and the fingerpad tends to move outwards due to the increased pressure. Because the object is rigid, its surface does not conform to the fingerpad. We denote the resulting contact area as A_{rigid} in Figure 2(b). The resulting pressure distribution over this skin area stimulates the skin mechanoreceptors, providing cutaneous information regarding the object's compliance.

Now, in Figure 2(c) and (d) we examine what happens when a finger contacts a *soft* object: the fingerpad perceives a **wider contact area** because the material itself is more compliant and conforms mechanically to the fingerpad. We denote the contact area as A_{soft}, shown in Figure 2(d), and the pressure spreads more evenly through this area [15]. Much like in a rigid press, fingerpad fat moves outwards due to the pressure. Moreover, the resulting pressure distribution on the skin stimulates the skin mechanoreceptors, which provides cutaneous information regarding the object's compliance.

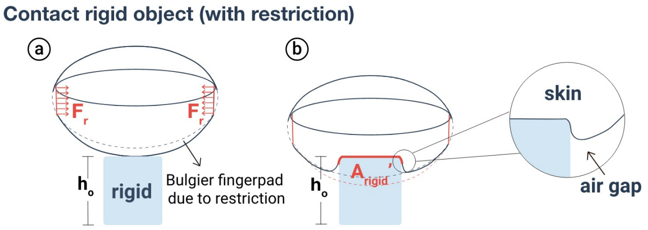

Figure 3: Depiction of contact area when interacting with a rigid object while having one's finger pad restricted to prevent large lateral deformations: (a) the restriction already deforms the fingerpad vertically prior to contact with the object and gentle side pressure is converted to bulginess of the pad; (b) when pressing an object, the restricted fingerpad has a larger contact area with the objects ($A_{rigid}' > A_{rigid}$), compared with touching the rigid stimuli with a bare fingerpad. This larger area is caused by the restriction.

Finally, let us examine what happens when the fingerpad is restricted in its lateral deformation (e.g., two rigid structures apply a constant force on the sides). As shown in Figure 3(a), the restricted fingerpad is about to touch a rigid object. The restriction force causes the fingerpad to be bulgier than it is in a normal state. Thus, when the finger contacts a rigid object, as depicted in Figure 3(b), this new lateral force from the restricting structures leads to a small part of the fingerpad to contact the side of the object. This results in a larger contact area, which we denote as A_{rigid}', and, as we will measure empirically, it is very similar to A_{soft}. In other words, the contact area and, thus, the cutaneous information from its pressure is similar to that of a soft object.

In Figure 4, we depict a typical contact area test using color dye. The pressing force was normal to the object and controlled at 150g for each trial using a load cell. As shown in Figure 4(c), pressing a rigid cylinder (hardness of 90A, 7mm radius, normal touch on top side) via our fingerpad with deformation restriction results in a larger contact area than pressing the same object without the restriction (Figure 4(b)). This validates that the contact area changes with the restriction. In fact, the contact area of pressing the rigid cylinder with our haptic device is most similar to the contact area of touching, with a bare fingerpad, a same-sized cylinder made from a softer material (40A), as shown in Figure 4(d).

4 BENEFITS, CONTRIBUTIONS AND LIMITATIONS

Our key contribution is a haptic device that alters the perceived softness of rigid objects, without the need to instrument these objects. Our device induces a softness illusion while leaves the center of the finger pad free; this enables users to feel the original texture of the objects while experiencing the *same* object switching between a hard and soft state. Our device opens possibilities in softness modification for everyday objects, 3D printed objects, props, or even small protrusions of existing appliances. Finally, we believe our work contributes to the importance of designing and engineering haptic devices that leave the fingerpad free, so that users can also feel the exciting haptics of our real world, not just virtual worlds.

Of course, our work is not without limitations: (1) Our device only works for objects/object parts that are smaller than the fingerpad areas, which limits its application to smaller regions or

