DragTapVib: An On-Skin Electromagnetic Drag, Tap, and Vibration Actuator for Wearable Computing

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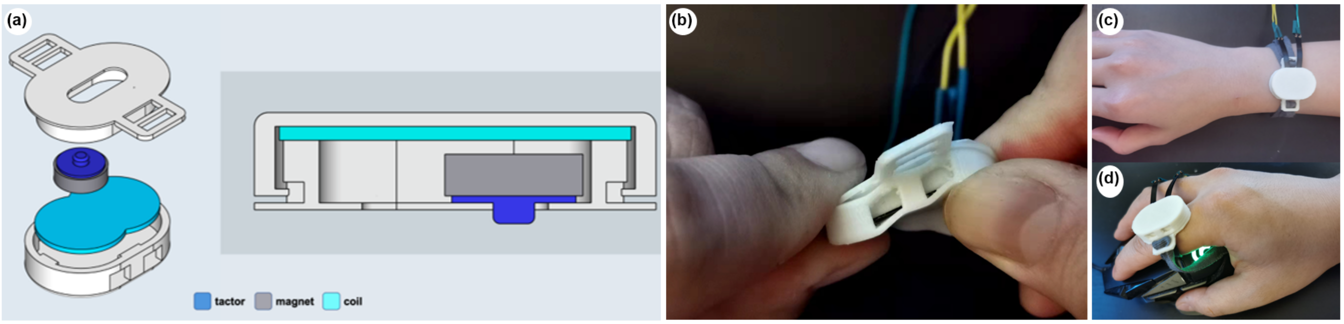

Figure 1: (a). Structure of DragTapVib; (b). DragTapVib is a flexible and wearable actuator that renders three haptic stimuli; (c) and (d). DragTapVib can be worn on different body locations.

ABSTRACT

The skin, as the largest organ distributed all over the human body, offers excellent opportunities for different kinds of input stimuli. However, most of the haptic devices can only render single sensations or they need to combine multiple complex components for generating multiple sensations. We present “DragTapVib” in this paper, a novel, ultra-low-cost, wearable actuator that can reliably provide dragging, tapping, and vibrating sensations to the user. Our actuator is fully electromagnetically-actuated with a moving tactor that can render three haptic feedbacks through systematically controlling the current inside the flexible PCBs. The actuator can be arranged with varying parts of the body which enriches the potentials to implement promising application scenarios including delivering the notification and providing immersive haptic feedback either in virtual reality or in gameplay. A prototypical technical evaluation demonstrated the mechanical properties of our actuator. We quantitatively conducted a series of psychophysical user studies (N= 12) to reveal the feasibility of our prototype. The overall absolute identification study for distinguishing three sensations accuracy at two body locations reached up to 97.2%.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; • **Hardware** → *Sensors and actuators.*

KEYWORDS

Haptic device design, Multimodal haptics, Wearable computing, Tactile actuator, On-skin device

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1 INTRODUCTION

Human skin, as the largest and most visible organ of the body, is capable of perceiving various sensations while at the same time offering ample space across the entire body to share information with the user. Moreover, the skin provides sensory input from the environment and houses *Touch*, the most ancient sense of the body, which is caused by the following factors: stimulation the skin mechanically, thermally, chemically, or electrically to produce a

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sensation of pressure, vibration, temperature, or pain [16]. Subsequently, users always "carry" their skin with them, creating an opportunity for immediate, subtle, and hidden feedback.

Different cells of the human skin react to other stimuli – e.g., for vibration detection on the hands Merkel, Meissner, and Pacinian cells react to very-low, low, and high frequencies ($\sim$ 5Hz, 5 $\sim$ 40Hz, 40 $\sim$ 400Hz), respectively [21]. Lower frequency tapping is perceived by cells that react to slow pressure (Merkel and Meissner cells). Skin stretching is perceived by Ruffini cells. The spatial and temporal resolution of the skin sensations is achieved by the cutaneous receptors (Pacinian corpuscles channel) that are spread in different densities across the body [36].

Due to the large variety of sensations perceivable on the skin, past work explored different actuation principles such as vibrotactile [4], dragging [14], stretching [37], temperature [26], or even airflow [35]. Generally, integrating multiple of the stimuli mentioned above in just one device is desirable. It maximizes the number of different outputs presented to the user while maintaining a small footprint on the skin surface. In past work, Zhu et al. [41] gave an excellent overview of different actuator designs and their respective stimuli.

Faced with this challenge, we proposed a new and novel prototype to flexible and wearable haptic actuators. To the best of our knowledge, we present the first electromagnetic actuator on a minimally scale that renders dragging, tapping, and vibrating sensations onto the user's skin with one simple device. Our approach is based on the effective electromagnetic system [4, 25], and it is an easy-to-manufacture, low-cost wearable device. Our work, depicted in Figure 1, works by driving a tactor that drags or taps the skin consistently. Our work potentially excels in wearable multimodal haptic interfaces and extends the possibilities of electromagnetic wearable actuators.

