Augmenting On-Body Touch Input with Tactile Feedback Through Fingernail Haptics

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ABSTRACT

The key assumption attributed to on-body touch input is that the skin being touched provides natural tactile feedback. In this paper, we for the first time systematically explore augmenting on-body touch input with computer-generated tactile feedback. We employ vibrotactile actuation on the fingernail to couple on-body touch input with tactile feedback. Results from our first experiment show that users prefer tactile feedback for on-body touch input. In our second experiment, we determine the frequency thresholds for rendering realistic tactile "click" sensations for on-body touch buttons on three different body locations. Finally, in our third experiment, we dig deeper to render highly expressive tactile effects with a single actuator. Our non-metric multi-dimensional analysis shows that haptic augmentation of on-body buttons enhances the expressivity of on-body touch input. Overall, results from our experiments reinforce the need for tactile feedback for on-body touch input and show that actuation on the fingernail is a promising approach.

CCS CONCEPTS

• **Human-centered computing → Interaction devices**; **HCI theory, concepts and models**; **Empirical studies in HCI**.

KEYWORDS

On-Body Interaction, Epidermal Interfaces, Wearables, Haptics, Vibrotactile Actuation, Fingernail devices

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1 INTRODUCTION

The human body offers a large and readily accessible surface for always-available, eyes-free interaction [25]. For these reasons, sensing touch input on the body has received considerable attention in the HCI community [2, 94]. Various technical approaches to sense input have been presented, including computer vision [29], magnetic [10, 36], bio-acoustic and electromagnetic wave propagation [32, 60, 107], and capacitive sensing [42, 65, 93, 95]. Additionally, multiple actuation mechanisms have been proposed to deliver haptic output to the body. These include conventional vibrotactile displays that render tactile spatiotemporal patterns [14, 50, 80], tattoo devices that deliver tactile feedback through electro-tactile stimulation [97], shape-memory alloys for squeeze sensations [23, 26], airflow-based non-contact wearable tactile displays [51], finger-worn devices that deliver haptic output through microfluidic [27, 28], and magnetic actuation mechanisms [55, 57, 71]. While several input and output devices allow for novel interaction techniques on the body, they have always been developed and evaluated as standalone devices.

Findings from prior research in which haptic devices were developed to deliver rich tactile sensations in extended reality (XR) environments do not translate directly to on-body interactions [72, 86]. This is because on-body interaction is fundamentally different from the interaction in XR environments. First of all, when we interact with our bodies (e.g. tap a button on the forearm), our inherent proprioception enables us to locate the button. When we tap it, we feel tactile feedback in two different places: a) at the point where the interaction occurred (e.g. forearm), and b) at the fingertip, allowing us to localize and feel the input even when we are without sight. In contrast, interaction in mixed reality environments demands visual attention (with minimal/no support for eyes-free interaction) and often lacks natural tactile feedback. Hence, understanding and incorporating tactile feedback for on-body touch input can enhance the expressivity of on-body interaction and can have diverse applications in the areas of gestural interaction and training, accessibility, and bio-feedback design.

The key assumption attributed to on-body touch input is that the skin that is being touched provides natural tactile feedback when interacting with the body. However, prior research has shown that coupling touch input with tactile feedback can be effective in the context of mobile interactions [33, 64], automotive UIs [62], and

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mid-air interaction [19]. We hypothesize that adding computer-generated tactile feedback to on-body interfaces, e.g., buttons, on the skin enriches the expressiveness of on-body interaction. To investigate this hypothesis, we, for the first time, comprehensively explore the coupling of tactile feedback for on-body touch input.

To deliver tactile feedback, we chose fingernails as the most promising location for three reasons: (1) firstly, they keep the fingerpad, which is one of the most sensitive locations, unencumbered (2) prior work has successfully shown that fingernails can deliver rich tactile experiences in the context of touchscreen and VR interactions [1, 72] (3) finally, fingernail and fingertip share highly contrasting mechanoreceptor sensitivity levels (sensitivity of fingertip is » fingernail) which is highly suitable for rendering *Referred Sensations* (see section 3 for more details on this phenomenon).

The main contributions of this paper are results from three psychophysical experiments that shed new light on the design of on-body touch input.

- In our first experiment, we investigated the user preference for tactile feedback coupled with on-body touch input across two interaction scenarios: Eyes-Free and Visual Feedback conditions. Results show that users preferred tactile feedback for on-body touch input in both interaction conditions.
- In the second experiment, we were interested in understanding the vibration thresholds for rendering realistic tactile "'click" sensations for on-body touch buttons and how the concentration of mechanoreceptors influences these thresholds. We conducted this experiment at three different body locations with varying levels of mechanoreceptor concentrations: fingertip (high), hand dorsum (medium), and forearm (low). Results show that the frequency thresholds for vibrations are similar across body locations: Fingertip (mean: ~120 Hz), Hand dorsum (~120 Hz), and Forearm (~124 Hz).
- Finally, to enhance the expressivity of on-body touch buttons, we augmented them with 20 different tactile effects rendered through vibrotactile actuation on the fingernail. We employ the classical non-metric multi-dimensional scaling (MDS) to show that haptic augmentation of on-body buttons can enhance the expressivity of on-body touch input. To the best of our knowledge, we are the first to employ this psychophysical method in the context of on-body interaction.

Overall, our findings reinforce the need and importance of incorporating tactile feedback for on-body touch input and show that fingernail actuation can be a simple but highly promising way of incorporating tactile feedback and increasing the expressivity of on-body touch input.

2 RELATED WORK

Our work falls at the intersection of interactive devices on nails, on-body interaction techniques and empirical studies for on-body interaction.

2.1 Nail-Worn Devices

Fingernails have been explored as a promising medium for interaction in HCI literature. They have been augmented with electrodes for sensing touch input [41, 49] and have been used for subtle interactions through magnetic sensing [10, 57]. Nails also have been augmented with displays for showing notifications [15], and for enabling always-available visual feedback [83]. There has also been prior research on chemical fingernail interactions, rather than electronic [47]. Haptics on fingernails is an emerging area with initial explorations by Ando et al. showing great promise for rendering tactile sensations of boundaries or textures [1]. More recently, Preechayasomboon et al. present a vibrotactile haptic feedback system worn on fingernails for virtual reality [72]. These works show the potential of using fingernails for interaction, however to the best of our knowledge, none of them explored the use of fingernails in the context of on-body touch input.

