Design Explorations in Distal Haptics for Touchscreen Input and Users with Upper-Body Motor Impairments

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Abstract

Haptic feedback, commonly experienced as vibrotactile cues on mobile devices, increases user performance and enhances user experience, but research addressing users with upper-body motor impairments remains scarce. In particular, variations in how touch input is performed across different motor abilities raise questions about the optimal location, on-device or on-body, for vibrotactile feedback to maximize its effectiveness. In this work, we apply design thinking to explore alternative approaches for delivering haptic feedback at locations distant from the on-screen touch point, such as the user's hand, wrist, forearm, or even the other arm. To inform our design explorations, we leverage empirical findings from a dataset of touch gestures performed on mobile devices by users with various upper-body motor impairments. We present future research opportunities at the intersection of haptic technology, wearable devices, accessible computing, and touchscreen input.

CCS Concepts

• **Human-centered computing → Gestural input**; **Systems and tools for interaction design**; **Accessibility systems and tools**.

Keywords

Touch input, haptics, accessibility, motor abilities, motor impairments, touchscreens, vibrotactile feedback, design thinking

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1 Introduction

Haptic feedback accompanying touchscreen input is known to improve user performance [2,4] and enhance the overall user experience [13,19], being prevalent on mobile devices as vibrotactile cues following touch input. Since vibrations are delivered through built-in actuators in mobile devices, feedback is localized to the device and sensed by the user through the contact point with the touchscreen, typically the index finger or thumb [10], with the majority of research in this space centering on on-screen feedback. However, users with upper-body motor impairments do not always rely on these fingers, or even their fingerpads, to touch the screen; instead, they adopt various coping strategies, using other fingers, lateral sides, knuckles, or even other body parts when engaging with touchscreens [1]. Moreover, sensitivity in the upper limbs may be reduced, which could make on-screen vibrations less effective on the hand implementing touch input. Designing vibrotactile feedback for users with upper-body motor impairments needs creative solutions but, unfortunately, has received limited attention and little information is available to researchers and practitioners on how to design more inclusive mobile interactions integrating haptics.

In this context, we focus on haptic feedback for users with upper-body motor impairments. Our approach leverages design thinking [17], centered around distinct core stages [3], of which we address in this work Empathize, Define, Ideate, and Prototype. In the first stage, we gain insights into how users with upper-body motor impairments interact with touchscreens by analyzing records from a large dataset [33]. In the second stage, we propose ability-first haptics adapted to the specific ways and body parts, e.g., fingerpad, knuckle, lateral side, used to interact with the screen. To this end, we adopt ability-mediating design [33] as a conceptual framework, where a device other than the touchscreen mediates the delivery of vibrotactile feedback to confirm on-screen touches, system actions, and deliver notifications. In the third stage, we apply divergent thinking to propose *distal haptics as an alternative to conventional on-screen haptic feedback,* targeting different locations on the user's body, distal to the on-screen touch point, based on the Distal Haptics Continuum [30]. For example, a pulse delivered on the wrist could signify the correct registration of an on-screen touch, while a sequence of pulses on the opposite forearm could be used for the delivery of a notification. In the fourth stage, we explore technical solutions for implementing distal haptics through a modular wearable device and specialized vibrotactile feedback design. Based on the outcomes of these stages, we propose future work opportunities.

2 Related Work

We connect to prior research on vibrotactile feedback accompanying touchscreen input and accessible interaction techniques for users with upper-body motor impairments, at the intersection of which lies the scope of our work.

Vibrotactile feedback is increasingly applied to enhance user experience in interactive computer systems [15,25], particularly in touch and mobile input [8,9] due to the widespread adoption of smartphones. However, most research in this area has focused