We furthermore contribute to the fabrication process to inspire the readers to replicate their own actuators. We conducted a series of technical evaluations to reveal the mechanical properties for verifying the feasibility of our approach. Also, we concluded findings from user experimental evaluations that investigate placement and actuation parameters for optimal perceptibility and distinguishability. We then conducted a user study investigating the performance the how users can distinguish each stimulus using our actuator (N=12) and found that we could achieve 98.6% and 97.2% stimulus identification accuracy at the user's Proximal Phalanx and Outer Wrist respectively. Last but not least, we demonstrated two compelling interactive application scenarios, including wearable notifications and augmenting the game play. In summary, our contributions are:

- the first electromagnetic on-skin actuator that can produce multiple sensations (drag, tap, and vibration) for the field of wearable computing;
- a detailed guidance to replicate and manufacture the electromagnetic actuator (flex PCBs + 3D printing) easily;
- a technical characterization of the proposed actuator to show the feasibility of DragTapVib;
- a systematic psychological user study to demonstrate the performance of our actuator when placed on different body locations;

2 RELATED WORK

Our research is inspired by prior work in the areas of wearable actuators in the HCI community. Tactile interaction has been well investigated in past decades [5, 7]. Many haptic feedback mechanisms providing not only kinesthetic but also static tactile stimuli [10, 13] have been reported. Prior work has proven that vibrotactile displays can be beneficial in many aspects, such as for notifications [4, 27, 41] and medical navigation [30]. We firstly summarised relevant publications of the actuators that integrate multiple stimuli. Then, we briefly introduce the wearable tactile devices that deform the skin in HCI research.

2.1 Multi-Stimuli Actuators

In past decades there has been a dramatic increase in unified devices that can provide multiple stimuli. Wang et al. [38] proposed the definition of multimodal haptic devices: " be able to produce multimodal haptic stimuli, including forces, vibration, thermal stimuli, and shape". Thanks to the combination of multimodal natures, these devices have greatly enriched the applications and potential of haptic perception [32]. Zhu et al. [41] presented a pneumatic forearm actuator that can produce multiple haptic stimuli, including compression, skin stretch, and vibration. Preechayasomboon et al. [28] reported *Chasm* which could render low-frequency skin-stretch and high-frequency vibrations, simultaneously and independently. Shim et al. [31] combines wind and vibration together around the wrist as a multimodal tactile display. Hamdan et al. [8] developed an on-skin interface to deform the skin directly based on shape memory alloy (SMA) springs. He et al. [11] presented a wearable device, which generates light presses and drags to assist blind and visually impaired (BVI) people to search for the correct objects in an unfamiliar surroundings. Multi-stimuli devices have yielded good results gradually and drawn a growing trend. However, all above-listed devices need to combine multiple different actuators or multiple adoptions of the same actuator (e.g., one with a tactor, one without ,etc.) to provide multiple sensations. In contrast, our *DragTapVib* leverages one simple actuator to implement all its three sensations.

2.2 Skin Drag Display

The application scenarios of wearable actuators depend heavily on the type of output the actuator produces on the human skin. In general, actuators generate tactile feedback by deforming the human skin. Therefore, previous works have used intuitive terminology to describe the output of the actuators, such as vibrotactile feedback, vibrating, tapping, pressing, squeezing, compressing, dragging, and stretching [14, 15, 24, 37] etc.. Our device integrates the pressure force and shear force to render multiply sensations. There are two typical ways to apply shear force on the human skin. One method involves fixing the endpoints of the actuator to the skin with tape or plaster, and the actuator deforms the skin by applying force directly to the attachment points. The other way is to drag a tactor on the skin. Therefore, we highlighted these two closest relevant methods to our work.

2.2.1 Attachment Points. Ito et al. [15] introduced a skin-stretcher worn around the users' neck for gently urging head rotation by using the servo motors to push / pull the skin. Muthukumarana et al. [24] embedded shape memory alloy (SMA) wires in a lightweight actuator to stretch the skin. Springlet [8] is attached to the skin by means of self-adhesive tape made of silicone rubber, which deforms the skin by applying force to the attachment points and supports six non-vibrating tactile primitives. SCWEES[9] is a lightweight 3D-printed semi-flexible actuator that attaches to the inner forearm skin at two points using two adhesive pads, which stretches and squeezes the surface of the skin gently. All these works have attachment points that is always in contact with the skin and through which the force is transmitted to the skin for perception.

2.2.2 Tactor. Skin displacements have also been proved to be useful in interaction and have the potential for several applications[6]. It is worth noting that the shear force is able to provide information about directions. Thus, related work has explored using the small shear stimuli to communicate direction cues via skin stretch. Most frequently various forms of shear force actuation are leveraged on the users' hand [6, 14, 17, 33], considering the practicality and light form factor. Gleeson et al. [6] reported a fingertip-mounted tactile device to convey direction information served as initial design guidelines for future devices. The tactoRing [17] drags a small tactor on the skin around the finger, preciously indicating qualitative and quantitative information. Skin Drag Display [14] drags a physical tactor across the user's wrist to produce a stronger tactile stimulus than vibrotactile, which allows users to recognize tactile shapes significantly. These works inspired our prototype design, and we also leveraged a flexible tactor driven by the magnetic repulsion to induce skin drag/tap/vibrate as a novel mechanism.

