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Pushing the Boundary: Force Sensitivity at the Edges of the Finger for Mixed Reality Haptics

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***Abstract*—We introduce an alternative paradigm for rendering high-force sensations to the fingertip by stimulating the edges of the fingerpad rather than the bare finger. This non-blocking approach enables virtual and augmented touch while preserving natural finger use, allowing simultaneous digital and physical haptic interactions. To explore this concept, we developed a plausible mechanotransduction working principle, conducted biomechanical and psychophysical experiments, and built a small wearable prototype device. Our findings suggest that the finger's edges are nearly as sensitive as the center for low forces (0.7 N), are about 150% as sensitive to moderate forces (1 to 3 N), and exhibit extended sensitivity at high forces (up to 5 N). Additionally, edge regions show nearly 140% of the stiffness of the center, and are capable of tolerating higher forces before participants report discomfort. These results support the viability of edges-based stimulation for nuanced, high-force haptic feedback, which could have implications for mixed reality and tele-operated interactive systems.**

***Index Terms*—haptics, psychophysics, mixed reality, force-feedback**

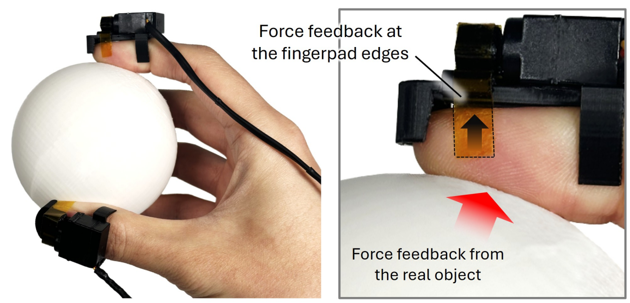

Fig. 1. Proposed method and example wearable device for delivering strong force sensations via actuation of fingerpad edges. Not that the majority of the volar fingerpad remains unblocked. Black DC motor is coupled to the edge skin using an amber colored polyimide band and skin safe adhesive.

I. Introduction

Wearable haptic devices have been explored for over a decade, emerging in a wide range of form factors designed for different body parts, including the arms, wrists, fingers, fingertips, chest, and more [1]. These devices deliver diverse haptic sensations, such as normal and lateral forces, slip, surface roll, vibration, thermal gradients, and electro-tactile stimulation [2]. Their potential for Augmented Reality (AR), Virtual Reality (VR), and dexterous robotic tele-operation has driven renewed interest, fueling a slew of recent "haptic glove" and "haptic thimble" prototypes in both academia [3]–[6] and industry such as "SenseGlove" and "WEART Haptics".

Many wearable haptic devices aim to directly stimulate the thousands of mechanoreceptors in the fingertip [7]. Distal actuation on the finger, as seen in haptic thimbles, offers key advantages: it reduces linkage size and complexity while improving overall wearability [1]. However, most fingertip-worn haptic interfaces share a major drawback—they obstruct the user's fingerpad, preventing natural tactile interaction with real objects. This challenge mirrors similar limitations in Head-Mounted Displays (HMDs), which blinded users to the real world before the widespread use of visual pass-through solutions. The restrictive nature of these finger-blocking displays significantly limits their usability and impact [8]. To provide tactile feedback while preserving natural interaction with real objects without obstruction, "feel-through" haptic interfaces have been proposed, designed to enhance haptic permeability through ultra-thin, conformal materials [9] or by incorporating small physical openings [8].

In this work, we investigate whether nuanced, high-force sensations can be generated solely through direct deformation of the fingerpad edges (Fig. 1). While edge-based force sensations may not fully replicate natural touch, we hypothesize that it can serve as a "minimally viable" haptic cue, striking a balance between realism and functionality. This approach could enable users to maintain haptic capabilities in both real and virtual environments simultaneously. The cue we focused on was moderate to high sustained pressures which are thought to play a critical role in dexterous grip and manipulation tasks [10]. Mechanically, this involves loading and unloading the finger-pad with up to 4-5 N of force, and with enough deformation to trigger strong response in populations of slow-adapting afferents (SAI and SAII). To this end, we developed an apparatus for applying known preload forces in this range to either the center of the fingerpad, or the edges. We then measured the effective stiffness of the fingertip in these conditions, and conducted psychophysical tests to measure the Just-Noticeable-Difference (JND) in response to different levels of additional displacement. Finally, we showcase how a simple,

