MagTics: Flexible and Thin Form Factor Magnetic Actuators for Dynamic and Wearable Haptic Feedback

Fabrizio Pece[1]†, Juan Jose Zarate[2]†, Velko Vechev[3], Nadine Besse[2], Olexandr Gudozhnik[2], Herbert Shea[2], Otmar Hilliges[1]
[1]ETH Zurich, [2]EPFL, [3]Chalmers University of Technology
{name.surname}@inf.ethz.ch, {name.surname}@epfl.ch, velko@student.chalmers.se

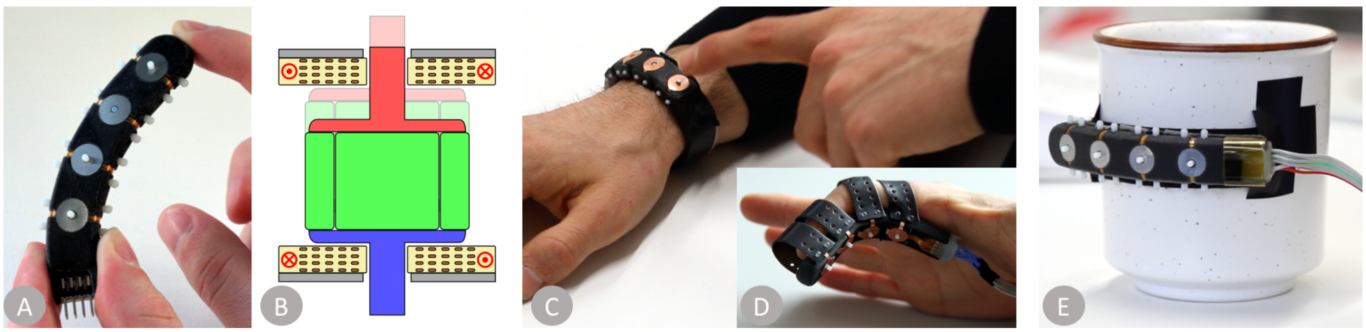

Figure 1. (A) MagTics is a flexible and wearable haptic interface that allows for localized haptic and tactile feedback. (B) We solve the problem of actuation in soft materials by presenting a new fabrication technique that integrates hard electromagnetic actuators in a soft holder, and by introducing a novel fast, but yet power efficient actuation technique. Inside each actuator unit, a laterally shielded magnet (green) equipped with a pin on each extremity (blue and red) moves vertically between two stable positions. MagTics can be worn on body (C-D) or attached to existing objects (E).

ABSTRACT
We present MagTics, a novel flexible and wearable haptic interface based on magnetically actuated bidirectional tactile pixels (taxels). MagTics' thin form factor and flexibility allows for rich haptic feedback in mobile settings. We propose a novel actuation mechanism based on bistable electromagnetic latching that combines high frame rate and holding force with low energy consumption and a soft and flexible form factor. We overcome limitations of traditional soft actuators by placing several hard actuation cells, driven by flexible printed electronics, in a soft 3D printed case. A novel EM-shielding prevents magnet-magnet interactions and allows for high actuator densities. A prototypical implementation comprising of 4 actuated pins on a 1.7 cm pitch, with 2 mm travel, and generating 160 mN to 200 mN of latching force is used to implement a number of compelling application scenarios including adding haptic and tactile display capabilities to wearable devices, to existing input devices and to provide localized haptic feedback in virtual reality. Finally, we report results of a psychophysical study, conducted to inform future developments and to identify possible application domains.

†Authors contributed equally to this work.

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INTRODUCTION
Wearables such as smart-watches, head-worn displays, fitness trackers and smart-garments are rapidly becoming a mainstream technology [42]. Being designed for mobile use, wearables face the issue of (visual) attention scarcity which is emphasized by small screens. Hence, alternative output channels such as haptic feedback play a heightened role in wearable devices. Currently such feedback is mostly rendered via vibro-tactile motors [43] which can only produce coarse, non-localized stimuli. Providing richer, spatially localized haptic feedback requires dense arrangements of taxels that directly stimulate different locations on the skin [5, 24]. However, these have so far been limited to mechanically complex, flat and rigid designs [17, 23, 52]. Furthermore, producing sufficient force often equates to large power consumption. These properties are at odds with the requirements of wearable and ultra-mobile technologies which demand thin and flexible form factors and low-power consumption.