2.2 Input and Output Devices on the Body

Touch input on the body has been extensively explored in the HCI community through various technical approaches. Prior work sensed input on the skin using RGB cameras [9, 59, 85], depth cameras [13, 24, 29, 30, 46, 82] or infrared sensors [21, 84, 99] for gesture recognition on or around the body. Other alternate approaches include the use of the human body as an electromagnetic waveguide [45, 106, 107], bio-acoustic sensing [32, 60], radar-based sensing [92], magnetic sensing [10, 36], electric field sensing [108] and pyroelectric infrared sensing [21]. A more recent line of work enables touch interaction on the body by augmenting the human skin with electronic functionality [42, 43, 53, 65, 93, 95]. In addition to enabling touch input on the body, prior research in HCI has also explored the design of haptic devices that deliver tactile feedback on the body. These include vibrotactile displays [50, 80], shape-memory alloys for squeeze sensations [23, 26], finger worn micro-fluidic displays [27, 28], and magnetic actuation mechanisms [55, 57, 71]. More recently, thin-film actuators have also been developed which render tactile sensations through dielectric elastomers [100] and electro-tactile actuation [97].

These input and output devices enable novel interactions on the body. However, they have typically been developed and evaluated as standalone devices. The coupling of tactile feedback with touch input has been extensively explored in the context of mobile interactions [33], automotive UIs [62], and mid-air interaction [19], but it is yet to be studied in the context of on-body interaction. Withana et al. [97] presented an initial exploration that coupled touch input on the body with electro-tactile feedback but this is limited to an application demonstrator with no formal empirical evaluation.

2.3 Empirical Studies for On-Body Interaction

Understanding on-body interaction is an active research topic in HCI. Several empirical studies focused on the body-centric interaction space [31, 90], identified user strategies for creating on-body gestures [68] and revealed that on-skin input increased the sense of agency [3]. Moreover, previous research has investigated mapping strategies for input elements on the skin. These include salient features on the palm [13, 25, 91], targets placed on the forearm [52], visual and tactile anatomical landmarks [2, 95] as well as mappings between skin and an off-skin display [4]. In addition to these studies, several elicitation studies have been conducted to understand gestural interaction on specific body locations such as ears [11], fingers [8, 77, 78], forearm [7, 94], nose [74], and, belly [89]. In addition to gestural input on body locations, elicitation studies have

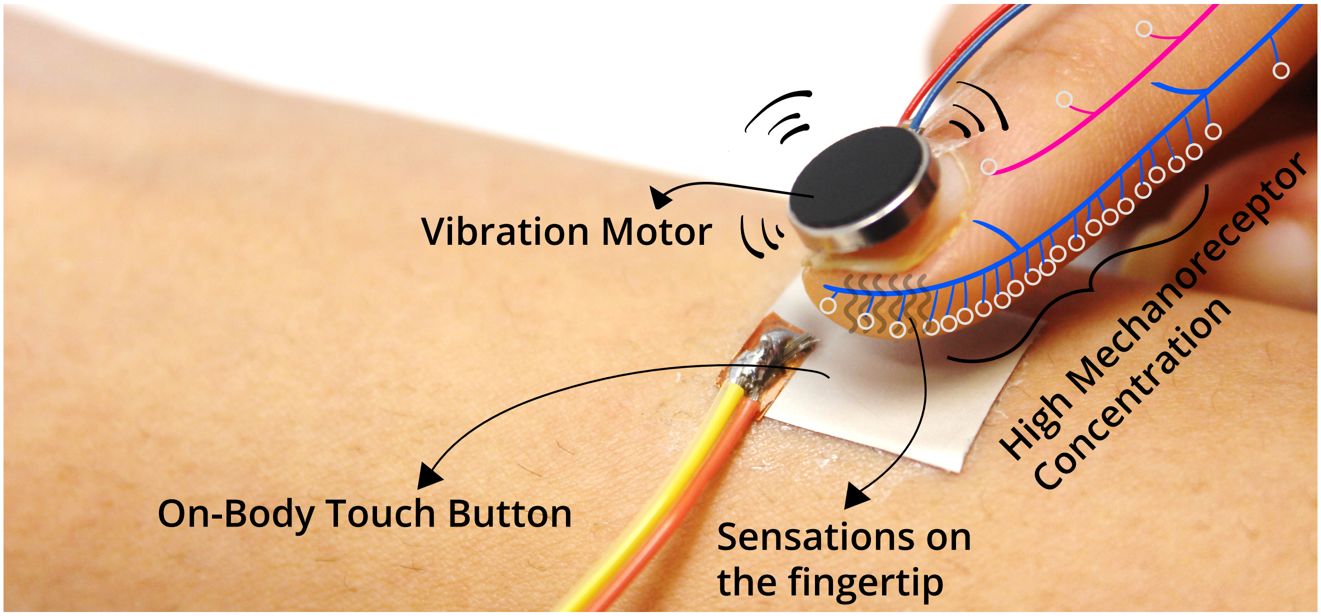

Figure 1: This work augments on-body touch input with tactile feedback through an actuator placed on the fingernail. By carefully stimulating the fingernail actuator at a specific frequency range, vibrations traverse through the underlying nerves rendering a sensation on the fingertip, giving the illusion that the button provided the tactile feedback. We refer to this as a tactile “click" sensation.

also been reported for skin-specific input modalities and user preferences for on-skin input [7, 94]. Finally, prior work also studied the social acceptability of gestural input performed on the body [67, 73], on epidermal interfaces [102] or directly on skin [94] and evaluated appropriate body locations for on-body computing [101, 102, 105].

While these research works studied on-body interaction in detail, to the best of our knowledge, this is the first work that focuses on understanding the coupling of on-body touch input with computer-generated tactile feedback.

3 WORKING PRINCIPLE

There are multiple approaches by which we can augment on-body touch buttons with tactile feedback. The first approach is to augment the skin with thin-film electro-tactile actuators [97]. However, this requires placing the actuator at every body location where there is an input widget, limiting the scalability of the approach. The second approach is to augment the fingertip with a thin-film actuator [26, 97] or through other approaches which actuate the fingertip [56, 86]. However, the drawback of the former approach is that thin-film actuators can be less robust mechanically [65, 97] and, if better robustness is required, then they can diminish natural tactile perception [63]. The latter approach that dynamically renders haptic feedback by placing an actuator on the fingertip works well in the context of XR. However, for on-skin interfaces, the rigid vibrotactile actuator comes in between the input widget and the fingertip altering the natural tactile perception.