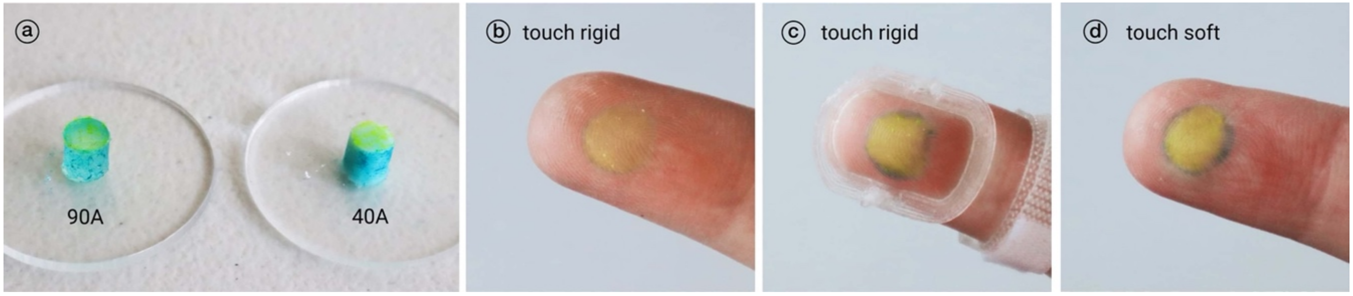

Figure 4: Visualization of contact area when touching cylindrical rubber stimuli of different hardness (touch was normal to object's top surface and controlled at 150 g for each trial using a load cell). Yellow paint covered the top of the object, while blue paint covered the side of the object. The color left on the fingerpad indicates the contact area between fingerpad and object. (a) simple objects used in this contact area test; (b) contact area of touching a rigid stimulus (90 A) with a bare finger pad; (c) contact area of touching the rigid stimulus (90A) with fingerpad deformation restriction; (d) contact area of touching a soft stimulus (40A) with a bare fingerpad.

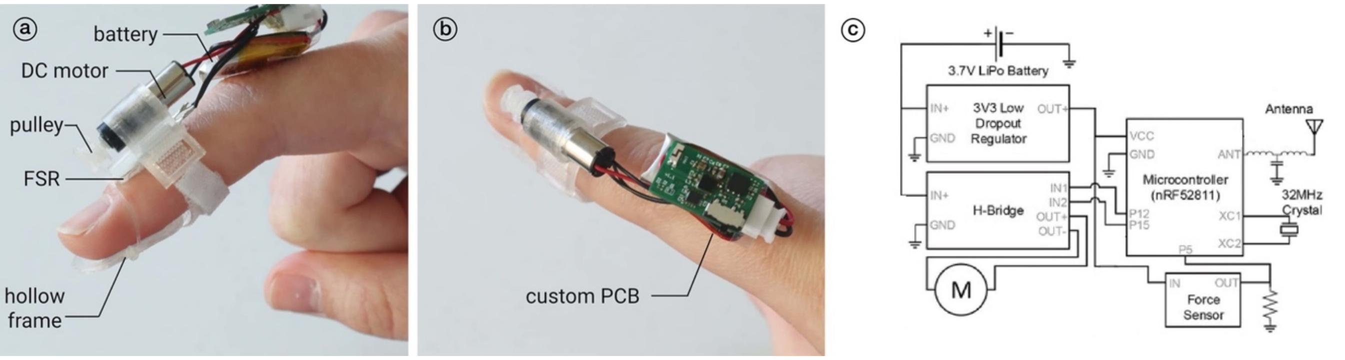

Figure 5: Our self-contained haptic device (a) viewed from the side, (b) viewed from the top, and (c) electronic details of our PCB.

protrusions on existing objects; however, this still leaves ample opportunities for designers to make use of this softness illusion in VR props, 3D printed objects and even small detents on real appliances. (2) Currently, the device allows for a simple switch on the softness state of an object. We expect that researchers building on our work might find ways to modulate this to more degrees of softness. (3) The softness illusion induced by our device works only down to objects around a hardness of 40A; in other words, at some point, it cannot render an object that is already soft, even softer. (4) While our device is unique in its design that leaves the center of the fingerpad free, its frame around the user's fingerpad can still be obtrusive, especially for applications with high dexterity on large surfaces. (5) Like any device that is finger-mounted, the vibration from the operation of the DC motor can be occasionally felt, despite being faint, as such it introduces additional tactile cues that are superfluous to the tactile experience. Still, the benefits of our device and mechanical design might inspire future work to tackle these limitations. (6) Finally, the number of participants employed in our first study is relatively low (N=5), which suggests that more replications should follow.

5 IMPLEMENTATION

We engineered a self-contained wearable device, depicted in Figure 5. To help readers replicate our design, we now provide the necessary technical details. Furthermore, to accelerate replication, we provide all the source code, firmware, 3D files, and schematics of our implementation[1].

Mechanical design. Our device actuates the hollow frame around the fingerpad using a pulley controlled by a small DC motor (136:1 Sub-Micro Planetary Gearmotor 0.55 kg-cm, Pololu), which is housed by a 3D printed casing at the first phalanx of the finger. When the motor is actuated, it pulls the frame towards the fingernail, gently squeezing the fingerpad—this restricts the fingerpad, which is key to enabling the softness illusion.