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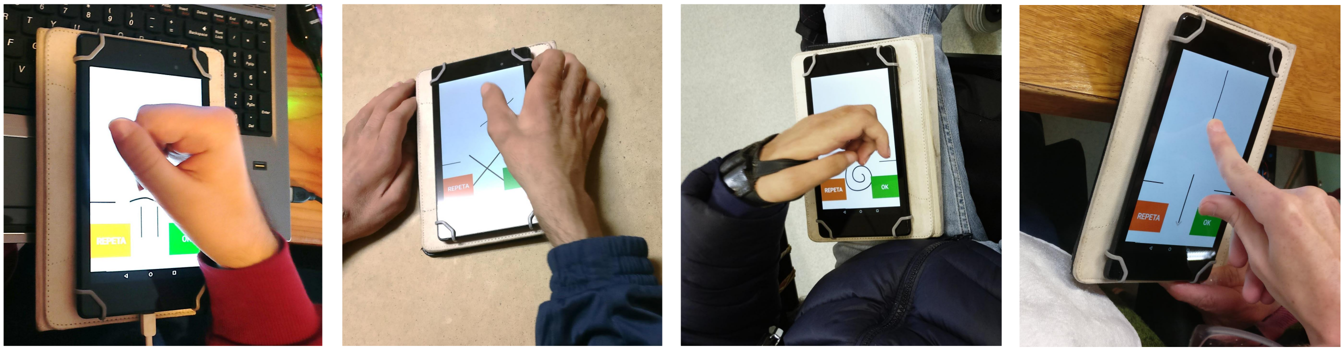

Spinal Cord Injury (C6) **Little finger (knuckle)** cannot move fingers

Spinal Cord Injury (C6) **Thumb,** other fingers kept fixed to the edges of the device

Spinal Cord Injury (C5) **Little finger (knuckle)** no wrist control, wears a hand strap

Cerebral Palsy **Index finger (fingertip)**

Phocomelia **Middle finger (fingertip)** other fingers missing

Spastic Tetraparesis **Index finger (fingertip)**

Muscular Dystrophy **Middle finger,** supported by the index and thumb fingers

Spinal Cord Injury (C5) **Input with a pen** attached to the palm with a hand strip

Figure 1: Examples of users with diverse motor abilities engaging in touchscreen input on a mobile device [34]. Note the various hand poses, the fingers used, and the specific parts of the fingers making contact with the touchscreen.

on users without motor impairments, while studies exploring vibrotactile feedback in relation to motor impairments have primarily addressed rehabilitation for specific health conditions, such as stroke [22], Parkinson's [26], muscular atrophy [27], and spinal cord injury [16], with the goal of improving motor control. Researchers have also explored wearables that deliver vibrotactile feedback to affected body parts, such as wrist-worn bracelets [11] or gloves [12]. For instance, Seim et al. [24] used a glove with integrated mechanical and vibrotactile feedback in chronic stroke rehabilitation, reporting improved voluntary movement in the affected arm; Krueger et al. [14] showed that vibrotactile feedback enhances and stabilizes hand and arm-reaching actions; and Held et al. [7] examined the user experience of wrist-level vibrotactile feedback for stroke patients, reporting a strong preference for haptics over visual and audio modalities. Vibrotactile feedback has also been applied in assisting grasping actions to provide sensory cues about hand aperture [20,23,35] and in enhancing the performance of myoelectric prostheses [6,20].

In conclusion, while vibrotactile feedback has been extensively studied in rehabilitation and prosthetics, its potential to enhance the user experience of touchscreen input on mobile devices remains underexplored, despite the widespread use of these devices and the extensive research focused on users without motor impairments.

3 Design Thinking, Stages #1 and #2: Empathize and Define

We used the open-access dataset of Vatavu and Ungurean [34], available online,[1] to examine touchscreen input behavior in users with upper-body motor impairments. The dataset includes a total of 4,662 stroke gestures performed on mobile devices by 35 individuals with diverse health conditions, including spinal cord injury, cerebral palsy, phocomelia, muscular dystrophy, Parkinson's disease, and spinal muscular atrophy. We identified various ways of touching the screen in terms of hand poses, fingers, strategies for maintaining stable contact between the fingers and the screen, and additional aids such as hand straps and pens; see Figure 1 for a few selected examples. For instance, a user with a spinal cord injury located at the C6 vertebra (first image on the top row in Figure 1) uses the knuckle of the little finger because their specific impairment prevents finger control and movement; another user with muscular dystrophy (third image on the second row) uses the lateral side

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[1] http://www.eed.usv.ro/~vatavu/projects/MotorImpairmentsGestureDataset

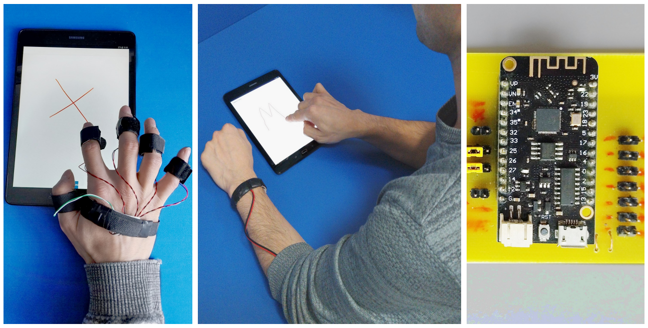

Figure 2: Vibromotors attached to different parts of the hand (left) and the opposite hand (middle) provide vibrotactile feedback during touchscreen input. On the right, a close-up of the central module in our prototype used to independently control a customizable number of vibromotors.