3 DRAGTAPVIB: TRI-STIMULUS ACTUATOR OVERVIEW

To illustrate how to build the actuator and support readers to replicate our design, we first introduced the core components and structure of DragTapVib, which is powered by an overlapping electromagnetic coil design in a 3D-printed enclosure. Furthermore, we open source all the 3D files, schematics of our implementation[1] and a detailed fabrication introduction to help others to replicate our actuator. Our approach can generate sufficiently strong electromagnetic fields to move a static magnet glued to a tactor to deliver various sensations based on different activation patterns.

3.1 Hardware Implementation

The core of our design lies in the electromagneti (EM) actuator that drives the tactor which is perceived by the users. As demonstrated in Figure 2, the core components of DragTapVib are two-layer off-the-shelf flexible PCBs[2] (each layer includes 2 PCBs), a permanent magnet, and a 3D-printed tactor and housings (< 3 € costs). Each flexible PCB coil comprises 70 turns of copper trace spread across two layers on a 17 mm diameter yielding 22.5 Ohms resistance per coil. Each PCB is 0.1 mm thick and weighs 0.066 grams. The size of the neodymium magnet is Ø 10 mm x 3 mm with a 2 kg maximum holding force. Both coils connect to an *Arduino Nano* microcontroller with 3.3V / 5V operating voltage. The total mass of the actuator is 4.3 grams and the outer dimensions are 6.5 mm × 28.6 mm × 20 mm (H∗W∗D). To allow rendering stimuli to the user by driving the static magnet and tactor (1.5mm stroke) vertically and horizontally, we leave 1.5 mm and 8.5 mm space in the case, respectively.

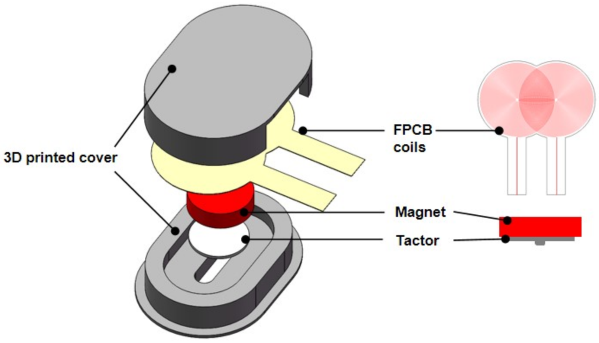

Figure 2: Overview of the components of DragTapVib.

3.2 Fabrication and Assembly

We hereby exhibit in detail how the main components of the actuator are assembled into a lightweight wearable haptic feedback device. With the "cook-style" instruction, readers can replicate and build their own DragVibTaps simply and effectively. Figure 3 illustrate this process.

Ingredients.

- 1 Magnet (Ø 10 mm x 3 mm);
- 4 Flex PCBs;
- Ultimaker 3 TPU 95A filament (2.85 mm, 750 g, white);
- Ultimaker 3 PLA filament (2.85 mm, 750 g, white);
- Double-sided tape;

Apparatus.

- Ultimaker 3 3D printer;

Instruction.

- Print housing using TPU 95A filament from the 3D printer;
- Print tactor using PLA filament from the 3D printer;
- Glue the tactor on the bottom of magnetic with double-sided tape;
- Superimpose and paste the two flex PCBs together and connect them in parallel;
- Insert the flex PCBs into the bottom part of the housing;
- Place the magnet with tactor on top of the flex PCBs;
- Assemble the upper and lower parts of the housing;

3.3 Electronics and Schematics

We built two versions of our actuator: a USB version for characterizing the properties, and a wireless version for more realistic applications scenarios. For the wireless version, we applied the ESP32 microcontroller integrated with Wi-Fi and dual-mode Bluetooth using the low-level library written in Python, which allows to connect the actuator to the mobile devices more portable. All evaluations interface presented in this paper have been developed with

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[1] https://github.com/teco-kit/DragTapVib
[2] https://flexar.io/

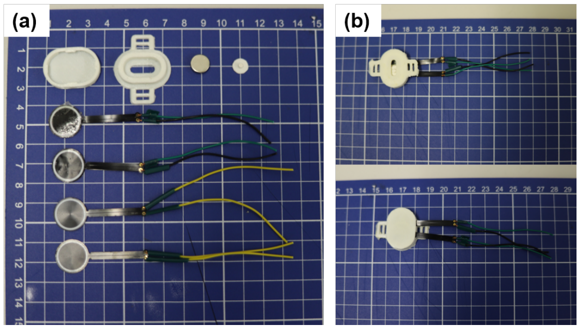


Figure 3: DragTapVib's components and assembly. (a). All components before assembly; (b). A completed device

Arduino IDE. Hereby, Figure 4 depicts the electronics schematic of our USB prototype which was controlled by an Adrduino Nano. Our prototype is connected with wires about 0.5 m long. Both coils connect to an H-bridge (L9110 Dual-Channel H-Bridge Motor Driver Module), and the H-bridge connects to an Arduino Nano microcontroller with 3.3 V / 5V operating voltage.

3.4 Working principle

DragTapVib operates based on the Lorentz force principle. A conductor generates an electromagnetic field around it once current flows. Consequently, changing the direction of currents can produce a variable electromagnetic field. Thus, systematically controlling the two electromagnetic coils in *DragTapVib* (repel and attract) can move a static magnet to render different motions of the tactor onto the users' skin producing different stimuli.