Our principle relies on using the fingernails to provide tactile feedback on the fingertip while interacting with the body. Actuation through fingernails provides an unobtrusive way to explore UI elements on the body. This approach has been previously explored for superimposing tactile information onto an object displayed on a computer monitor [1]. However, firing the actuator at default frequency and voltage results in non-natural and strong vibrations that are very unnatural, as reported in prior work [86]. On the other hand, fingernail vibration can be preferable when interacting with soft objects. We hypothesize that by modulating the operating frequency of the fingernail actuator, we can realize sensations that simulate the realistic tactile “click" sensations for touch buttons on the body.

Conceptually, we rely on *Referred Phantom Sensations* a natural phenomenon that is common with electro-tactile and vibrotactile stimulation and is extensively used for providing tactile feedback in prostheses and amputated regions of the body [12, 16, 17, 75]. When a stimulus is presented on a skin area close to a nerve, the current or vibrations can reach the sensory afferents deeper in the tissue, thus inducing sensations that are spread to a wider and/or more distant area. These sensations are termed *Referred Phantom Sensations* [12, 17, 20]. Phantom sensations are usually perceived more distally with respect to the actual stimuli site [16].

These sensations typically occur when there is a high difference in tactile sensitivity between two regions. The underlying nerves transmit the tactile signals which are perceived at a body site having higher tactile sensitivity. For e.g. Pan et al. [69] report that by providing a stimulus at the calf/leg (lower mechanoreceptor concentration) sensations can be evoked on the toes/foot (higher mechanoreceptor concentration). In our case, the inherent tactile sensitivity of the fingernail is very less compared to that of the fingertip [5, 6, 38, 54, 76, 88]. As a result, when a stimulus is presented at a specific lower frequency range, they are unnoticeable at the fingernail because of low concentration of mechanoreceptors(see Figure 1). But the vibrations traverse through the underlying nerves to the fingertip. And since the fingertip has a high concentration of mechanoreceptors, these vibrations can be perceived as feedback on the fingertip, resulting in a more natural sensation of touch input on the body. We rely on these sensations to render natural tactile feedback for on-body touch buttons.

4 EXPERIMENT 1: DO USERS PREFER AUGMENTING ON-BODY TOUCH WITH TACTILE FEEDBACK?

Firstly, we were interested in understanding if users preferred augmenting on-body touch input with tactile feedback. We were also interested in understanding if visual feedback of touch input influenced user preference. Hence, we considered employing tactile feedback for on-body touch input in two different interaction scenarios: (1) EYES-FREE INTERACTION - where there was no visual feedback of touch input and (2) VISUAL FEEDBACK condition where a virtual button press was visually presented on a monitor. We chose the first condition to be in line with situations where on-body touch input can be used for on-the-go eyes-free interaction [98]. We chose the second condition to be in line with situations where on-body input is mapped to an off-skin display [4]. We asked the participants to rank their preferences on a 7-point Likert scale reading where 1 was the least preferred and 7 was the most preferred.

4.1 Apparatus

To measure on-body touch events precisely, we to employed capacitive sensing technique [65, 93]. An epidermal touch sensor was affixed on the center of the forearm. The touch sensor (3 cm (length) × 4 cm (width)) was fabricated by screen printing silver ink (Sun Chemical Gwent C2110817D5) on a TPU (Thermoplastic PolyUrethane, Platilon® U073, Covestro) substrate. The entire device was ~50-70μm thick. Based on prior work, this device provides a good balance between mechanical robustness and minimally influences the inherent tactile perception [63]. The touch sensor was interfaced with a touch controller (MPR 121, NXP semiconductor). For actuation on the fingertip, we used an ERM (Eccentric Rotating Mass Actuator, [216 - 266]Hz; 8mm diameter), interfaced with an Arduino and triggered with the default voltage.

4.2 Task and Procedure

We recruited 12 participants (5 female, mean age: 31.33, sd: 4.97) for the study. The local ethics board approved the study. We conducted the study in a silent room. Participants wore noise-cancelling headphones playing white noise to eliminate potential auditory cues. They were seated upright on a chair with the touch sensor placed at the center of their non-dominant forearm. We affixed the actuator on the index fingernail of the dominant hand. Since body capacitance varies from person to person, we calibrated the touch thresholds for each participant to ensure that the actuator triggered synchronously with the touch input. The experimenter instructed the participant to perform a simple "tap" on the touch button, similar to how they would press a key while performing text entry on mobile devices. When the touch event was detected, the actuator vibrated at its default intensity (216 Hz). The experiment had a 2x2 (INTERACTION SCENARIO × TACTILE FEEDBACK) factorial design resulting in a total of 4 conditions :

- EYES-FREE INTERACTION WITHOUT TACTILE FEEDBACK: in this condition, participants performed touch input on the forearm with their eyes closed by wearing a sleeping mask. They relied on their inherent proprioception to locate the touch button and perform touch input. No tactile feedback was presented.
- EYES-FREE INTERACTION WITH TACTILE FEEDBACK: in this condition, participants performed touch input on the forearm with their eyes closed. However, unlike the previous condition, there was tactile feedback presented when the touch event occurred.
- VISUAL FEEDBACK: in this condition, the visual feedback of the button press was presented on a desktop monitor. When the tap event occurs, a virtual rectangle that has the same dimensions as that of the touch sensor is filled with green and returns to gray on a touch release event.
- VISUAL AND TACTILE FEEDBACK: this condition is similar to the previous condition except that the tactile feedback is rendered on the fingertip when the touch event occurs.

The design of the experiment has been informed from prior work [35, 63, 66]. We counterbalanced the order of presentation of each of these conditions. For each condition, the participant performed five successive repetitions of a tap with a 1s interval between each tap. The number of repetitions is informed from prior work where the same number of repetitions was used for determining absolute thresholds for on-body stimuli and also for determining parameter thresholds for rendering vibrotactile cues on the body [63, 66]. The inter-stimuli interval of 1s was chosen to ensure that there was an adequate gap between successive stimuli [35]. Hence each participant performed 4 (conditions) × 5 (repetitions) = 20 trials resulting in a total of 20(trials per participant) × 12 (no.of participants) = 240 trials. The entire experiment took approximately 40-60 minutes. After the experiment, we conducted a semi-structured interview to gather qualitative feedback. The interviews were audio-recorded.