Electronic design. Figure 5(c) depicts the electronics schematic of our device. Our 16.8 ×10.3 mm PCB houses at its core a nRF52811 microcontroller with on-board Bluetooth Low Energy (Nordic Semiconductor). To decrease its footprint, we used a ceramic chip antenna (W3008C, Pulse Larsen), instead of the traditional zig-zag PCB antennas. We power the entire device using a 40 mAh LiPo battery.

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[1] http://lab.plopes.org/#altersoftness (link to PCB, schematics, 3D files, source code, VR applications, etc.).

Force sensing. To measure the force that the frame applies on the fingerpad so that we can interactively toggle fingerpad deformation restriction on and off during use, we attached a force sensor (FSR, Taidacent) between the finger and the device. A thin silicone pad (2mm, 20 Shore A hardness) is layered on top of the FSR to ensure good contact with the skin. Then, we use a PID (proportional–integral–derivative) controller to adjust the motor to achieve a consistent restrictive force level of 60 g.

Wearability. Inspired by Pacchierotti et al.'s taxonomy [32], we also believe that it is important to emphasize the wearability of our system. The device has a total dimension of 55L × 16W × 25H mm and a weight of 5.03g.

6 OVERVIEW OF USER STUDIES

We conducted two user studies. Our first study consisted of a softness perception experiment, based on a psychophysics design employed specifically to measure the perceived softness [5, 27–30]. The result of this first study established that our device brings down perceived softness of objects between 50-90A to around 40A (on the Shore A hardness scale). While this first study focused on the psychophysics aspects of the softness illusion, our second study concerned observing *in use* device in two interactive applications: (1) a VR application, in which our approach allows the same passive prop to exhibit both a soft and hard state; as well as (2) a simple video game played by pressing a button of a 3D printed remote control, in which the rigid button was made to feel softer using our approach. The result of our second study was that our haptic device was, overall, the preferred interface with regards to haptic realism across both applications.

7 STUDY#1: RESTRICTED FINGERPAD DEFORMATION MAKES HARD OBJECTS FEEL SOFTER

Our first study focused on validating the softness illusion induced by our device. In this study, participants were asked to touch objects of varying hardness and determine the softness of objects touched with a finger wearing our haptic device. This study is based on a traditional psychophysics study employed to measure perceived softness [5, 27–30]. Each trial of this experiment consisted of a 1-up 1-down adaptive staircase procedure.

Our main hypothesis (H1) is that *restricting the deformation of the fingerpad would alter the perceived softness of touched rigid objects*; in other words, we expect that objects touched while wearing our haptic device would appear softer than when touched with the bare fingerpad.

This study was approved by our Institutional Review Board (*IRB21-0397*).

7.1 Apparatus

Figure 6 depicts the setup used in our first experiment. Participants sat on a chair in front of the experiment desk. They could rest their forearms comfortably on the table to manipulate objects. A cardboard stand blocked the participants' view of the actual objects, ensuring that no visuals would confound the softness perception. Participants wore our haptic device (see *Implementation* for details) connected directly via USB, to exclude any confound caused by wireless latencies.

For the stimuli, i.e., the objects that participants touched, we used 10 objects of varying hardness, all within the Shore A hardness scale, specifically: 2A, 10A, 20 A, 30A, 40A, 50A, 61A, 70A, 80A, 90A. This scale captures a "wide range of hardness from extra soft, to soft, to medium soft, to medium hard, and to hard materials" [42]. Each test object was a rubber rectangular prism (6mm x 6mm x 7mm). These objects are all part of a pre-calibrated hardness durometer kit from both *VTSYIQI* (precision ±2 HA per object) and Smooth-On vendors.

7.2 Study procedure

Stair-case design. Our study is modeled after psychophysics studies employed to measure perceived softness [5, 27–30]. The objective was to find what level of hardness/softness does our device induce. We used a 1-up 1-down adaptive staircase design. In each trial of the staircase, participants touched two sample objects: (1) a *test* object touched by one of their index fingers, which wears our haptic device; and (2) a *reference* object touched by the index finger of the opposite hand, which is not instrumented with any haptic device (bare fingerpad). Per trial, participants touched the *reference* and *test* object at the same time for five seconds and responded whether the test object felt softer. As in traditional staircase study designs, if the participants responded "yes," i.e., the test object felt *softer*, the hardness of the next reference stimulus was decreased by 1 (i.e., they were presented with a softer reference object); conversely, if the participants responded "no," i.e., the test object *did not* feel softer), the hardness of the next reference stimulus was increased by 1 (i.e., they were presented with a harder reference object).