Hereby, we also explored how the arrangement of the coils affects the induced magnetic field. Figure 5 illustrates a simulation of two arrangements of the coils (software: *COMSOL Multiphysics*). When two coils are placed side-by-side, the distribution of the induced electromagnetic field alongside the direction of two coil centers is primarily concentrated in the center of each coil and too weak to attract the magnet firmly. However, when two coils overlap, the magnetic field alongside the direction of the two coil centers is strengthened, generating a stable and more uniform magnetic field. Thus, we applied the overlapping design in favor of a more robust electromagnetic field with better actuation performance during tapping and vibration as the horizontal movement of the magnet and tactor is minimized in the overlapping configuration.

3.5 Rendering Three Haptic Sensations

To produce various haptic sensations, we control the electromagnetic field based on the actuation principle mentioned above. Figure 6 demonstrates the motion of tactor under different magnetic field with changing current flows inside the flex PCBs. *Dragging* drives the tactor back and forth on the skin surface by opposite attraction and repulsion of the two coils, and *Tapping* lightly taps the user by retracting the tactor pin inside and pushing it outside the case. *Vibrating* keeps the tactor on the user's skin and quickly moves it up and down to render a vibration sensation due to the rapid retraction of the magnet.

Subsequently, we introduced three haptic sensations:

1. **Dragging**: This sensation is generated from the horizontal movement of the tactor, which contact and stretch the skin laterally to produce on the shear force directly[37]. We alternately activated the magnetic field to drive the magnet and tactor. Then, the mechanism keeps dragging the users' skin directly at a predetermined speed. The maximum tactor movement distance in our device is 8.5 mm, which is far higher than the small amount of skin stretch could be easily detected (0.27 mm) [29].
2. **Tapping**: Tapping consisted of applying and removing contact to the same region, maintaining approximately equal force at the same rate[19]. We controlled the magnetic field to attract the repel the magnet periodically to manage the vertical movement of tactor. Thus, the tactor could contact and leave the skin at a specific rate.
3. **Vibrating**: This sensation is also generated from the vertical movement of the tactor. However, we leveraged a higher frequency to control the alternation of the current. Thus, the user feels the vibration of the whole actuator more than the movement of the tactor.

4 TECHNICAL CHARACTERIZATION

To explore the technical properties of DragTapVib, we conducted a set of experiments. Firstly, we characterized our device by measuring its actuation speed and noise level. We further characterized the relationship between magnet movement and the resulting maximum force during *Dragging*, *Tapping*, and *Vibrating*, respectively. For all calculations, we applied a gravity value of g = 9.80 m/s^2.

4.1 Measuring Speed & Noise

Latency: *The system takes 25 ms to actuate (the period from when power is switched on to the mechanism starts operation), which is measured using a slow motion camera (240 fps) [34]. This relatively fast speed thanks to the effective electromagnetic system allows us to create seamless real-time interaction by rendering multiply sensations on the skin directly. We compared the rise up time between common actuator in haptics and our prototypes: ERM actuator: 40-100 ms (Texas Instruments DRV2605 data-sheet, p. 15, Table 1) and LRA actuator: 12.9 ms [28].*

Operational noise: *We also measured its operational noise using a microphone leveraging the similar method in [34]. Our device produced around 35 dB SPL(Sound Pressure Level), and this measurement was recorded at arm's length from the device and in reference to a quiet background. As a reference, a normal conversation at 4 foot produces around 60 dB SPL.*

4.2 Dragging

Frequency. We placed a slow motion camera (240fps) facing the actuator from the bottom view and recorded the movements of the tactor. We characterized the relationship between frequency and magnet movement according to the electric actuation frequency by iterating 1-30 Hz with a step-size of 1 Hz. Figure 7 (a) illustrates how far the tactor is dragged horizontally across the slit in the device in regards to actuation frequency.

The moving range of tactor decreased with increasing actuation frequency. The actuator worked most reliably at around 1 Hz to 3 Hz.

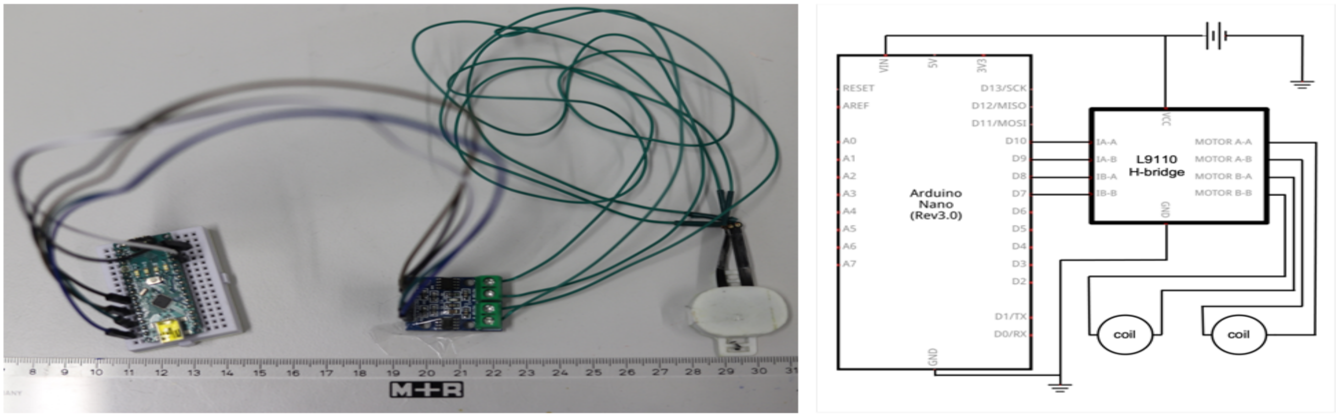
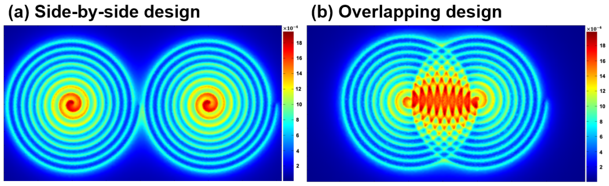