4.3 Results and Discussion

The results support our hypothesis that tactile feedback is preferred by users. The average Likert scale readings show that participants preferred tactile feedback in both the EYES-FREE INTERACTION and VISUAL FEEDBACK conditions.

Friedman's test showed a significant influence of the interaction condition on the Likert scale reading ($F_r = 31.88$, $p = 5.53 \times 10^{-7}$). Nemenyi's post-hoc test further revealed a significant difference between the EYES-FREE CONDITION WITHOUT TACTILE FEEDBACK and EYES-FREE CONDITION WITH TACTILE FEEDBACK ($p = 0.008$). Similarly, tactile feedback played a significant influence in the VISUAL FEEDBACK condition too ($p = 0.036$).

4.3.1 *Importance of Tactile Feedback.*

Our semi-structured interviews highlighted the importance of tactile feedback. Specifically, in the case of eyes-free interaction, participants suggested that while the inherent proprioception allowed them to perform the touch input, the tactile feedback served as an additional confirmation that the input was performed correctly: ".. *the feedback is important*

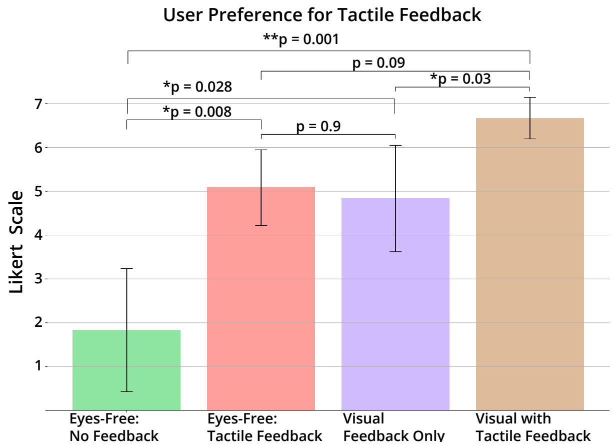

Figure 2: Results from Experiment 1: User preferences for incorporating tactile feedback in two interaction conditions: Eyes-Free and Visual Feedback. Results show that tactile feedback for on-body touch input was highly preferable in both conditions. Error bars show standard deviation.

because it helps me know that I have performed the input or a gesture accurately" (P3).

4.3.2 Feedback Intensity. While the tactile feedback was helpful, the intensity of the vibration on the fingernail was found to be too strong and unnatural as suggested by one of the participants: "*the vibration is too strong and it feels as if the fingernail is dominating the feel of touch input* (P1)".

4.3.3 Variation in Feedback. Another valuable insight that we got from the participant feedback is the need for variation in tactile feedback. Rendering different tactile effects can help participants to map various actions to specific tactile effects: "*..having more effects is better because based on the type of vibration pattern, I can know if its a notification from my e-mail or other social media accounts." (P4)*

5 EXPERIMENT 2: RENDERING REALISTIC TACTILE CLICK SENSATION ON THE FINGERTIP

Experiment 1 showed that while tactile feedback for on-body touch is highly preferable, the vibration intensity was too strong. Hence, we conducted a second experiment to measure the vibration thresholds that can render a realistic sensation of tapping a button on the skin. While prior work has demonstrated that modulating the vibration frequency can enable rendering of various tactile sensations on a touchscreen [1], and identified the most pleasant tactile feedback for mobile touchscreen buttons [48], to the best of our knowledge, we are the first to identify the thresholds for rendering the most suitable "tactile click" for touch buttons on the skin.

We hypothesized that by modulating the intensity (controlled through amplitude and frequency) of vibration, the sensation of "tactile click" can be rendered on the fingertip rather than the fingernail, providing a more natural and realistic sensation of tapping a button. Conceptually, we are interested in investigating the phenomenon of *Referred Sensations* to render the "tactile click" sensation on the fingertip by actuating the fingernail. Since body location plays a crucial role due to inherent variation in the concentration of mechanoreceptors, we performed this experiment on multiple body locations in line with prior work [63].

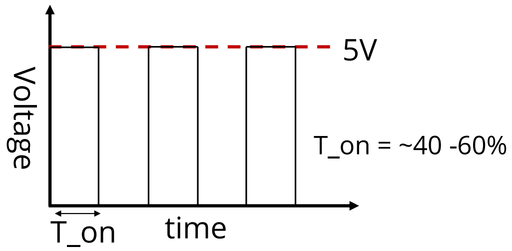

Figure 3: Instead of firing the actuator at the default voltage level, we use pulse width modulation to vary the intensity of vibrotactile feedback to render "tactile click" sensations for on-body touch buttons When the duty cycle of PWM is between [40-60]%, "tactile click" sensations can be rendered.

5.1 Apparatus

In line with prior work [63], touch sensors were fabricated and placed on three body locations: the tip of the index finger (Fingertip) (Figure 4), the dorsal side of the hand (Hand Dorsum), and the volar side of the forearm (Forearm). The main reason for choosing three body locations was to understand how the vibration thresholds vary depending on the natural sensitivity and acuity of skin sites. The locations have varying levels of cutaneous receptors (fingertip > hand dorsum > forearm) [54]. The apparatus for the vibration motor was the same as experiment 1, but instead of triggering the actuator at a single voltage, we used pulse width modulation to adjust the frequency and driving voltage (Figure 3).

5.2 Task and Procedure

We recruited the same 12 participants (5 female, mean age: 31.33, sd: 4.97) from the previous study. We counterbalanced the order of skin sites and used the Method of Limits [39] to determine the thresholds. A total of four alternating ascending or descending series were administered (as shown in Figure 6 (a)) We chose the starting series (ascending or descending) randomly. To reduce the cognitive load on the participants, the experimenter informed them of the location where the participant has to perform the touch input. To keep the interaction conditions consistent, we affixed all the touch sensors on the non-dominant forearm and asked the participants to perform touch input with the dominant index finger. For the descending series, the trial started from the maximum possible frequency (~216 Hz).