Staircase starting conditions. Participants started each staircase procedure by comparing the test object to the softest stimuli in the kit (2A). The test objects were: 40A, 50A, 61A, 70A, 80A, 90A. This test object scale includes two "medium soft" objects (40A, 50 A), two "medium hard" objects (61A, 70A), and two "hard" objects (80A, 90A) based on Shore A hardness scale [42].

Staircase stopping conditions. Each staircase continued until five reversals were reached. The final discrimination value was obtained by averaging the last three reversals [13].

Repetitions and counterbalancing. Because we asked the participants to use their two hands (one instrumented with our device and another without), we repeated each staircase twice, swapping which hand wore the haptic device. The order of these was counterbalanced across all participants.

Procedure duration: In total, each participant completed 12 staircases (six *test* objects × counterbalancing of which hand wore the haptic device), which took around 60 minutes to complete. Participants were able to take short breaks in between staircases as desired.

7.3 Qualification round

We conducted a simple experiment to ensure our participants have enough haptic discrimination to identify the difference between our base stimuli. We asked participants to order all the stimuli (the 10 objects previously described) in ascending hardness. If a participant

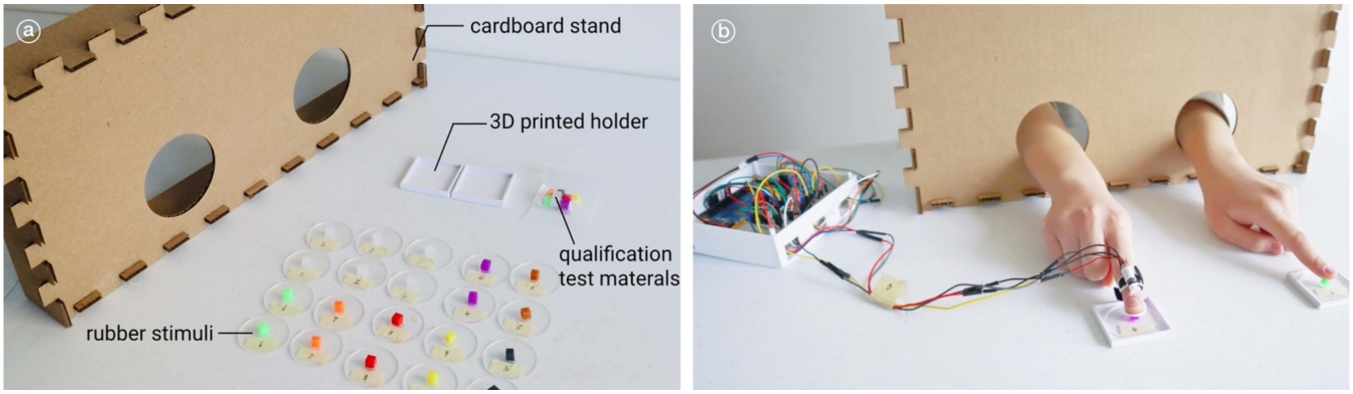

Figure 6: Depiction of (a) the experimental apparatus used in our study 1; (b) a participant touching two different samples to judge softness.

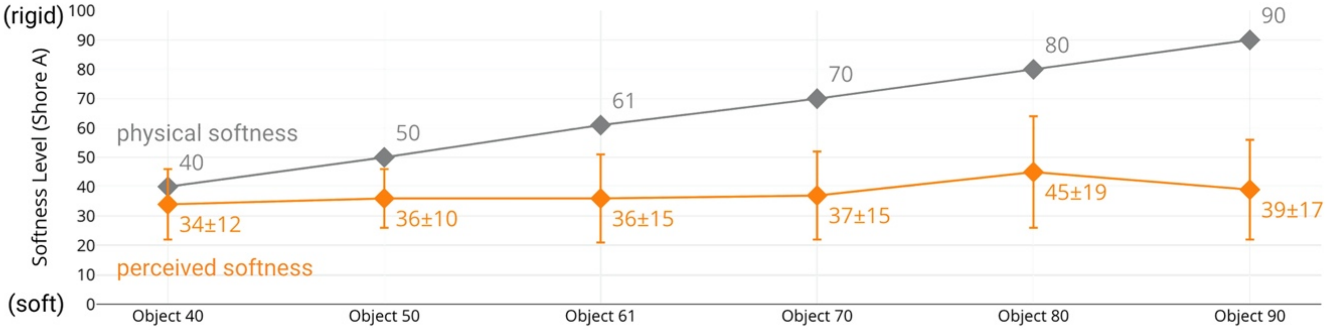

Figure 7: Study 1 result. Grey markers visualize the physical softness of test objects participants touch in each trial. Orange markers indicate the average of perceived softness across all five participants (10 hands) and the standard deviation.

was not able to rank correctly in five trials, we did not include their comparison data. We conducted the qualification round after all the study tasks were completed to avoid the participants memorizing the test stimuli softness.