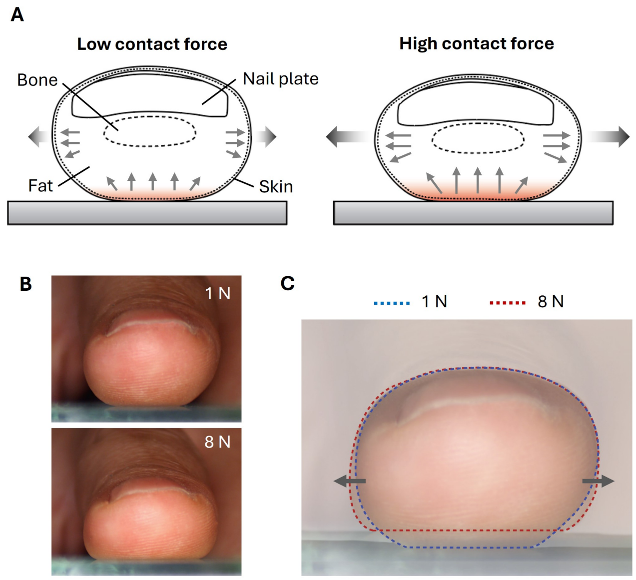

Fig. 2. (A) Illustrated force distribution and skin deformation at the fingerpad edges due to contact force applied at the fingerpad center. (B) Images of the fingerpad under 1 N and 8 N contact forces. (C) Image showing the outward bulging of the fingerpad edges at higher contact forces.

single degree-of-freedom (DOF) device can be constructed to reproduce this cue in a minimal, wearable manner.

II. Related Work

1) Related Devices: Numerous wearable devices have been conceived and built which are aimed at providing complex contact information to the fingerpad [2]. Many of these can be thought of as wearable versions of contact based devices such as the Morpheotron [11] and early grounded tele-operation displays [12]. Of this class of devices, banded approaches are most similar to our unblocked fingerpad vision, as they cover the finger with a thin, flexible band. This is tensioned via motors at the edges or top of the finger but allows some deformation of the finger through the band's flexibility. An early device typifying this style was Gravity Grabber [13], though many have followed, with notable mention of hRing [14], which used a ring form factor, and W-FYD [15], which utilized fabric-based device. More recently, researchers have proposed replacing the band with a string to achieve a more compact form factor [16]. Fingeret [17], also attempted fingerpad free forces, however it seems the main effect was from device vibration, and perhaps a slight squeeze at low forces (<1N). Tao et. al also introduced similar low edge forces (0.6 N) to the finger via a small circular frame [18], but only to alter real world stiffness perception, and not as a direct feedback effect. Multiple devices have attempted fingerpad free vibrotactile playback [19]–[22], which are interesting, but incapable of providing sustained contact information.

2) Perception of Force at Finger Edges: Little perceptual investigation has focused specifically on force perception at the edges of the finger. The majority of work has focused

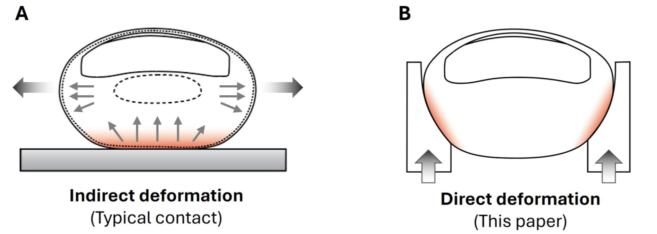

Fig. 3. (A) Skin deformation at the fingerpad edges due to the contact force. (B) Principle of deformation at the fingerpad edges in this study, where the edges of the fingerpad are directly pushed.

on the center of the fingerpad due to its exquisite FAI and SAI sensitivity to very low forces and surface curvatures [23]. Work in non-human primates, however has shown that SAI receptors located on the edges of the finger reliably respond to stimulation coming from the center, especially for flat contact surfaces [23]. Work from Birzieks and colleagues has shown that contact force triggers a wide range of afferents (SAI, SAII and FAI) in the fingertip [24], and follow-up work specifically investigated SAII afferents in and around the edges of the nail, which were directionally sensitive and thought to play a role in encoding high force (up to 4 N) contact orientation [25]. It is notable to mention that non-human primates lack SAII afferents, which has hindered much of our understanding of them, though recent works have confirmed they are associated with pressure and stretching sensation in humans hands and fingertips [26].

