Balancing Wearability and Functionality in the Design of a Haptic Fingertip Device

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ABSTRACT

The FingerTac provides vibrotactile feedback at the palmar side of the finger while keeping it unobstructed. Yet, wearability aspects have been a shortcoming in the design. We propose a redesign that enhances wearability while preserving functionality. The redesign was evaluated compared to the original design in a user study. Our design was perceived as more comfortable, while performance and haptic sensation were sustained. However, the redesign was inferior in generating localized vibrotactile perceptions on the finger. This highlights the importance of balancing wearability and functional requirements when developing vibrotactile feedback devices. Further research is needed to address this challenge and understand the implications for FingerTac and the design of any haptic device.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **User studies**.

KEYWORDS

haptic devices, usability, tactile internet, augmented reality

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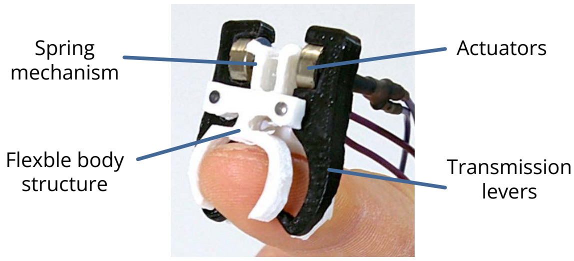
1 INTRODUCTION

The versatility of vibrotactile feedback extends to numerous applications, with its ability to effectively substitute kinaesthetic feedback for force feedback in teleoperation [11, 15], enhance learning skills [6, 12], and improve precision within Virtual Reality (VR) environments [3]. Consequently, there has been a notable proliferation of fingertip [13] and smart glove [2] devices incorporating vibrotactile feedback. Placing the actuator on the dorsal side of the finger has been a common practice for many of these devices to minimize interference during grasping tasks. This approach involves transmitting the actuation through mechanical linkages to introduce stimuli at the palmar side of the finger [5, 7]. The FingerTac [9] applies this concept to vibrotactile fingertip devices. By symmetrically introducing vibrotactile stimuli lateral to the finger pad, the FingerTac creates the illusion of a vibration being exerted in the middle of the palmar side.

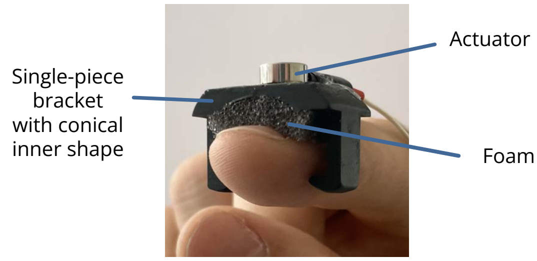
While the FingerTac pushes into the realm of augmented haptics for interacting with real and virtual objects, the original design by Hulin et al. [9] (Fig, 1a) still offers room for improvement from a user-centered perspective. The device adds considerable bulk to the back, exerts uncomfortable pressure on the fingers, and does not ensure sufficient stability on the finger. We propose a design to mitigate these wearability issues while trying to maintain the functionality of the original design, i.e., users' haptic sensation and ability to distinguish vibration patterns and the devices capability to provide localized stimuli at the fingertip.

2 THEORY

We focus on three aspects: wearability, haptic sensation, and performance. Pacchierotti et al. [13] have identified form factor, weight, impairment, and comfort as the essential requirements concerning the wearability of hand and fingertip devices. Devices must adhere closely to the body shape, minimize movement restrictions,



(a) The prototype of the original design with two actuators



(b) The prototype of the redesign with a single actuator

Figure 1: Prototypes of the original [9] and the proposed design of the FingerTac compared in the user study

and ensure a high level of *comfort* to enable long, fatigue-free, and efficient use.

The classification and reproduction of *haptic sensations* pose challenges due to their diverse nature [10]. However, researchers have attempted to classify vibrotactile stimuli based on adjectives and emotional criteria. For instance, Choi et al. [4] classified vibrations solely based on static frequencies using adjectives. Seifi et al. [14] explored more complex vibration patterns representative of those found in products. They defined four haptic facets to describe such complex vibrations, with one facet being sensation. In their work, the authors developed a semantic differential to evaluate *haptic sensation*, consisting of five scales: strength, speed, arousal, smoothness, and pleasantness [14].