7.4 Participants

We recruited five participants (two self-identified as female, three self-identified as male, all right-handed; with an average of 24.4 years old, SD=1.02). No participants reported prior injuries on their hands. Participants received a compensation of $30 for their time.

7.5 Results

All five participants passed the haptic discrimination qualification test, and no data was excluded. Figure 7 shows the main findings, which validated that our device made objects feel softer than they were.

The average perceived softness was found to be around 38A, considering all test objects. For test stimuli with the physical softness of 40A, 50A, 61A, 70A, 80A, and 90A, our device brings the perceived softness down to 34±12A, 36±10A, 36±15A, 37±15A, 45±19A, and 39±17A. Except for the 40A object, all other stimuli have their physical softness at least a standard deviation above the perceived softness. It includes all the test stimuli classified as "medium hard" and "hard" (61A, 70A, 80A, 90A), and one "medium soft" object (50A), based on the durometer shore hardness scale [42].

The above results suggest that our main hypothesis is supported, i.e., restricting finger pad deformation makes rigid objects feel softer than they physically are. Furthermore, we see our device played a role in a medium soft stimulus that is closer to the hard object end (50A), but not the stimulus closer to the soft object end (40A).

8 STUDY#2: OUR SOFTNESS DEVICE ADDS REALISM TO HAPTIC PROPS IN INTERACTIVE APPLICATIONS

Our first study validated the softness illusion in a controlled psychophysics experiment using abstract objects (i.e., rubber stimuli from a durometer kit). Our second study focused on the device's effectiveness when participants touch real objects serving as props in interactive applications. We wanted to validate how the softness illusion induced by our device adds benefit to two applications: (1) a VR shopping application, where the users are presented with two VR pencils with different cap erasers. Here, our haptic props are a pair of chopsticks and yet, our device allows the user to feel that one of the chopstick tips is soft, which corresponds to the softer cap eraser in VR; and (2) playing a jump 'n' run game using

Figure 8: Study 2 applications. (a) chopstick as a prop for VR pencil rubbers; (b) 3D printed gamepad for jump-and-run game.

a 3D-printed remote control, in which the button on the remote control is touch-sensitive, inspired by the work from Savage et. al [37]; our haptic device can add the sense of softness when the user pushes the rigid buttons.

Our hypothesis is that by wearing our haptic device, participants would experience more realistic haptic feedback while touching the everyday props or 3D-printed objects in the interactive applications.

This study was approved by our Institutional Review Board (IRB21-0397).

8.1 Apparatus and applications

Figure 8 depicts the setup used in our experiment. We utilized the same haptic device as in our previous experiment. Participants sat on a chair in front of a desk. They could rest their forearms comfortably on the table while interacting with the VR scene or with the 3D-printed remote control. Unlike in our previous experiment, the participants' view was not blocked or restricted in any way (except by the HMD in the case of the VR application).

VR application. Our application is a VR shopping experience, in which the participants touched two pencils' cap erasers with their dominant index finger to compare the softness before purchasing. Visually, they would see one of the cap erasers deform upon touch, indicating that the eraser was soft. In reality, we used chopsticks as VR props. For the device condition, we actuated the device on the index finger when the user's fingers were approaching the "softer" cap eraser and deactivated it when they moved away. The deformation of the eraser and the actuation timing of the device were both calculated based on distance between fingertip and the eraser top, detected via Oculus' hand tracking.

Video game application. For the video game, we asked users to play a jump 'n' run game using a custom 3D printed remote control. The controller button was touch-sensitive enabled by capacitive sensing. Participants were asked to put their thumb finger on a resting area on the controller when not pressing the "jump" button. Our device actuated when the participants move their fingers from the resting area to the button area and deactivates when they moved the fingers back. In this application, participants wore the haptic device on their thumb, which allowed as to explore the device on other fingers as well.