III. Working Principle

Based on our direct experience, pushing on the edges of the fingerpad creates strong sensations of pressure and force, however there appears to be a lack of prior perceptual work in this area to elucidate what mediates this specific perception. Regardless, we wish to put forward the following as a nominal hypothesis. Under normal loading of a fingertip, it is known that the edges of the finger bulge outward (Fig. 2). This bulging has been recorded by wearable sensors to be on the order of 100-200 μm [27], and is consistent with our own visual observation, Fig. 2B and C. This bulge results from the anatomical structure of the fingertip, which is composed of a collagen fiber network which connects the fingerpad skin to the bone and is filled with fatty liquids which visco-elastically move and relax under applied pressure. In general the behavior of the fingertip can be estimated by an incompressible fluid enclosed by an elastic membrane, a so-called "waterbed" type model [28], [29], with visco-elastic time constants of approximately 4 ms, 70 ms, and 1.4 s [30].

Thus, applied pressure to the volar fingerpad creates a dynamic internal pressure in the fingertip, as illustrated in Fig. 2A, and due to the constraint of the bone and the relatively stiff nail bed and plate, volume must be conserved by the edges of the finger bulging outward. This effect would be exacerbated at even higher contact forces, as seen in Fig. 2B, due to further displacement of the contact patch. This bulging

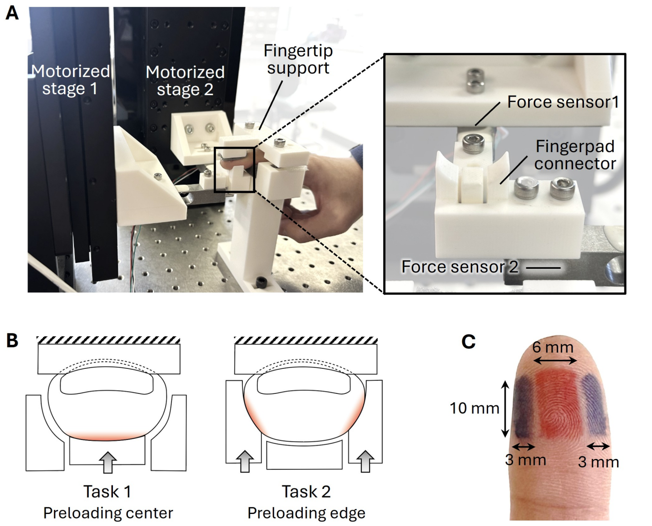

Fig. 4. (A) Experimental setup for the user perception test. (B) Mechanisms of deformation generation at the center and the edges of the fingerpad. (C) Contact area on the fingerpad.

would stretch the edge of the finger, as it deforms outwards. Populations of SAI and SAII afferents could easily pick up this static deformation, which would primarily occur after the finger has been loaded with over 1 N of force, a typical force at which fingerpad contact area is saturated and the entire fingerpad is engaged [10]. Therefore, it seems plausible that this population of afferents may be optimally tuned to the bulges of the fingerpad beyond 1 N of contact loading, as shown in Fig. 3A, and we believed it useful to investigate their sensitivity directly by pushing on them directly, as illustrated in Fig. 3B. Pushing inward should activate similar perceptions as bulging outwards, since the afferents of the fingertip are known to respond in either direction of deformation [31], [32]. We also suspect that bulging nail deformation may play a role in perception, as small deformations do appear to occur in the nail [33], which could be detected by SAII-Nail afferents [25].

IV. Methods

A. Experimental setup

We designed an experimental setup to investigate tactile perception at both the center and the edges of the fingerpad. The setup includes two motorized linear stages (Optics Focus MOX-02-100), two force sensors (5 kg strain gauge load cells), and 3D printed components for fingertip support and fingerpad connectors, as shown in Fig. 4A. The normal contact forces applied to the center and edges of the fingerpad were individually controlled using the motorized linear stages, as shown in Fig. 4B. Left and right edges were simultaneously engaged. The fingerpad connectors were specifically designed to match the natural curvature of the fingerpad, ensuring intimate contact with the skin at small preloads. Additionally, both the center and edges fingerpad connectors were designed to have the same contact area to ensure equal pressure under for any given preload force. To validate this, we marked the center and edges connectors red and blue paint respectively, and pressed them against the finger. Results, as shown in Fig. 4C, confirmed that the contact areas at the center and the edges of the finpgerpad were similar, with an area of approximately 60 mm^2. A fingertip support was designed to keep the participant's fingertip in a fixed position throughout the experiment, providing consistent conditions for data collection. To minimize discomfort and prevent restricted blood flow, a thin, soft polymer pad made of 3M VHB 4910 was added between the fingertip and the support. The force sensor data was acquired using a data acquisition device (NI USB-6211). During the tests, participants wore noise-canceling headphones playing white noise to eliminate auditory effects and were asked to close their eyes to eliminate any visual effects.