Figure 4: Electronics schematic of our circuit.


(a) Side-by-side design

(b) Overlapping design

Figure 5: Simulation of the magnetic field: (a). side-by-side coil design; (b). overlapping coil design.

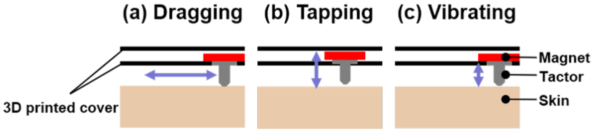


Figure 6: Schematic cross-section of the motions of the tactor: (a). dragging; (b). tapping; (c). vibrating.

However, the results in the frequency response characterization show that the actuator's output significantly decays from 4 Hz onward, and the motions of the magnet tended to zero beyond 30 Hz.

Force. We first explored the maximum dragging force during the linear reciprocating motion. The tactor on the magnet was connected to a weight with a thread via a pulley (see Figure 8 (a)). We stopped adding weight when the tactor could not lift the weight anymore. The maximum weight was 1.9 grams (18.6 mN).

Then, we also explored the dragging force when the magnet is held at the center of one coil with the same setup as before. We stopped adding weight when the electromagnet could not hold the magnet firmly at the center anymore. The maximum weight was 4.9 grams (48.0 mN).

4.3 Tapping

Force. We explored the maximum mechanical force the actuator could generate to actuate the user. A plate was attached on top of the tactor to hold the weight (see Figure 8 (b)), and we stopped when the tactor could not stick out the 3D-printed cover thoroughly. The results indicated maximum weight was 5.2 grams (including a magnet and connection mechanism weighing 1.7 grams). Thus, the maximum static tapping force for our prototype reaches 51.0 mN. Compared with most of previous works [3, 18, 22] which reported detection thresholds of 25-40 mN for static tactile displays, our actuator could generate higher force with shorter actuation periods, thusm the stimuli could be more perceivable [12]. Pece et al. [25] reported the force up to 160-200 mN with an operating voltage at 24 V and a 4-layer coils mechanism, where the voltage is much higher than the voltage that we leveraged in our prototype (3.3 V - 5 V) and more coils were applied.

4.4 Vibration

As illustrated in Figure 7 (b), the tactor's horizontal movement sharply declines in the 20-30 Hz range, indicating that it could not be able to reach out the cover thoroughly to generate sufficiently strong mechanical force beyond that point. Thus, we explored the relationship between frequency and the magnet from 30 Hz onward. We attached a 9-axis IMU (model: ICM-20948) to record Z-axis acceleration changes. We changed the actuation frequency from 30 Hz to 250 Hz at a step-size of 10 Hz and from 250 Hz to 1000 Hz at a step-size of 50 Hz. The readings of the accelerometer's Z-axis were applied to characterize the relationship between actuation frequency and actuator amplitude while vibrating. As shown in Figure 7 (c), the normalized acceleration value indicates a downward trend with a significant decrease above 50 Hz and readings close to zero from around 130 Hz onward.

5 USER EVALUATION

To characterize *DragTapVib* and investigate its potential application scenarios, we conducted a series of user evaluations of our prototype. The light form factors design and tri-stimuli properties of DraTapVibs enrich its feasibility in new scenarios, and particularly across different body locations to show various tactile acuity [39] or advance the development of wearable haptic displays capable of delivering more than vibrations to the skin. It is notable that our prototype can render three main sensations (Drag, Tap, and

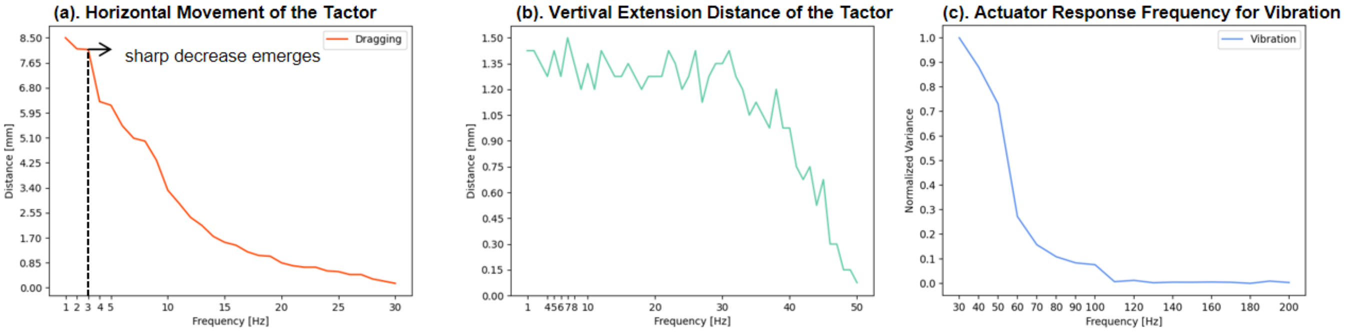
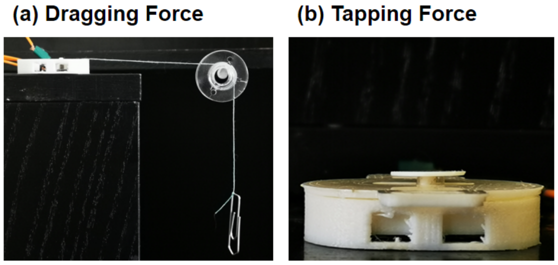