8.2 Study procedure and interface conditions

Participants experienced each application twice, one for each interface condition: with **haptic feedback** from our device and **without** (baseline). The order of applications and the order of conditions in counterbalanced across all participants. For each trial, they experienced the application for three minutes.

After each trial (i.e., playing one) participants were asked to rate how realistic were the pencil top eraser or button pushing felt on a Likert scale (1 to 7), with 1 being "not realistic" and 7 being "realistic." At the end of both trials for one application, we asked participants which interface condition they preferred with regards to the haptic realism. At the end of the study, we conducted an interview to understand participants' general experience.

8.3 Participants

We invited 10 participants for this study (three self-identified as female, seven self-identified as male, all right-handed; with an average of 23.2 years old, SD=2.48). Five participants previously participated in study #1; none of them reported injures on their hands. Each participant received a compensation of $30 for their time.

8.4 Results

Figure 9 depicts the results of our study. Overall, we found out that our haptic device provided more realistic haptic feedback for the gamepad and was the preferred interface by the participants in both conditions.

We analyzed our data using two-way repeated measure ANOVA and found a significant difference in rated realism of the props between two interface conditions (with and without the device F (1, 9) = 15.47, $p < 0.005$). This suggests that our hypothesis is supported, i.e., participants experienced a more realistic haptic feedback when touching haptic props with our device (M = 4.6, SD =1.2) compared to without the device (M = 3.2, SD =1.7). Moreover, we found no interaction effects between the two interface conditions and the application types (p = 0.34). We further conducted Tukey multiple comparisons to understand realism rating in individual applications regarding interface conditions. It shows a statistically significant

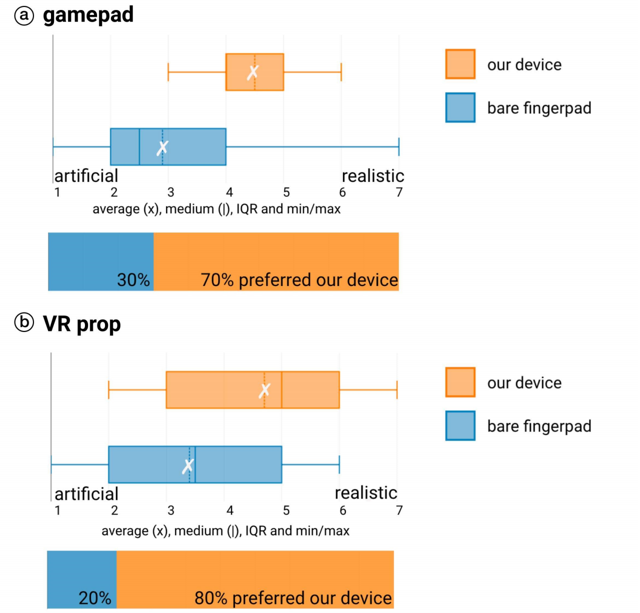

Figure 9: Realism and preference across all participants for: (a) the gamepad interaction, and (b) VR prop interaction.

difference between the interface conditions in the video game application ($p < 0.05$). Button pushing is more realistic under our haptic device condition. Seven out of ten participants claimed that they prefer our haptic device regarding haptic realism after trying out both conditions. For the VR application, while there is no statistically significant difference between the two interface conditions ($p = 0.09$) in the realism rating, their comments, and their preference toward our device (8 out of 10 participants preferred our device), suggested they might have found it beneficial as well.

8.5 Qualitative feedback

Feedback on video game application. When asked about participants' experience in interacting with the 3D printed remote control *without* the haptic device, almost all participants mentioned that the button felt unrealistic as it was rigid and could not be pushed down. For example, P1 stated "it's weird to press something hard; I didn't feel how hard I need to push on it to make it work". P8 and P5 added that the button "has no feedback" (P8) and "doesn't feel like interactive, only a solid object" (P5). The three out of ten (P2, P3, P9) that preferred this condition, were hesitant in choosing a favorite for this application. In particular, P2 and P3 stated that they did not feel a significant difference in the two conditions to warrant a favorite, while P9 felt the softness difference but also felt additional feedback from the motor vibration, which they disliked.

Conversely, with our haptic device, participants felt the button pushing experience was more realistic. In fact, a majority preferred our haptic device to the baseline condition (seven participants out of 10). For example, P7 commented that "the button is clickable. It feels like moving away from a real button, which has a spring." Similarly, P8 commented "there is a changing resistance from the button." P10 and P1 emphasized the reaction from the button, saying the button "reacted to what I did [pressed]" (P10) and "felt response to my input" (P1). Both P10 and P5 also brought up the feeling of "deformation sensation." P9 related the experience to pushing a button on iPhone and commented that "feel nice about something is being pushed to make the action happen." Again, it is worth noting that this button is rigid, and all these evoked haptic sensations arose due to our device.