Since we were interested in identifying the thresholds for rendering the most suitable tactile click sensation, we asked the participants to compare the sensation to the tactile click that they experience while performing a text-entry task on a mobile device. We used this prompt for the following reasons: (i) it is easily relatable to all our users as all of them perform mobile text entry very frequently (on a daily basis) (ii) the tactile feedback strikes a good balance between being strong enough to be felt by any user and

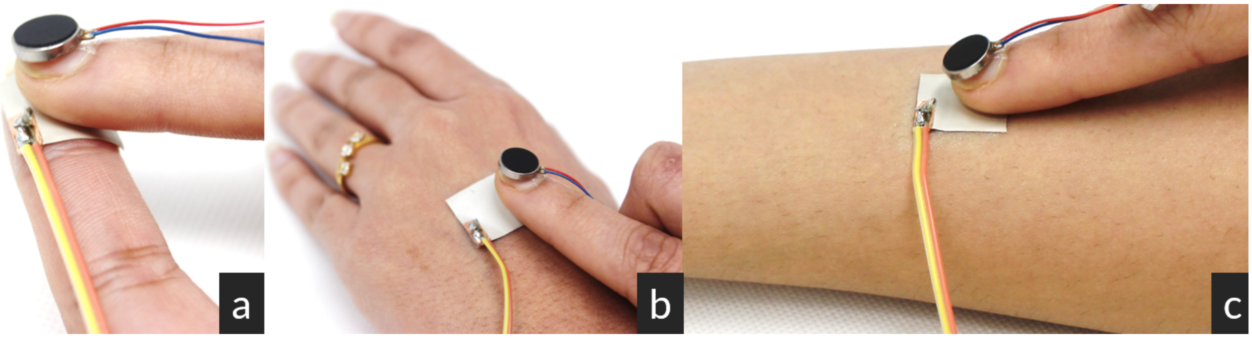

Figure 4: Body locations used in Experiment 2: fingertip (a), back of the hand (hand dorsum)(b) and forearm(c). Each of these locations has varying levels of mechanoreceptor concentration (fingertip > hand dorsum > forearm)

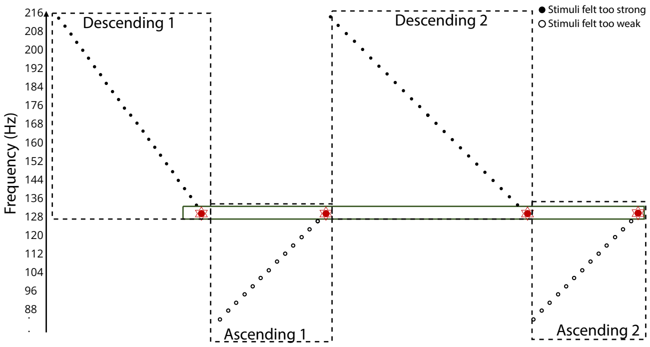

Figure 5: Alternating descending and ascending set of trials administered via the method of limits [40]. For each series, a threshold (indicated in red) is identified. The final threshold is the average of the four series.

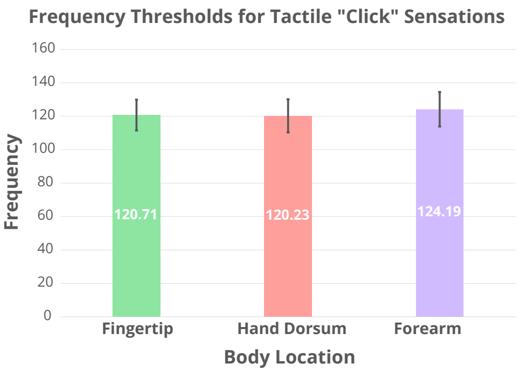

Figure 6: Results from Experiment 2: Frequency thresholds for rendering *Referred Sensations* which give the perception of a tactile "'click" sensation when tapping an on-body touch button.

subtle enough to not distract the users from the primary task (iii) the sensation is felt on the fingertip to indicate that the button has been pressed.

The just noticeable difference (JND) typically used in psychophysical experiments is determined by Weber's fraction [40]. Weber's fraction for vibrotactile stimuli ranges from 3-30% for frequencies in the range [0-200] hz which translates to 6hz considering the smallest possible change in frequency. But because the frequency range of the actuator is >200Hz, in our pilot test with 6 participants, we tested three frequency steps (6hz, 8hz, 10hz) to identify the just noticeable difference. The frequency step of 8Hz offered a good balance between the high resolution of JND and the number of trails which also impacts the duration of the experiment. Informed by this, we modified the intensity of tactile feedback in steps of 8 Hz. We reduced the intensity levels until participants could no longer feel the tactile feedback. Since the frequency response of ERM motors is not linear with the driving voltage, we converted the PWM voltages to appropriate frequency levels based on the spec sheet of the manufacturer [1].

5.3 Results and Discussion

Figure 6 shows the frequency ranges for each of the body locations which elicited suitable sensation for simulating a tactile button click sensation. As shown in Figure 6, for the fingertip, the average frequency is ~121 Hz (sd= 9.94). For the hand dorsum, the mean frequency was similar to that of the fingertip, with a mean of ~ 120 Hz (sd = 9.23). Finally, the forearm had higher thresholds compared to the fingertip and hand dorsum (mean frequency: ~ 124 Hz, sd = 10.33). These results show a consistency in the range of *Referred Sensations* at all the locations. One-way repeated measures ANOVA showed a significant influence of body location on the frequency ($F_{2,22} = 6.4881,\ p = 0.0061$). Tukey pairwise comparisons revealed a significant difference between Fingertip and the hand dorsum (p = 0.02), fingertip, and forearm (p = 0.001). However, there was no significant difference between the Forearm and hand dorsum (p > 0.5). In line with prior work [63], these results show that body location does play a crucial role in rendering *Referred Sensations*.

For rendering tactile "click" sensations the vibrational waves need to be subtle enough so that they are not detected by the fingernail and strong enough to pierce through the underlying tissue so that they can be picked up by the mechanoreceptors in

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[1] https://www.precisionmicrodrives.com/ab-004

the fingertip. As such, the interpersonal variations in the tissue structure and density can be a factor. However, in our experiments, which had normal healthy participants, there was no large deviation in the frequency thresholds (the sd was 10 Hz for all the locations). These frequency thresholds will help other researchers to compare their results if similar experiments are conducted with other tactile rendering technologies (e.g. electro-tactile or magnetic actuation). The thresholds we found are also similar to the resonant frequencies found near the fingertip and forearm (∼ 110-120 Hz) [81].