of the middle finger, supported by the adjacent fingers; and users with missing fingers, as seen in the case of phocomelia, face limited options for both interacting with the touchscreen and maintaining the device in a stable position (first image on the second row). By analyzing the videos in the dataset to manually extract information about the touch implementer, we noted that the index finger was most commonly used (17/35=48.6%), followed by the little finger (8/35=22.9%), thumb (5/34=14.3%), and middle finger (4/35=11.4%). The fingerpad was primarily used for touch input (24/35=68.6%), followed by the knuckle (9/35=25.7%). Some participants (11.4%) used a hand strap for additional finger support and stability. We refer to Vatavu and Ungurean [34] for additional findings on how participants with upper-body motor impairments from this dataset articulated stroke gestures on touchscreens, including numerical measures of gesture performance and recognition accuracy rates.

Individual motor symptoms, along with specific health conditions, determine the observed touchscreen input behavior. For example, the user in the first photo on the top row of Figure 1 reported experiencing spasms, low strength, rapid fatigue, difficulty grasping, holding, and controlling both direction and distance of movement, as well as a lack of sensation. In contrast, the missing fingers in phocomelia (first photo on the second row) lead to difficulty in grasping, but not other symptoms. By consulting the literature where similar information was considered, we found that a lack of sensation was frequently self-reported by study participants—3 out of 12 participants (25%) in [5], 2 out of 12 (17%) in [21], 4 out of 12 (33%) in [18], 10 out of 21 (48%) in [32], and 15 out of 41 (37%) in [31] reported this symptom. These findings show that touchscreen input behavior is significantly different compared to its use in the absence of motor impairments [10] whereas reduced strength, spasm, missing fingers, and lack of sensation in fingers constitute challenges in effectively delivering on-screen vibrotactile feedback.

Drawing on these findings, an alternative device affixed to the body could deliver vibrational cues upon touchscreen input, regardless of how the touches are performed. According to ability-mediating design [33], this additional device would serve to mediate the ability to effectively sense vibrations by involving a different body part than the one used to touch the screen. In the next section, we explore design options for ability-first distal haptics, where vibrotactile feedback is delivered to various body parts.

4 Design Thinking, Stages #3 and #4: Ideate and Prototype

We ground our exploration of distal haptics for users with upper-body motor impairments in the distal haptics continuum (DHC) [30] and ability-mediating design [33], addressing various on-body locations and vibrotactile feedback delivered through a custom-made wearable and a diversity of vibrotactile patterns. According to DHC, vibrotactile feedback can be delivered at a distance from the on-screen touch point across the dimensions of body laterality and body proximity. For users with upper-body impairments, receiving feedback on affected fingers, hands, or arms, particularly those used for touchscreen input, as shown in Figure 1, may be ineffective, uncomfortable, or even disruptive. To mitigate this, we used DHC [30] to explore alternative feedback locations, such as the upper arm, torso, or even the opposite arm by adopting a divergent thinking approach. These areas, potentially more sensitive due to not being affected by motor impairments, can be customized based on the user's health condition and preferences for receiving feedback.

To explore such opportunities and complement prior work addressing users without motor impairments [8,29], we developed a modular device designed to accommodate vibrotactile feedback at different body locations. The device consists of multiple wearable peripheral modules, each incorporating 10 mm DC coin vibromotors that deliver vibrotactile feedback via Pulse Width Modulation (PWM), enabling both simple on/off pulses and complex vibrotactile patterns. The peripheral modules can be integrated into various form factors, such as a hand-augmentation device or a glove with the actuators affixed to the fingers and dorsal side of the hand (Figure 2, left) or a bracelet designed to be worn on the opposite arm than the one engaged in touchscreen input (Figure 2, middle). These modules connect to a main unit centered around an ESP32 controller (Figure 2, right), either via wired I2C or wirelessly using the ESP-NOW protocol.[2] The central unit acts as a bridge between the peripheral modules and the mobile device, receiving commands over Wi-Fi and distributing vibrations to one or more peripherals.