B. Participants

Six participants took part in the experiment, with an average age of 27.8 years. Among the participants, three identified as male and three as female, and all were right-handed. Participants were recruited via email and compensated \$10 for their participation. The experiment was conducted in accordance with the University of Illinois Institutional Review Board (IRB) ethical guidelines.

C. Procedures

First, we measured the relationship between the contact force and the deformation at both the center and the edges of the fingerpad to estimate applied mechanical stiffness. Initially, we applied a small preload of 0.5 N to both the center and the edges of the fingerpad. Then, the load at the center of the fingerpad was gradually increased using position control using 0.1 mm increments at a rate of 0.2 mm/s. Participants were asked to report when they felt any discomfort which bordered on a sensation of pain. During this test, the preload at the edges was maintained at 0.5 N. The same procedure was repeated at the edges of the fingerpad, with the preload at the center maintained at 0.5 N. Contact force data was collected using 1 DOF force sensors, and deformation data was obtained through the motorized stage controlled step size. The stiffness of the force sensor supports was increased to ensure that no appreciable deformation occurred between the motorized stage and the fingerpad connectors.

Subsequent to stiffness characterization, we measured JNDs for the force magnitude estimation at both the center and the edges of the fingerpad under various loading conditions. We utilized a two-interval forced choice (2IFC) paradigm and a descending 1-up-2-down staircase procedure to estimate 70.7% JND threshold. To prevent participant fatigue and sensory adaptation, staircases were concluded after 8 reversals and the last 4 reversals were averaged. Similar to the previous tests, all trials began with an initial controlled preload of 0.5 N. This preload prevents initial contact transients from playing a significant role in perception. After preloading, two stimuli were presented in back-to-back intervals. One was a reference value, while the other was a force value greater

TABLE I
MEASURED DEFORMATION AND FORCE RANGE OF COMFORT REGION

Participants	Deformation (mm)		Force (N)	
	Center	edges	Center	edges
S1	1.9	2.3	3.6	8.1
S2	1.9	2.2	3.3	7.6
S3	2.1	2.5	4.5	9.1
S4	2.3	2.8	4.3	9.5
S5	1.9	2.5	4.1	8.5
S6	2.1	2.2	6.1	8.2
Average	2.0	2.4	4.3	8.5

than the reference (order randomized). Force was increased at a rate of 5 mm/s to an adjustable level, was maintained for 2 seconds, and then decreased back to 0.5 N at the same rate. After one second, the second stimuli was presented and participants were asked to identify which force felt stronger. This test was carried out using four different force reference levels (0.7 N, 1.4 N, 2.1 N and 2.8 N), and repeated using the edges of the fingerpad with five different force reference levels (0.7 N, 1.4 N, 2.1 N, 2.8 N and 5 N). The ranges of the reference forces were determined based on the previous results of the discomfort level test.

V. RESULTS

A. Mechanical impedance of the fingertip

The relationships between contact force and deformation at both the center and the edges of the fingerpad is plotted in Fig. 5A for all participants. On average, participants reported discomfort at a deformation of 2.0 mm and a load of 4.3 N at the center of the fingerpad, and at a deformation of 2.4 mm and load of 8.5 N at the edges of the fingerpad, as summarized in Table I. The useful deformation range was similar for both sides. However, due to differences in stiffness profiles, the useful force range at the edges of the fingertip was approximately twice as high as that at the center. Based on the relationship between the contact force and the deformation, we estimated the mechanical stiffness of the fingerpad in the center and edges. The stiffness profile was smoothed using a moving average filter with a window size of 2. The results, shown in Fig. 5B, indicate that mechanical stiffness increased according to deformation, broadly consistent with known behavior of the fingertip. In addition, the mechanical stiffness at the edges was greater than that at the center for the same deformation.