6 EXPERIMENT 3: ENHANCING THE EXPRESSIVITY OF ON-BODY BUTTONS WITH TACTILE EFFECTS

In this study, we aimed to enhance the expressivity of buttons on the skin by rendering various tactile effects on the fingertip. A key motivation for this study was the finding from Experiment 1. Participants informed us of the need for variation in the tactile feedback, which can be beneficial in creating a mapping between the tactile effect and an application scenario (e.g. a strong vibration can be associated with an urgent email that needs a response immediately). Prior work has shown that directional patterns can be rendered on the fingernail using an array of actuators [35]. Here, we are interested in understanding the limits of a single actuator for delivering rich tactile effects that can be coupled with on-body touch input.

6.1 Perceptual Spaces and Dimensions

Perceptual space is an n-dimensional Euclidian space that visualizes the intrinsic metric relationships between stimuli based on perceptual similarity/dissimilarity [104]. Perceptual space is constructed from the perceptual distances estimated between the stimuli of interest.

Multidimensional scaling (MDS) is an established technique to examine the role of dimensions in the perceptual organization of sets of stimuli [79]. In this method, measurements of subjective dissimilarity are combined to yield a model of perceptual space in which each point represents a specific stimulus (in our case one of the 21 chosen tactile effects). The distance between any two points provides a good estimation of how perceptually different the stimuli are. This approach has been an exceedingly effective tool in comprehending the perceptual structure of many types of haptic stimulus, e.g., texture [34, 61], vibration [37, 44], and material [87]. However, to the best of our knowledge, we are the first to employ this method in the context of on-body interaction.

6.2 Apparatus

The apparatus was similar to the one used in the previous experiments. However, to render tactile effects, we used a haptic motor driver (Texas Instruments, DRV2605L) to interface the ERM motor. The motor driver supports the rendering of 118 different tactile effects. We employed this approach because it allows us to easily test diverse tactile effects. Additionally, the same haptic controllers have been used commonly in HCI literature for developing haptic effects and testbeds [18, 58].

While the motor driver supports a vast number of tactile effects, not all of them are applicable to on-body buttons as they are designed for touchscreen interactions. Hence, to choose the most desirable ones among the large pool of effects, we conducted a pilot study with 4 participants. In the study, each participant tested the suitability of an effect for on-body touch buttons. A touch button was placed on the forearm and when a participant touched the button, a chosen tactile effect was rendered. Participants could select the desired effect through a custom WPF application. They were free to test the effect multiple times to have a good understanding of its suitability for on-body touch buttons. Participants had a forced-choice yes/no paradigm [40], where they had to answer "yes" or "no" for determining if the effect was suitable for on-body tap input. For each participant, we collected a set of suitable effects. The final shortlist of effects was the intersection of all the sets among the participants. This gave us a list of the most desirable effects across users. In addition to the 20 effects, we added the baseline condition: i.e., just the natural tactile feedback from the body resulting in a total of 21 tactile effects. Table 1 shows all the effects used in the experiment.

Effect #	Effect	Effect Family
1	Strong Click -100%	**Click**
2	Strong Click - 60%	**Click**
3	Strong Click - 30%	**Click**
4	Sharp Click - 100%	**Click**
5	Sharp Click - 60%	**Click**
6	Soft Bump – 100%	**Bump**
7	Soft Bump – 60%	**Bump**
8	Soft Bump – 30%	**Bump**
9	Soft Fuzz - 60%	**Fuzz**
10	Strong Buzz - 100%	**Buzz**
11	750 ms Alert	**Alert**
12	1000ms Alert	**Alert**
13	Medium Click - 100%	**Click**
14	Medium Click - 80%	**Click**
15	Medium Click - 60%	**Click**
16	Short Double Click Strong - 100%	**Click**
17	Buzz 1 - 100%	**Buzz**
18	Buzz 2 - 80%	**Buzz**
19	Buzz 2 - 60%	**Buzz**
20	Buzz 2 - 40%	**Buzz**
21	No Feedback	**Baseline**

Table 1: Tactile effects which were used in Experiment 3. Through variations in amplitude, frequency, and time intervals, these waveforms can generate a variety of tactile sensations.

6.3 Task and Procedure

We recruited 12 participants (5 female, mean age: 30.36, sd: 5.24) for the study. The on-body touch button was placed at the center of the non-dominant forearm. For similarity judgment between the vibrotactile sensations, this experiment used the cluster sorting method [70], where participants had to group the effects based on their similarity. They sat in front of a monitor which had experimental software (WPF application interfaced to a microcontroller connected to the haptic driver (as shown in Figure 7). Through the application, the participant can select a desired tactile effect (from a total of 21) from a drop-down list. Once selected, the effect is played when the touch input is performed on the on-body touch button. Participants' task was to compare the tactile effects and group them into a given number of clusters based on their similarity. They wore noise-canceling headphones that played white noise to block any sound The experiment had three sessions that respectively used 3, 4, and 5 clusters. After clustering, participants were also asked about the possible mapping and scenarios where they would use the clusters. We randomly ordered the clusters to the three sessions. In addition, to prevent memory effects, stimulus numbers were randomly assigned during every session. The entire experiment took 60-90 minutes.

6.3.1 Data Analysis. The data from cluster sorting was processed following the procedure described in prior work [70]. The similarity score s_{i_j} between effects i and j was initialized to 0 for each participant. If effects i and j were grouped in a session with N clusters, s_{i_j} was increased by N. We repeated this for all pairs of effects. From these similarity scores, a normalized dissimilarity matrix $\{d_{i_j} | 1 \leq i, j \leq 25\}$ was obtained by a linear transformation:

$$d_{i_j} = 1000(1 - \frac{s_{i_j}}{3+4+5}) \quad (1)$$

where each pairwise dissimilarity scores d_{ij} is normalized between 0 and 1000. For instance, if a participant grouped two effects i and j to the same bin for all cluster sizes, then the d_{i_j} for this pair is 0. On the contrary, if they were allocated to different bins for all cluster sizes, then d_{ij} for this pair is 1000. Similarly, if they were grouped in the same bin for cluster size 3 and different bins for cluster sizes 4 and 5, then d_{ij} is 750

We calculated average scores from these individual scores. Then, we applied non-metric classical MDS to the dissimilarity matrix to find perceptual spaces with appropriate dimensions. We evaluated the goodness of fit using S-Stress (SS) [103]. SS varies between 0 and 1, and a SS value closer to 0 indicates a better fit.