Our implementation is compatible with VIREO [28], a specialized software tool for vibrotactile pattern design and integration of vibrotactile feedback into mobile and wearable applications. This further enhances flexibility, allowing each modular component to render custom vibrotactile feedback. The patterns can be used in various practical mobile interactions, from confirming touchscreen input to accompanying the articulation of swipes and stroke gestures, or signaling different application notifications and events. Since each peripheral module operates independently, vibrations can be customized to the corresponding body parts where the modules are affixed, according to user abilities and preferences. For instance, users with reduced finger sensitivity may benefit from vibrotactile feedback redirected to unaffected body areas, such as the upper arm or torso. Some users may require vibrotactile feedback of longer duration to allow more time for its processing, such

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[2] ESP-NOW ESP32, https://docs.espressif.com/projects/esp-idf/en/stable/esp32/api-reference/network/esp_now.html

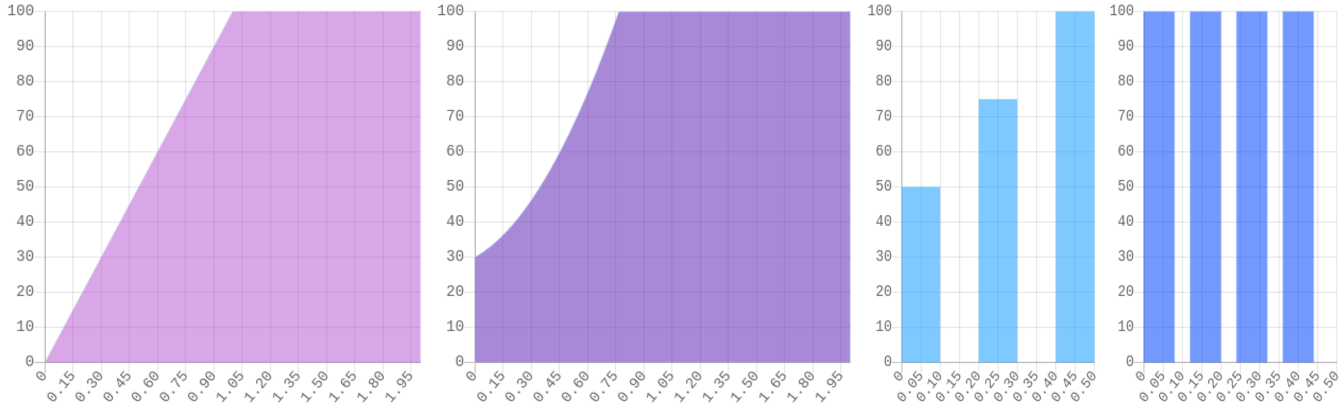

Figure 3: Examples of vibrotactile feedback patterns, designed using VIREO [28], that can be delivered through our wearable device, ranging from single pulses of varying intensity (left and middle-left) to pulse sequences (middle-right and right). ***Notes:*** **the horizontal axis shows time in seconds; the vertical axis shows vibration intensity as a percentage.**

as a vibration that gradually increases in intensity before stabilizing (Figure 3, left and middle-left). Conversely, other users with reduced dexterity or tremor may find short, rapid vibration sequences (Figure 3, middle-right and right) more effective and richer in information. Vibrotactile patterns such as these can accompany touch input in various ways, from confirming correctly registered on-screen touches, to conveying information about the outcomes of actions being performed by the device, to delivering notifications at different locations on the body.

5 Conclusion and Future Work

We proposed in this work a technical solution for implementing distal haptics for users with upper-body motor impairments engaging with touchscreen input on mobile devices. By leveraging a wearable device with a modular design as a mediator for haptic feedback, we achieved flexibility and customizability. We envision interesting future work culminating in creative designs for enabling effective and information-rich vibrotactile feedback for users with upper-body motor impairments. First, participatory design are recommended to document preferences for receiving vibrotactile feedback at various body locations. Second, integration of distal haptics into various mobile applications, such as social media, video games, and news feeds, will reveal new opportunities for custom vibrotactile patterns, along with technical solutions for implementing them (e.g., using Bluetooth instead of Wi-Fi for communications with the wearable device). Third, evaluating and comparing the user experience reported by users with upper-body motor impairments to that of users without impairments will enable a better understanding of accessible haptic design for mobile devices. These future work directions require creative approaches that would go beyond current norms, decoupling the locations of input and output to maximize accessibility across a diversity of motor abilities.

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