B. Perception result

Figure 6 shows the result of the JND test at the center (grey line) and at the edge (black line) of the fingerpad. The graph in Fig. 6A represents the deformation JND for force magnitude recognition. Both deformation JNDs monotonically increase with the reference force. The error bars indicate the standard error (SE) of all participants' data relative to the mean value. Results show that at a low reference force of 0.7 N, the deformation JNDs at the fingerpad center and the edges are comparable, both being less than 35 μm. However, for reference forces ranging from 1.4 to 2.8 N, the deformation JNDs at the fingerpad edges are smaller than the center. Specifically, the measured deformation JNDs at the fingerpad edges are 66%, 73%, and 77% of those at the center for reference forces of 1.4 N, 2.1 N, 2.8 N, respectively. Notably, the deformation JND at the edges for a 5 N reference force (139 μm) is smaller than the deformation JND at the center for a 2.8 N reference force (140 μm). A two-way

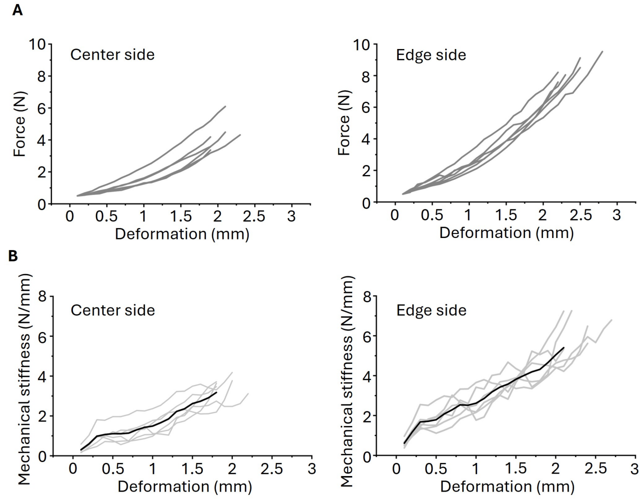

Fig. 5. (A) Recorded relationship between skin deformation and contact force at the center and edges of the fingerpad for all participants. (B) Calculated mechanical stiffness as a function of skin deformation at the center and edges of the fingerpad. The gray lines represent individual participant data, while the black line represents the averaged data.

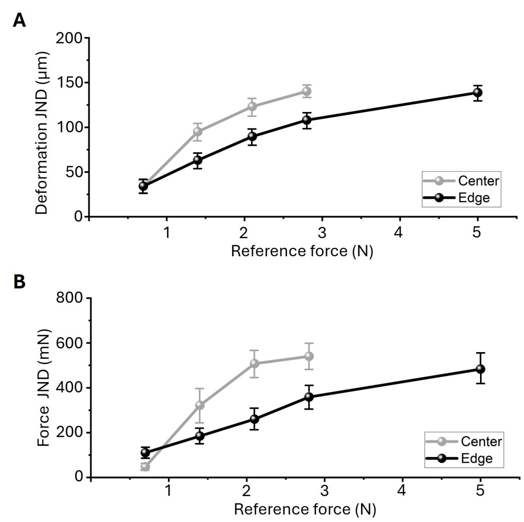

Fig. 6. (A) Measured deformation JND at various reference forces. Circular dots represent the mean, and error bars indicate the standard error of participants' data. (B) Measured force JND at various reference forces.

TABLE II
AVERAGE MINIMUM INCREMENTS IN THE INPUT ENERGY FOR NOTICEABLE DIFFERENCE

Reference forces (N)	Center (μJ)	Edges (μJ)
0.7	0.8	1.9
1.4	15.3	5.8
2.1	31.2	11.7
2.8	37.9	19.4
5.0		33.6

repeated measure ANOVA (Location center vs edges and Reference Forces as within subject factors, and deformation JND as a dependent variable) show significant effects of Location [$F(1,5)$=15.7; p=0.01; η^2=0.24] and Reference Force [$F(3,15)$=28.3; p<0.001; η^2=0.71]. Interaction between within factors is not significant [$F(3,15)$=1.98; p=0.16; η^2=0.1].

Figure 6B represents the force JND for force magnitude recognition. Results show that at a small reference force of 0.7 N, the force JND at the fingerpad center are smaller than those at the fingerpad edges. However, for reference force from 1.4 to 2.8 N, the fingerpad edges become more sensitive than the fingerpad center. Specifically, the force JNDs at the fingerpad edges are 57%, 51%, and 66% of those at the center for reference force of 1.4 N, 2.1 N, 2.8 N, respectively. A two-way repeated measure ANOVA (Location center vs edges and Reference Forces as within subject factors, and force JND as a dependent variable) show significant effects of Location [$F(1,5)$=11.4; p=0.02; η^2=0.21] and Reference Force [$F(3,15)$=22.1; p<0.001; η^2=0.58]. Interaction between within factors is also significant [$F(3,15)$=5.3; p=0.01; η^2=0.18].