Figure 7: Evaluation results


(a) Dragging Force

(b) Tapping Force

Figure 8: Force test setup: (a). dragging; (b). tapping.

Vibration, see Figure 6) and that these can be programmed to deliver rich information to the skin. Moreover, thanks to the effective electromagnetic system, our device could be activated under a wide range of actuation periods. The results from previous technical evaluations partly revealing the actuator's output response to the frequency, has narrowed down the range of working frequencies. However, it remains to be important to scale this scope down further to filter out the parameters that are perceived and distinguished clearly by users. Hence, we explore the answers of the following research questions based on our user evaluations:

- **RQ1**: How the varying locations of the body could influence perception in terms of (A) *sensation sensitivity*, (B) *comfort*, (C) *distinguishability*?
- **RQ2**: How could the actuation period ranges affect while perceiving and discerning sensations well?
- **RQ3**: How to assess participants' ability to tell the three stimuli apart?

5.1 Exploratory Study

We conducted an exploratory study to narrow down the number of potential placements (RQ1) and to find an optimal actuation period (RQ2) for our device. Previous studies reported six body locations [23, 25] including: outer-wrist, index finger, palm, center-chest, ankle and upper-arm. Considering that our prototype works based on the Lorentz force, that is the actuator maximize its functions when placed as horizontal as possible, and the sensitivity for different locations on arm [40], we selected four positions for the exploratory study: *Index Finger Proximal Phalanges*, *Index Finger Intermediate Phalanges*, *Outer Wrist* and *Inner Wrist* (see Figure 10).

We tested actuation frequencies for **Dragging** of 1, 2 and 3 Hz and for **Vibration** of 30, 40, and 50 Hz following the above results. **Tapping** [19] is composed of applying and removing contact with the skin with the same rate. Previous work reported [2, 25] reported a best actuation period of 0.25 and 0.5 seconds respectively. Thus, we tested the actuation interval for **Tapping** of 0.25, 0.5, 0.75 and 1 seconds.

Six healthy participants (M=27.7; SD=3.6; 1 female) took part in the study. They were seated in a regular office chair with their dominant arm placed on the table. The actuator was attached to the users' forearm using an elastic strap. Then, a familiarization pattern with three sensations was introduced to them. Lastly, we asked them to wear noise-canceling headphones to eliminate actuator noise.

In each test, we actuated the tactor five seconds with a randomly selected parameter from the testing ranges. We repeated this procedure for all the testing periods, within a 20s pause between trials. The test orders of wearing locations for participants had been counterbalanced. After each type of stimulus, the participants were requested to report a). report which sensation they had perceived and b). whether the speed of the stimulus is appropriate to perceive, neither too low nor too fast. Finally, participants were asked to answer the following questions from three aspects: (A). sensitivity: "I could easily and clearly feel the exact movement of tactor on my skin."; (B). comfort: "I would use the device to receive notifications at this location."; and (C). distinguishability: "It was easy to tell which type of stimulus was activated and I felt.". Simultaneously, all the participants were asked to complete a 7-point Likert scale for rating. Participants took a 5-minute break between each location test.

Figure 9 summarizes the results of exploratory study. **Index Finger Proximal Phalanx** and **Outer-Wrist** are the trade-off locations which are ranked as the most sensitive, comfort and distinguishable. P1 and P5 provided the feedback "It is weird and uncomfortable to wear the actuator on the Index Finger Middle Phalanx where needs to be bent often, though this part conveyed stronger sensations sometimes." and "Notifications could be easily missed when the finger is bending, for instance, typing with the keyboard.". P2 reported that "The sensation of *Dragging* feels a lot like someone is scratching me, which is a surprise for me and I like it." Almost all the participants highlighted the **Outer Wrist**, which is the most common location for the wearable computing. As a result, the best actuation frequencies for the *Dragging* and the