Feedback on VR application. Participants had mixed feelings regarding touching the pencil eraser with their bare fingerpad, i.e., *without* the device. The majority of the participants felt a mismatch between the visual and haptic experiences. For example, P9 explained that it was "just visual response on softness deformation, nothing on my hand; both [props] felt the same as rigid". Some participants (P4, P6, P10), however, were tricked by the visuals, which indeed deformed the virtual rubber. P4, for example, stated they felt a haptic difference by "just seeing the visuals," which is typical of these kinds of pseudo-haptic experiences elicited by visual modalities.

Conversely, while wearing our device to touch the rigid haptic props, the majority of participants (eight out of ten) reported a closer match between haptic and visual experience when touching the eraser. P8, for example, said "when I rub the finger on the chopstick [prop], it does feel bouncier." P5 also added that "physically what I felt match with the visual bounciness." Even for participants who were tricked by visual cues, the device still played an effect. P4, P6, and P10 all stated that the softness level rendered by the device is closer to the visual softness as compared to the no-device condition. Last, there are two (out of ten) participants (P2, P3) who reported that they did not feel a strong sensation difference and thus did not choose our haptic device as a preferred interface.

9 DEMONSTRATING HOW TO APPLY OUR SOFTNESS DEVICE TO INTERACTIVE SYSTEMS

The applications of our softness device can be categorized with three main scenarios: (1) augmenting haptic props in VR, (2) adding interactivity to everyday appliances, and (3) altering softness for 3D printed objects. We achieve all use cases without further instrumentation on the object side. Beyond video game application and VR pencil eraser application demonstrated in user study 2 (Figure 8), we implement more applications for each category.

9.1 Application #1: Augmenting haptic props in virtual reality

Our softness device enables rigid haptic props to display both "soft" and "rigid" states when users touch it. We demonstrated its effectiveness in the VR shopping application in user study 2. To further showcase its usage, we created a simple "pat the Batman rubber duck" scene (shown in Figure 10), in which the users would be able to feel different rubber softness when the finger taps on the ears of the Batman rubber duck. One of them would feel soft as our device is on and the other would feel hard with our device off. The haptic prop we leverage is a power plug common to households. The modification of perceived softness of existing objects without further instrumentation would allow users to better leverage daily objects as props in VR to provide a haptic experience.

Figure 10: Allowing VR props to switch softness: (a) one ear of the rubber duck feels soft, since our device restricts the fingerpad as the user presses the prop (here, a simple power plug). Conversely, (b) with our device off, the other ear feels hard.

9.2 Application #2: Adding interactivity to everyday appliances

Beyond VR, our haptic device can add interactivity to daily objects in our physical environment. In Figure 11, we demonstrate an application in which we repurpose the screws on a 3D printer as keys for playing melodies (we implement this using simple capacitive sensing). When touched with a bare fingerpad (or when our device is off), the screw feels rigid. However, when our device is active, the same screw feels as soft as the pad of a rubbery button.

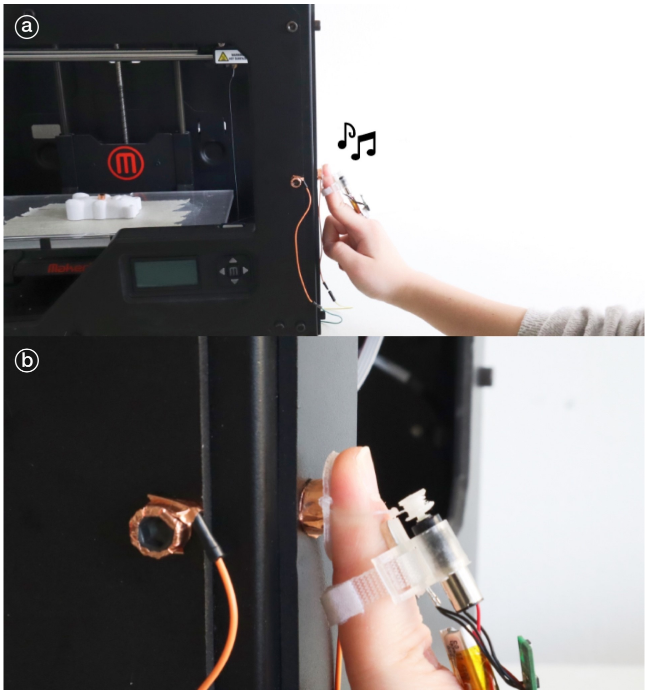

Figure 11: Shows application of (a) adding interactivity to 3D printer, where (b) the screws on the 3D printer feel like soft buttons.