Notably, the force JND at the edges under a 5 N of reference force (483 mN) is smaller than the force JND at the center under a 2.1 N of reference force (507 mN). In order to compare our results with prior literature, we compute the Weber Fraction (WF) for forces as the force JND divided by the reference force. The WFs at the fingerpad center are 6.8%, 23%, 24%, and 19.3% for 0.7 N, 1.4 N, 2.1 N and 2.8 N, respectively. These WFs are higher than those reported in the literature (7–10% range in [34], [35]). These differences could be due to variations in the contact area, surface curvature, applied force range, and due to the fact that the prior literature utilized active finger movements, while in the present study the finger remained stationary. The WFs at the fingerpad edges are 15.8%, 13.2%, 12.4%, 12.8% and 9.7% for 0.7 N, 1.4 N, 2.1 N, 2.8 N and 5 N, respectively, which are more similar to prior literature.

Finally, in an effort to contextualize these numbers in more concrete terms, we calculated the minimum input energy for force magnitude recognition based on the deformation JND and the force JND results. This energy represents the additional elastic potential energy that an actuator would have to exert to deform the fingertip and become noticeable to the user. We believe this could be a useful metric for designing future devices. The energy is, in all cases, surprisingly small (in the tens of μJ range), implying that strong force perceptions can be generated with very little mechanical energy. Furthermore, the results (Table II) indicate that the edges of the fingerpad require at least half the input energy to achieve comparable force perception as the center. This suggests that the edges may, in some sense, be a more energy-efficient region for tactile stimulation. For wearable devices that rely on exceptionally small battery power, this effect could be significant.

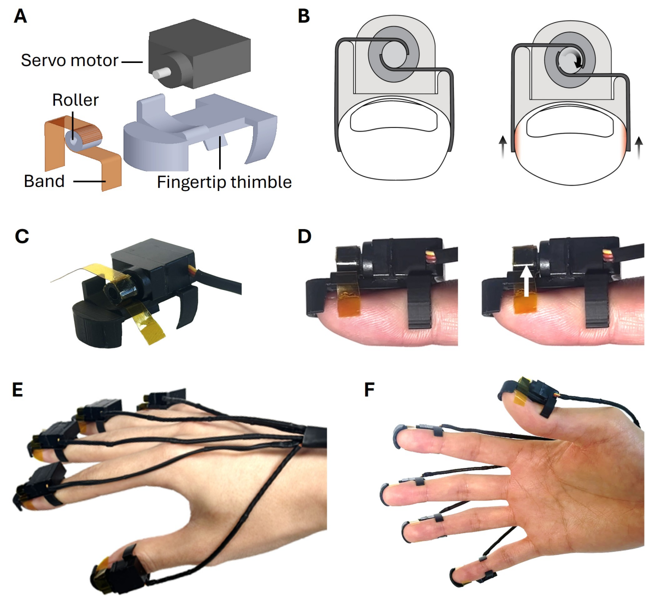

Fig. 7. (A) Components of the wearable haptic device, and the associated mechanism (B). (C) Fabricated prototype. (D) Wearable haptic device in use, providing a force at the edges. (E) Five-finger haptic device, which leaves the volar surface free (F).

VI. WEARABLE PROTOTYPE

Building on the findings from our JND test results, we developed a wearable haptic device capable of producing skin deformation specifically at the edges of the fingerpad. The wearable haptic device consists of a low-cost micro servo motor (DM-S0020), a fingertip thimble, a roller, and two connecting bands, as shown in Fig. 7A. The fingertip thimble is 3D-printed and designed for a comfortable fit on the fingertip. The maximum pulling force of our haptic device is calculated as 6.5 N, which is sufficient to provide force feedback at the edges. For this prototype, we used an instant cyanoacrylate adhesive (3M PR100) that ensures a strong bonding between the band and the fingerpad edges. In the future, this adhesive could be replaced with a modified 2-Octyl cyanoacrylate skin adhesive (trade name Dermabond) to provide more flexible skin-safe bonding.