Location	Sensitivity			Comfort			Distinguishability		
	D	T	V	D	T	V	D	T	V
Proximal Phalanx	**6.5 (6.25-7.00)**	**7 (6.25-7.00)**	7.00	6 (6.00-6.75)	**6.5 (6.00-7.00)**	**6 (6.00-6.75)**	**7 (6.25-7.00)**	**6.5 (5.25-7.00)**	**6 (4.25-7.00)**
Middle Phalanx	**6.5 (6.25-7.00)**	6.5 (6.00-7.00)	7.00	6 (6.00-6.75)	6 (5.25-6.00)	5.5 (5.00-6.00)	6(5.25-6.75)	5.5 (4.25-6.75)	5.5(3.25-7.00)
Inner Wrist	6.25 (6.00-7.00)	6.5 (6.00-7.00)	7.00	5 (4.25-5.00)	5.5 (5.00-6.00)	5.5 (5.00-6.00)	5 (5.00-6.50)	5 (5.00-5.75)	5.5 (4.00-7.00)
Outer Wrist	6.25 (6.00-7.00)	**7 (6.25-7.00)**	7.00	**7(6.25-7)**	6.5 (6.00-7.00)	**6 (6.00-6.75)**	5.5 (5.00-6.75)	5.5(4.25-6.75)	**6 (3.50-7.00)**

Figure 9: Exploratory study results. The median and interquartile range from 7-point Likert scale ((1 = strongly disagree and 7 = strongly agree).

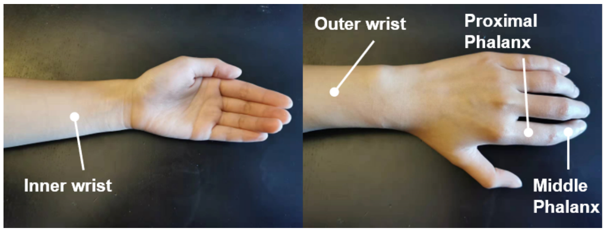


Figure 10: Schematics of the locations in our tests.

Vibration are **2** and **40 Hz**, and the best actuation interval for the *Tapping* is **0.5** seconds across all locations.

5.2 Main Study

The objective of our main study was to validate our prototype's ability to render triple sensations that could be perceived and distinguished by the users. We followed the above results we narrow down for the study. The main study consists of two parts: *Perception* and *Distinction.*

5.2.1 *Participants.* We recruited 12 participants from our campus (M=28.2; SD=3.3; 2 females), none of whom had taken part in the previous exploratory study. All of them were seated in an office chair with a noise cancelling headphone.

5.2.2 *Task and Procedure.*

Perception. Participants were asked to perceive all three stimuli at two locations. The orders for stimulus and locations had been counterbalanced. During each trial, one stimulus was rendered by the actuator. Each stimulus was activated three times for five seconds with a five seconds pause. Participants were asked to press the button as quick as possible after they had recognized and identified the stimulus to log their response time for the stimulus. The participants were asked to classify the type of stimulus they had perceived and rate the recognition performance with a 5 point Likert-Scale after each trial. A 30-second break between trails and a 50-second break in-between location blocks were given to the participants for the rest and recording their feedback.

Distinction. We conducted an absolute identification study to assess participants' ability to tell the three signals apart. The participants were only informed that each of them would be conveyed 12 stimuli (including 4 Dragging, 4 Tapping and 4 Vibration), the order of which was randomized, and they were not aware that how many of each different type of stimulus is available. Each stimulus was played once and lasts for three seconds within a 10-second pause between subsequent stimuli to allow the participants to press the button corresponding to the stimulus they perceived. Once completion of the entire experiment, we conducted a short conversation with participants and encourage them to indicate the potential applications and comments for our device.

5.2.3 *Design.* We applied a within-subject design with two independent variables: *Location{ Index Finger Proximal Phalanx, Outer-Wrist}* and *Stimuli{Dragging, Tapping and Vibration}*. We measured accuracy for both parts of the study and response time for the *Perception.* The overall experiment is comprised of *Perception*: 12 participants * 2 body locations * 3 stimuli * 3 repetitions; *Distinction*: 12 participants * 12 random stimulus * 2 body locations. The duration of test took approximately 40 minutes per participant.

5.3 Results

5.3.1 *Response Time.* Figure 11 reveals the response time of participants from when the stimulus was triggered to the corresponding action. It indicates that the response time at the finger is shorter than at the wrist for all three stimuli, due to the different sensitivities of these two locations [40].

5.3.2 *Accuracy.* Perception accuracy reached an overall accuracy of 87.5%. We reviewed the experimental data and found the errors occur in the *Dragging* and *Tapping*, with the *Vibration* being flawless. Moreover, the location had an effect on the perception accuracy, with the finger being significantly more accurate than the wrist.

Distinction accuracy reached an overall accuracy of 97.9%, 98.6% for *Proximal Phalanx*, and 97.2% for *Outer Wrist* respectively. Figure 11 indicates the results of the distinction study, which is easy to see all the errors occurs in confusing two sensations: *Tapping* and *Dragging*. Also, the experimental results indicates that *Finger Phalanx* achieves a higher accuracy than the *Outer Wrist.*

5.4 Discussion

This evaluation aims to answer the research questions we proposed before. For the **RQ1**, we narrowed down the potential locations to *Proximal Phalanx* and *Outer wrist*, which are the widely used in the HCI community. During our main study, there is a little effect of this two locations observed. The *Proximal Phalanx* has the shorter response time and higher accuracy. The results we obtained are in agreement with the previous literature [39], where the tactile acuity of the index finger is higher than that of the outside of the wrist. For the **RQ2**, we identified the optimal actuation parameters. We combine the analysis of the technical evaluation results and previous research on skin perception frequencies[16, 21], and the optimal actuation period we leveraged for *Tapping* is in line with the previous literature [1, 2, 20]. For the **RQ3**, the results indicate the