In the context of early prototypes that lack an implemented task or application, researchers often evaluate their designs based on more general principles of *performance*, such as their capacity to convey vibrations or forces. Hulin et al. [9] conducted an evaluation in which participants were tasked with differentiating between various rectangular vibration patterns. These types of design evaluations provide valuable insights into the effectiveness of early prototypes in conveying tactile information.

3 METHODS

In the present work, we focus on enhancing the wearability and maintaining the functionality of the FingerTac device while also evaluating the impact of the implemented changes on *comfort*, *performance*, *haptic sensation*, and *spatial localization* through a user study. To achieve these objectives, we present the redesign of the FingerTac and outline the methodology employed in our user study in the subsequent subsections.

3.1 Redesign of the FingerTac

To minimize impairment, our focus was on reducing the size of the device. Through initial testing, we discovered that a single-piece design with a single actuator could offer a comparable *haptic sensation* to the original design, which utilized two actuators. This approach not only removed complexity but also resulted in a smaller overall size. Importantly, we utilized the same actuator as in the original design, ensuring consistency in the haptic experience. Fig. 1 depicts the prototypes of (a) the original design [9], and (b) our redesign side-by-side. One can see that the redesign was a successful improvement on the key requirements of wearability in terms of form factor and weight.

The original prototype posed discomfort in two ways: sharp edges and an uncomfortable pressure exerted by the spring mechanism on the skin. To address these issues, we made several modifications. Firstly, we increased the contact surface area and rounded the edges to distribute the clamping force more evenly. Additionally, the inner shape of the device was designed to be conical, allowing the pressure exerted by the device to be determined by the user pushing it onto the finger. Since the flexible body frame was removed, we needed to find a replacement for its dampening function. Foam was employed to effectively dampen the vibrations transmitted to the dorsal side of the finger. However, the single-part design limited the device's adaptability to different finger sizes. While the conical inner shape allowed for limited adaptation, we still had to create three sizes (small, medium, and large) to accommodate a wide range of finger sizes.

3.2 User Study

Study Design. A comparative user study was conducted to assess and compare the redesigned version of FingerTac with the original design (within-subject design).

Materials. The actuators were driven using commercial hardware and software provided by Hapticlabs GmbH [8]. The vibrations consist of blocks defined by duration t, t_{on} and t_{off}, intensity I, and a fixed frequency $f = 235\,Hz$, which is given by the actuator resonant frequency.

Comfort. Based on previous findings [1], participants were asked to rate the *comfort* of each prototype on a five-point Likert scale (pleasant–unpleasant). To capture potential variations over time, two ratings were obtained: one immediately after the prototypes were put on and another after the completion of the individual data collection.

Haptic Sensation. Two custom-designed vibration patterns were used to evaluate *haptic sensation* and are described in Table 1. The Vibrations are exemplary for real-world applications. Vibration A represents a confirmation, while Vibration B starts with a long fixed intensity, ending with a down-stepping pattern representing monitoring with a failure in the end.

Participants rated the vibrations of each item on the semantic differentiall [14] using a five-point Likert scale for both prototypes. The vibrations were repeated for each item, and participants could request another playback. The order of prototypes and stimuli was randomized. This task aims to enhance understanding of the

Table 1: Two custom-designed vibration patterns (A and B) were used to evaluate *haptic sensation* and pattern L for the *spatial localization* task.

	t (in ms)	N_{pulses}	t_{on} (in ms)	I (in %)	t_{off} (in ms)
pattern A	480	6	80	{13, 27, 43, 76, 47, 7}	0
pattern B	1040	4	{450, 230, 200, 100}	{80, 56, 37, 14}	20
pattern L	775	5	{390, 70, 150, 100, 65}	{20, 0, 30, 70, 20}	0

design differences, especially the number of actuators, on the *haptic sensation* and, thus, user experience.