The working mechanism is illustrated in Fig. 7B. When the motor rotates clockwise, the band pulls on the fingerpad edges, causing localized skin deformation. Conversely, when the motor rotates in the opposite direction, the skin deformation is reduced. The fabricated wearable module features a compact

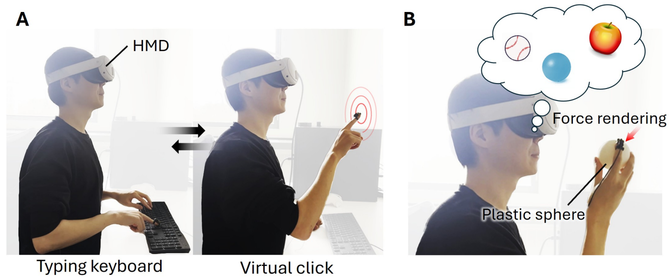

Fig. 8. A device build with our method allows user to (A) switch back and fourth between physical and virtual environments, or (B) receive modified force cues from real objects.

form factor (15 mm × 15 mm × 29 mm) and a lightweight construction (3.6 g), making it suitable for extended use and integration into portable applications, as shown in Figure 7C. By modulating the pulse width of the input signal from the control board (Teensy 4.0), the rotational angle of the actuator can be precisely controlled, enabling fast and real-time skin deformation, as demonstrated in Figure 7D and our Supplementary Video. As shown in Figure 7E, we also developed a five-finger haptic device capable of delivering pressure feedback to all fingerpad while leaving the volar surface of the hand unobstructed.

As shown in 7F, the primary advantage of our wearable haptic device is its ability to provide nuanced force feedback without completely blocking the fingerpad. This unique feature allows users to seamlessly switch between interacting with real objects, such as typing on physical keyboards, and virtual objects, such as tapping on floating UI elements and menus (Fig. 8A). It also allows modification of real objects with augmented properties, such as rendering modified softness of a rigid plastic sphere (Fig. 8B).

VII. Limitations and Discussion

We proposed a new method to provide force perception at the edges of the fingerpad, but several challenges remain. The participant sample size in this study is relatively small for drawing general conclusions and should be expanded in future work. Furthermore, the measured Weber fraction values in the center (6.8–24%) are higher than the standard values reported in the literature (7–10%) [34], [35]. We believe this is primarily due to differences in the contact area. Prior works applied force across the entire fingerpad, but our system applied force to a localized areas of 60 mm². Consistent with our findings, previous research has also demonstrated that force JND increases as the contact area decreases [36].

Although this study focused on providing normal force feedback by producing symmetric forces at the edges of the fingerpad, we envision generating shear force feedback in the future by applying asymmetric forces to each edge. As an advancement to the current wearable prototype design, we could implement two servo motors instead of a single motor to independently control the forces on each side. This would allow for more complex and expressive haptic sensations, potentially further enhancing the user's experience in mixed reality environments.

Fingeret presented a similar prototype offering both force and vibrotactile feedback at the fingerpad edges using two motors [17]. However, their roller mechanisms appeared insufficient for delivering large forces exceeding 1 N without applying substantial preload. We believe that directly pulling the edges of the fingerpad using a band is a more effective approach for achieving high force feedback around 5 N. To withstand these strong pulling forces on the skin, we employed strong bonding with a skin adhesive. Although this adhesive provides secure strong bonding, it is not an ideal solution for practical use. As a future improvement, we believe that using a banded approach [13] but modifying it to incorporate a single large hole in the center could enhance usability and accessibility while maintaining haptic permeability [8].

VIII. Conclusion

In this paper, we proposed a new method for presenting high force cues to users by using the sides of the finger instead of the center and independently investigated the perceptual sensitivity of each location. First, we measured the stiffness of both the edges and the center of the fingerpad. The results revealed that the edge regions exhibit higher stiffness than the center, offering a broader useful range without a feeling of discomfort. Through the JND test on perceived force, we found that the edges of the fingerpad are as sensitive as the center for a small forces, at least 0.7N, though we did not fully investigate exceedingly small force (e.g. initial contact force). Surprisingly, our evidence suggests that sensitivity at the edges surpasses that of the center at moderate forces (1 to 3 N) and extends to higher forces (up to 5 N). Based on these findings, we developed a wearable haptic device prototype capable of providing force feedback at the finger's edges without completely blocking the fingerpad. This help paint our vision of seamless haptic interaction both digital and physical worlds, allowing users to quickly switch between them or even interact in mixed reality (VR/AR) environments simultaneously.

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