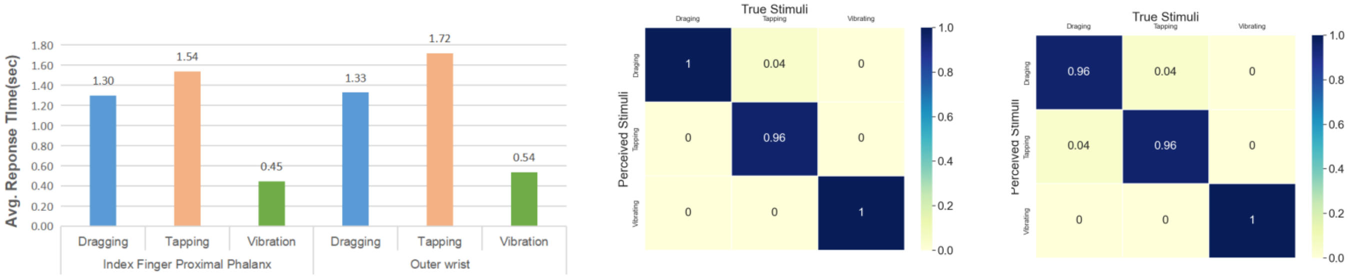


Figure 11: Left: Average response time grouped by type of stimuli and location; Mid: Confusion matrix for Proximal phalanx; Right: Confusion matrix for Outer wrist.

excellent performance cannot be contested, and reveal the feasibility of this prototype's potential application scenarios.

Almost all the participants highlighted the light-weight design of the actuator. Nine of twelve participants reported they could imagine using the actuator for notifications, and one suggested using it for more immersive gaming experiences. One participant complained that the actuator would get a little hot towards the end of the experiment. Another user reported that he (she) felt a little painful sometimes when the actuator was dragging the *Outer Wrist*. Further, our results show that not all stimuli had the same level of perceived stimulation intensity. Following up with participants, we found that vibration was more intensive to perceive than the others (N = 6). We plan to explore further this in the future.

6 APPLICATION SCENARIOS

To demonstrate the feasibility of actuator in the realistic daily life, we used the wireless prototype of DragTapVib whose technical basis is an ESP32 module connected to the smartphone via BLE. We hereby demonstrate two simple application scenarios.

6.1 On-body Notifications

DragTapVib is suitable for standard wearable form factors, as shown in Figure 1 (c). The user wears the DragTapVib on the outer wrist in order to feel the tactile feedbacks. We developed an Android App that simulates incoming calls, new messages and alarms. These information is forwarded from different sources by different stimuli: *dragging* for incoming calls; *tapping* for new messages, and *vibrating* for alarms respectively. The uses could be eye-free without missing any information and being interrupted from their primary activities.

6.2 Game Play

As shown in Figure 1 (d), the DragTapVib could also be worn on the index finger proximal phalanx. Given its flexibility and light weight, DragTapVib can be used to provide an immersive game play experience. The user holds a mouse and plays the shooting game. DragTapVib can simulate different feelings to produce a more interactive gaming experience. The actuator would drag the user's skin when the firearm is being reloaded. As a user makes a single shot, DragTapVib taps on the user's skin providing physical awareness. Similarly, the actuator vibrates when the user makes a continuous shot.

7 FUTURE WORK

A challenge we identified was small amounts of Joule heat generated from coil due to switch of current direction. Though, only 1 participants reported this problem and it occurred when using the actuator for longer times w/o breaks (> 30 mins). We seek to fix the problem in the future version of our device such as silicone molding and adding a heat insulation layer.

Another long-term goal is the movement space of the tactor could be further explored, such as changing the dragging or tapping range. Additionally, the tactor might be moved along a 2D space above the skin by increasing the number of coils in two directions. This could become particularly interesting in the context of VR.

Last, in this paper, we explored the optimal actuation parameters (frequency / period) and demonstrate the performance of three sensations under the optimal parameters. However, there remains to be a lot of space to explore, the tactile expression space of the *DragTapVib* could be widened by 'multiplying' each tactile modality's output, for instance, the tactor could be not only oscillated in vertical directions but also in horizontal directions if the dragging rendering mechanism is well controlled. Therefore, combining the various actuation could enrich the potential of delivering more haptic information to the users.

8 CONCLUSION

This paper presents DragTapVib, an innovative and lightweight electromagnetic wearable haptic interface that can deliver three haptic and tactile feedbacks (Dragging, Tapping, and Vibration) individually. We have presented the design, fabrication, and actuation mechanisms of our device. Due to its simplicity to replicate, we provided a new approach to the community of wearable actuators. Technical evaluation results validated the performance of the actuators and demonstrated its inherent mechanical properties. User study results revealed the quantitative perceptibility and distinguishability of each haptic stimulus. Both the technical evaluation results and user studies suggest DragTapVib is an innovative wearable haptic interface and greatly extends the possibilities of electromagnetic wearable actuators. As wearable device integrated with richer haptic feedbacks become a mainstream, DragTapVib is a step towards this goal. We are working on the next version of our device and hoping that our work could foster the further research in the direction.

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