Performance. A pattern recognition task was conducted, inspired by the methodology of Hulin et al. [9] evaluating the original design. We focused on two vibration patterns with the smallest difference from Hulin et al. [9]. Both vibration patterns had an on-time duration of $t_{\text{on}} = 50\,ms$, with varying pause times of $t_{\text{off}} = 25\,ms$ and $t_{\text{off}} = 50\,ms$ between vibrations and were associated to colors (blue and red). For both prototypes, participants were introduced to the patterns in a predetermined sequence to familiarize themselves with the associated colors. Subsequently, the patterns were played back in a predefined randomized sequence. Participants were then asked to identify each pattern by naming the corresponding color. The number of errors made by participants in recognizing the patterns for each prototype was recorded. This task allowed us to assess whether the proposed design diminishes effectiveness in conveying the intended vibration patterns.

Spatial Localization. Participants indicated where they localized a given vibration by marking the area on a body map of a finger (see Fig. 3) using pen and paper. The employed stimulus is detailed in Table 1 as pattern L. This task evaluated whether our proposed design can isolate vibrations from being felt at the dorsal side of the finger.

Participants. A total of 20 participants (16 male, 3 female, 1 participant did not disclose their gender; $M = 28.25$ years, $SD = 3.50$, 2 left-handed) took part in the study. All participants provided written informed consent . All participants were native speakers and reported as healthy with normal perception. Two participants were excluded from further analysis of all variables except *comfort* due to technical issues during data collection.

Procedure. Participants sat comfortably at a desk during the study. A privacy screen prevented the participants from seeing the prototypes in order to eliminate visual influences. For each participant, the best size of the proposed design ($n = 20$, $n_{\text{small}} = 4$, $n_{\text{medium}} = 5$, $n_{\text{large}} = 11$) was determined. Participants wore both prototypes (original and redesign) simultaneously on their index fingers. The side on which the devices were worn was randomly assigned. Responses were given verbally and were recorded by the experimenter. Participants recorded their responses to the *spatial localization* task themselves.

4 RESULTS

Comfort. The average time between measurements was 17.42 ±2.94 minutes. A Friedmann Test was performed to examine differences in *comfort* ratings between the two prototypes across the two measurement times (Fig. 2a), revealing a significant difference in ratings ($\chi^2(3) = 8.92$; $p = .030$). Post-hoc tests (Bonferroni corrected) indicated a significant difference in *comfort* between prototypes only for the first measurement point ($z = -.83$; $p = .043$; $r = .19$), with the proposed design ($M = 3.7$, $SD = .19$) being rated as more comfortable compared to the original one ($M = 3.00$. $SD = .18$). No significant effect was found between prototypes for the second measuring time ($z = -.73$, $p = .903$), and there were no significant effects for the change of *comfort* over time for both the original design ($z = -.05$, $p = .903$) and the redesign ($z = .10$, $p = .806$).

Haptic Sensation. To test for differences regarding the *haptic sensation* for both vibration patterns (A & B) and both prototypes (original and redesigned), Friedman tests were performed for the semantic differential scales strength, speed, arousal, smoothness, and pleasantness.

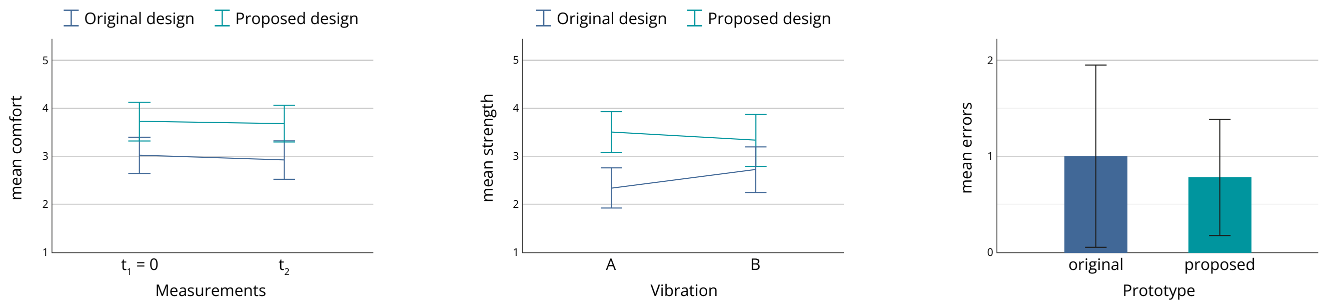
Results are shown in Table 2 and reveal a significant main effect in ratings regarding strength and speed. Dunn-Bonferroni post-hoc tests were employed to elucidate the main effects. Only for the strength variable, the tests unveiled a statistically significant difference between the two prototypes for vibration A ($z = -1.33$; $p = .002$; $r = .31$). The stimuli elicited by the redesign ($M = 3.50$; $SD = .20$) was perceived as significantly stronger in comparison to those produced by the original design ($M = 2.33$, $SD = .20$). The effect was not present for vibration B ($z = -.78$; $p = .071$; Fig. 2b).