9.3 Application #3: Altering softness for 3D printed objects

Finally, we generalize the usage of our softness device to 3D printed objects that users can fabricate on their own. As depicted in Figure 12(a), we depict how our device can soften a "button" on a 3D-printed remote-control/gamepad (demonstrated in study #2) or a 3D printed phone case. When touched via a bare fingerpad (or when our device is off), any of these protrusions on the 3D printed objects are relatively rigid. However, when our device restricts the fingerpad, these protrusions feel softer (almost like "clickable"). Thus, in these examples, our device enables a richer haptic experience when the users interact with these 3D printed devices. For example, in the smartphone case example, our softness device can augment experiences such as playing games or taking photos.

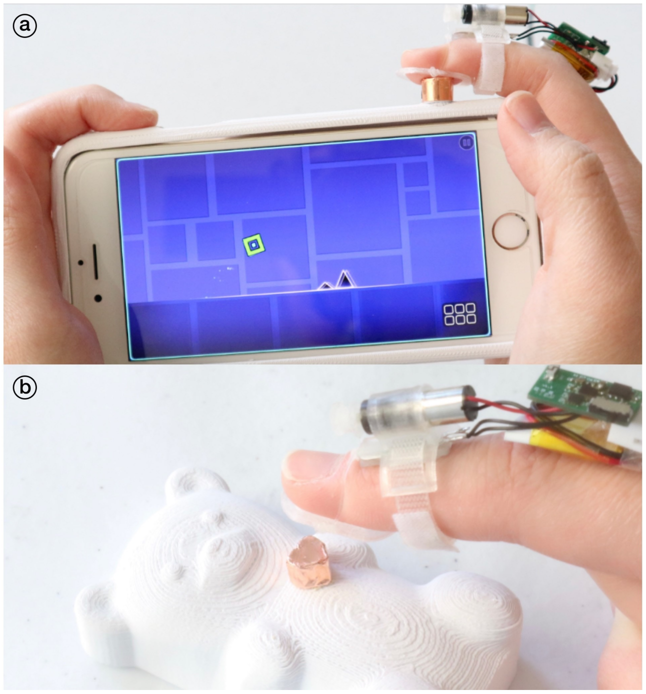

Figure 12: Examples of altering softness of regions on fully rigid 3D printed objects (made from PLA).

Moreover, we also expect the "softened" 3D printed parts might be helpful for designers in the prototyping stage. As shown in Figure 12(b), when designers evaluate their 3D printed prototype (i.e., a teddy bear), they can wear the device and experience "how it would feel like" if they switch specific parts (i.e., the teddy bear's heart) to a softer material. It requires no extra fabrication from the designer side.

10 CONCLUSION

In this work, we proposed a haptic device that alters the perceived softness of rigid objects by restricting fingerpad deformation. What is unique about our proposal is that it allows for simple (on/off) interactive softness modifications of a rigid object *without the need to instrument objects themselves.* Our haptic device pulls a hollow frame around the fingerpad and thus changes the contact area experienced by the fingerpad when the user touches a small rigid object. Our first user study validated that the now augmented fingerpad would perceive test stimuli softer than it is. It brings objects from 50-90 A to an average of 40 A softness level. Unlike previous work, our device leaves the center of the fingerpad free, which enables users to feel the objects they interact with.

Then, in our second study, we demonstrated that our device is a preferred interface with regard to haptic realism in interactive applications that utilize haptic props, such as making VR props softer and altering the softness of a 3D printed remote control on its button. Last but not least, we demonstrate with more applications of this haptic device, in the context of augmenting haptic props in virtual reality, adding interactivity to everyday appliances, and altering softness for 3D printed objects.

Moreover, we firmly believe our work contributes to the importance of designing and engineering haptic devices that leave the fingerpad free, so that users can also feel the exciting haptics of our real world, not just virtual worlds.

Finally, we expect that researchers building on our hardware, which we will make available to the community[1], will extend our findings in several new ways, such as exploring other regions of the skin and body where this might be applicable, modulating more degrees of softness and so forth. Some exciting future directions include varying the restriction force provided by the device and altering the size of the hollow frame.

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