6.4 Results and Discussion

To examine the goodness of fit, we examined SS values resulting from MDS while increasing the space dimension. Both 2D and 3D spaces were adequate (SS = 0.111 and 0.122; 0.15 is a recommended level [96]). Figure 8 shows the 2D perceptual space for simplicity in which all the 21 tactile effects are shown as points. We also examined the results from both the 2D and 3D representations and found that the major results were almost similar. The overall point distribution in the perceptual space demonstrates that the vibrotactile augmentation of an on-body touch button is a very effective technique in adding expressivity to on-body touch buttons. This is confirmed by the wide spread of the augmented buttons, almost covering the entire spectrum. It is also worth noting that these diverse tactile sensations can be perceived with a single actuator. It is interesting to note that the baseline condition (i.e. button without tactile feedback) is on the right end of the spectrum and at a distance of >200 units from 15 tactile effects and >100 for 4 tactile effects suggesting that there is always a distinct difference in perception on augmenting tactile feedback. Similarly, the largest difference in perceptual distance was observed between effect #2 (Strong Click -60%) and effect #7 Soft bump - 60% with distance $D_{2,7}$ = 503.54.

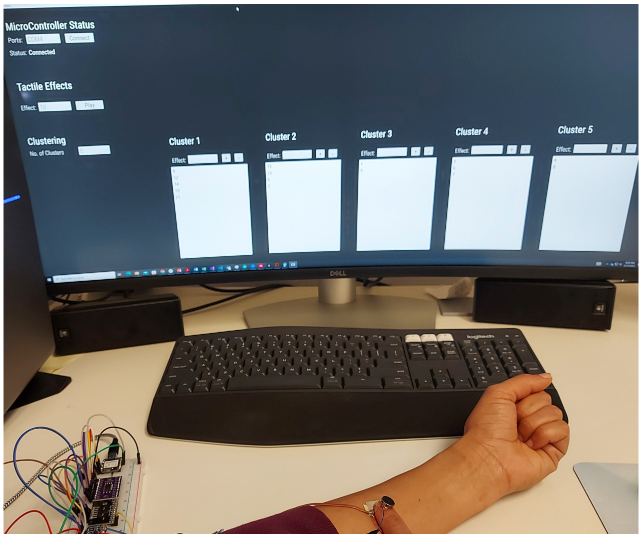

Figure 7: Setup for Experiment 3: Participants played each of the tactile effects and then clustered each of the effects into different bins. Effects can be added or removed from each bin through dedicated buttons placed above the bin.

Another observation is that just by modifying the amplitude of the waveform, highly distinct tactile effects can be rendered (effects #1 & #2 ($D_{1,2}$=263.49), effects #7 & #8 ($D_{7,8}$ = 312.98)). Overall, these results confirm that even with a single actuator on the fingernail, we can render many distinct tactile effects .for on-body touch input. Such distinct tactile effects can be useful for creating tactile mappings for on-body touch input (e.g. assigning a specific effect for a social media button).

6.4.1 Participant Feedback and Mappings. : Overall, our participants were highly excited that they could perceive as many tactile effects with an actuator. They highlighted the importance of adding computer-generated tactile feedback for on-body touch buttons and suggested possible mappings and application scenarios for all the tactile effects. Specifically, the majority of users suggested effect #1 (750ms Alert - 100%) for signifying urgency or emergency messages that need immediate attention. A family of soft tactile effects 6,9,16,19 was deemed suitable for providing subtle tactile feedback for text entry on the body. Strong click sensations were suggested to be suitable for rendering error notifications (e.g. typing errors during a text entry) or for text entry for specific cases like passwords: "I think these can be appropriate for typing passwords, as the slightly stronger feedback will make me more aware while typing my passwords" -P4.

7 DISCUSSION LIMITATIONS AND FUTURE WORK

Frequency Thresholds: While we report on the average thresholds across participants, it should be noted that these thresholds also depend on individual variations in tactile sensitivity. For the fingertip, we noticed that the thresholds varied between a minimum of 104 Hz to a maximum of 133 Hz. For the hand dorsum and forearm,

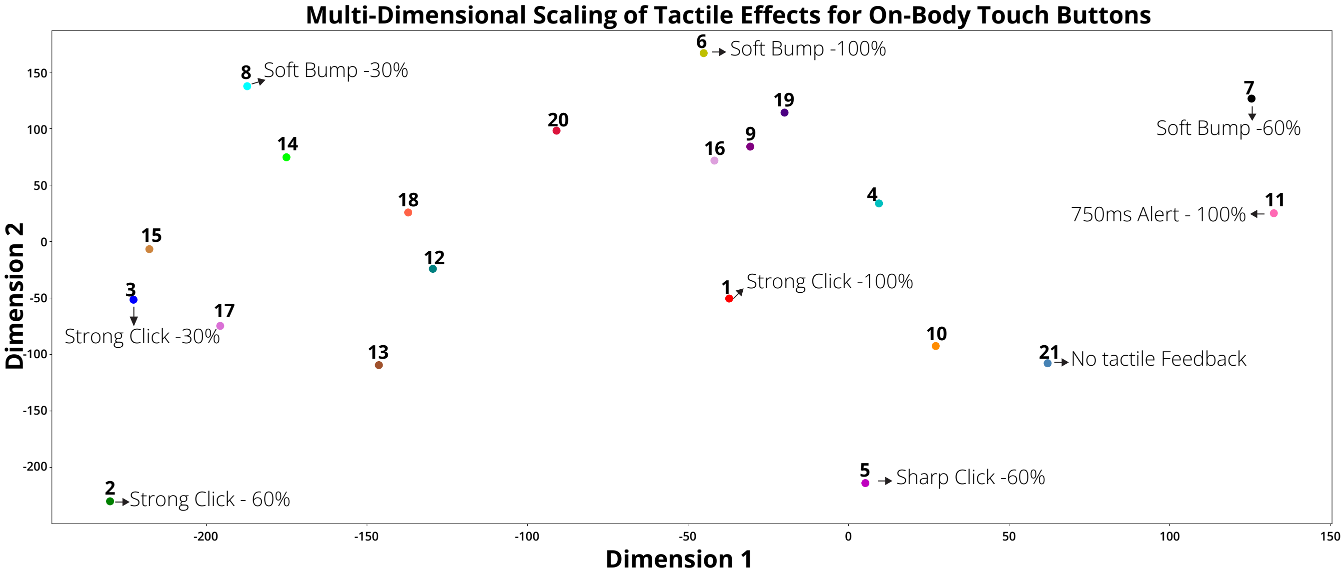

Figure 8: Results from Multi-Dimensional Scaling in Experiment 3: Each of the points in the scatter plot represents a tactile effect and the X and Y axis represent the perceptual dimensions. The similarity between the effects is represented by the distance between the points i.e. higher the distance, the more distinct and dissimilar they are.