Performance. To evaluate *performance* data, descriptive statistics of the recognition errors were analyzed (see Fig. 2c). The participants failed to recognize the pattern more often for the original prototype ($M = 1.00$; $SD = 1.84$) as compared with our proposed design ($M = .85$; $SD = 1.27$).

Spatial Localization. The results are summarized in a body map for each prototype in Fig. 3. For the original design (Fig. 3a), vibrations were localized mainly on the palmar side of the finger, while for our proposed design (Fig. 3b), two hot spots appear on the dorsal and the palmar side of the finger.

5 DISCUSSION

The redesign exhibited a marginal increase in *comfort* during the initial measurement, albeit with a weak effect. One possible factor that may have undermined the *comfort* of the redesign was the use



(a) **Comfort (n=20)** (b) **Haptic sensation: strength (n=18)** (c) **Performance (n=18)**

Figure 2: Diagrams for the study results regarding *comfort, haptic sensation,* and *performance* (error bars = 95% CI)

Table 2: Results main effects for *haptic sensation.*

strength	speed	arousal	smoothness	pleasantness
$\chi^2(3)$ = 16.35; p= .001	$\chi^2(3)$ = 10.47; p= .01	$\chi^2(3)$ = 7.28; p= .064	$\chi^2(3)$= .51; p= .916	$\chi^2(3)$ = .56; p= .906

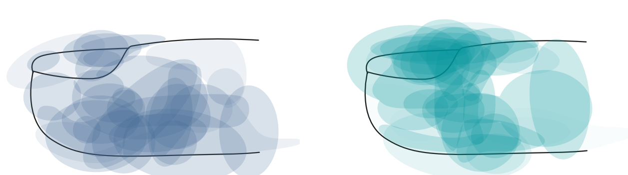
of a privacy screen, which prevented participants from adjusting the device for maximum *comfort* on their fingertips.

Regarding *haptic sensation*, our redesign was perceived similarly to the original FingerTac on the semantic differential scales. Surprisingly, despite using fewer actuators, vibration A was perceived as stronger for the proposed design. Both devices exhibited similar *performance*, while the original design outperformed our redesign in terms of *spatial localization.* Overall, with the redesign, we could improve *comfort* while maintaining functionality. Potential drawbacks from the more distributed *spatial localization* of the perceived vibration stimuli will have to be evaluated regarding specific use cases. Further, minimizing the device's size contributes to lowering impairment, which we intend to evaluate in further studies, as well as other wearability factors. Furthermore, we intend to evaluate the overall appraisal of the device and the instrumental and non-instrumental qualities affecting user experience in specific use cases to foster a better understanding of design decisions balancing wearability and functionality.

6 CONCLUSION

In conclusion, the original design exhibited shortcomings in terms of wearability, which prompted us to make adaptations to address this issue. In evaluating our redesign, we conducted a comparative analysis with the original design, focusing on wearability (*comfort*) and functionality aspects (*haptic sensation*, *performance*, and *spatial localization*). Our proposed design was perceived as more comfortable, yet the distribution of vibrotactile stimuli across the finger (*localization*) differed from the original design. The practical implications of the design choices will be uncovered as soon as the device is employed to enhance augmented reality interfaces with haptic feedback.

Eventually, achieving an optimal balance between wearability and functionality necessitates making trade-offs. Researchers and developers in haptic device design should employ appropriate methodologies to navigate these trade-offs effectively and create designs that excel in wearability and functionality.



(a) **Prototype original design** (b) **Prototype proposed design**

Figure 3: Body heat maps of the *spatial localization* task

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