the ranges were [104 - 144] Hz and [104 - 137] Hz respectively. We also noticed that the lower bound of 104 Hz is also due to one participant who had lower thresholds than the rest. Similarly, we also noticed that there were individual differences in how participants perceived the sensation on the fingertip. In a few cases, our participants reported that they could not differentiate if the sensation was felt on the fingertip or the fingernail, however, they did confirm that the intensity for producing such sensations was close to the vibrotactile sensations that they perceived while performing text entry on mobile devices.

Integration into artificial nails: While in this paper, we explored the theoretical and tactile perception capabilities of fingernail actuation for on-body touch input, from a technical standpoint, we envision that a self-contained fingernail actuation system can be developed which can be worn in the form of artificial nails similar to nail-based interactive devices reported in literature [15, 41]. However, a key limiting factor that prohibits such design is the power needed for driving the actuators. Recent work presents the first step in this direction albeit by placing the batteries on the finger phalanxes [72].

Scaling to Other Sensing Techniques: Our approach of using actuation on the fingernail should be scalable to other sensing techniques for detecting touch input on the body. In our initial pilots and experiments, we explored using optical sensing techniques shown in prior work [29] for detecting on-body touch and then coupling it with tactile feedback. However, since capacitive sensing techniques have shown to be more precise at recognizing touch-up and touch-down events [22, 65, 93], we used them in our experiments. Also, we used a thin-film touch sensor that provides a good balance between mechanical robustness and minimally influences the inherent tactile perception capabilities [63]. Hence, we speculate that the thresholds reported in this work should also hold well for other sensing techniques which do not instrument the human body.

Coupling Force Input: In our current experiments, we augmented touch input with tactile feedback. However, the interactions that we focused on in our experiments were taps. Sensing high-resolution force and pressure input on the body without significantly diminishing our tactile perception capabilities is still an active research area. However, once such enabling technologies are created, force-coupled on-body tactile feedback can be designed which can deliver even richer tactile and kinesthetic experiences.

Extending beyond Taps: In this work, we primarily focused on button taps. However, richer on-body interactive experiences can be delivered when tactile feedback is coupled with other on-body widgets such as sliders, and deformation input. To design haptic feedback for on-body sliders, in addition to the usual parameters (e.g. length, number of levels, type of feedback (constant, linear, etc.)), the influence of many-body specific parameters (e.g. body locations, friction at a specific body location (e.g. glabrous vs non-glabrous regions) also need to be thoroughly studied While previous work has contributed devices for sensing pressure or shear sensing [95], for deformation input, the technology that enables continuous high-resolution, pressure shear and deformation sensing on the skin is yet to be mature enough. Additionally, the haptic feedback design for this input modality needs to identify and meticulously study various body-specific parameters. Put together, material experiences can be rendered on the body by coupling tactile feedback with such movement-based input. It would be interesting to investigate how the surface properties of the human skin can be artificially altered by rendering material experiences while manipulating on-body interface controls.

Scaling to Multiple Actuators: We opted to use a single actuator and understand its limits in rendering rich tactile feedback for on-body touch buttons. Prior work has shown that using an array of actuators, directional patterns can be rendered [35]. Additionally, augmenting all the fingers with actuators presents another opportunity for exploring the coupling of higher-resolution tactile feedback for on-body touch input.

Actuation Mechanism: We used vibrotactile feedback for augmenting on-body touch input with tactile feedback. We chose this approach because (1) firstly, it allows us to prototype and evaluate the tactile effects with readily available off-the-shelf components. (2) The approach is highly scalable and can be easily prototyped by novice users. However, other actuation mechanisms such as electrotactile actuation can also deliver referred sensations. Future work should investigate the thresholds and the extent of tactile effects that can be delivered through multiple actuation mechanisms (e.g. electrotactile stimulation, magnetic actuation, etc.) for on-body interaction.

Additionally, for rendering vibrotactile feedback, ERM and LRA (Linear Resonant Actuators) are the most commonly used actuators. We initially intended to use LRA motors which are more crisp and expressive (ERMs are comparatively slow to start up). However, ERMs have been extensively used in HCI literature to render expressive tactile effects including spatio-temporal and directional patterns without any noticeable latency [35, 81]. Hence, we chose ERMs as it also allows us to compare our results with the literature.

8 CONCLUSION

In this work, we, for the first time, comprehensively explored the coupling of tactile feedback for on-body touch input. We chose fingernail as a viable medium to deliver vibrotactile feedback for on-body touch input. In our first experiment, we were interested in understanding if users preferred augmenting on-body touch input with tactile feedback. Results show that tactile feedback was highly desirable for users while performing touch input on the body. Our second experiment takes a step further by understanding and measuring the thresholds for rendering suitable tactile sensations that simulate a "tactile click" sensation while interacting with an on-body touch button. To understand the influence of body location on the thresholds, we conducted this experiment at three locations (fingertip, back of the hand, and forearm). Results show that the frequency thresholds for vibrations are similar across body locations: Fingertip (mean: ~124 Hz), Hand dorsum (~120 Hz), and Forearm (~121 Hz). In the final experiment, we investigate the extent to which diverse tactile effects can be rendered on the fingertip to increase the expressivity of on-body touch input. Through non-metric multi-dimensional analysis, we show that haptic augmentation of on-body buttons can enhance the expressivity of on-body touch input. **Overall, this is the first work to comprehensively investigate the coupling of tactile feedback for on-body touch input and opens up the vast research area for haptic augmentation of on-body interfaces.**

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