Embracing this challenge we contribute a novel approach to flexible and wearable haptic feedback. Our approach is based on a novel and power efficient actuation mechanism. The scheme is based on bistable electromagnetic (EM) latching and we propose a fabrication process that embeds several actuator cells into a 3D printed soft and flexible substrate.

This allows for the design of flexible, thin form factor haptic feedback devices that can be integrated into straps of smartwatches, can be worn as standalone feedback devices on various body positions or could be integrated into smart garments. The mechanism is power-efficient, generates 160–200 mN forces and can be switched at high frame rate (~20 Hz).

Clearly achieving rich haptic actuation with thin, soft and flexible materials is challenging: soft actuators deform themselves upon impact rather than imposing deformation on the wearer, and hence produce less force than rigid actuators. At the same time, employing hard actuators for localized tactile feedback requires the taxels to be in contact with the skin and the pins to consistently move orthogonally to it. This makes using fabric, unless wrapped tightly without allowing for stretch, infeasible. To address these challenges we propose to combine arbitrarily placed hard actuators in a 3D printed soft frame, allowing for wearable devices and keeping the force generation capabilities of hard materials. We present *MagTics*, a novel flexible haptic interface based on magnetic actuation that can be easily worn on the body (Fig. 1). At the core of the hardware are rigid latching electromagnetic (EM) actuators, integrated into a soft 3D printed and flexible frame. Each actuator cell (Fig. 1, B) contains a laterally shielded magnet, pushing two hard pins at its extremities up and down. Traditional EM devices need current in the coils to hold magnets in either of the positions, impacting power consumption negatively. In contrast we use two thin latching plates made of a soft magnetic material and flexible printed circuits boards (PCBs) to achieve energy efficient bistable magnetic latching. Short current pulses (10–20 ms and up to 6 A) applied to the coils allow for fast switching between states. No power is consumed after latching.

We furthermore contribute a novel fabrication process overcoming two main challenges in making high-density, soft EM actuators. First, multi-layer flexible PCBs are used to make the actuation coils instead of hand-wound coils. This drastically reduces bulk and hence increases flexibility and possible actuator count. Second, strong magnet-magnet interaction and resulting cross-talk has been a long-standing challenge for EM actuator arrays and is typically addressed via heavy and rigid EM shielding. We show a novel and extremely lightweight shielding technique which employs a thin lateral shield attached to each magnet without the need of a heavy fixed frame. This allows neighboring magnets to move without influencing the others.

To demonstrate the efficacy of our approach we designed a functional prototype comprising of four actuator cells with 1.7 cm pitch. The prototype (Fig. 1) can render pull and push notifications, can be worn on-body and can be mounted on objects. *MagTics* supports static and dynamic actuation modes and can provide haptic feedback and serve as tactile display. Furthermore, we have developed different compelling interactive application scenarios including wearable notifications, augmentation of passive objects and haptic feedback for VR. Finally, we discuss findings from two preliminary experimental evaluations that investigate placement, frequency and modes for optimal discernibility and conclude by discussing implications for future applications.

RELATED WORK

Haptic feedback is a well studied area of research and many feedback mechanisms providing *kinesthetic* (e.g., feeling the weight of an object) and *tactile* stimuli (i.e., cutaneous – perceiving local texture) have been proposed [19, 21]. We briefly discuss large-force haptic feedback in VR, haptic feedback for mobile settings and high-density tactile displays.

Large-Force Haptic Feedback in VR

Haptic feedback in VR increases the sense of presence and immersion by rendering collisions, shapes, and forces between the user and virtual objects. Many VR systems leverage vibro-tactile actuators, embedded in hand-held controllers (e.g., HTC Vive), displays [59] or worn on the body [14, 39]. This feedback modality can only offer coarse, non-localized haptic sensation. More complex setups often involving articulated arms or external braking mechanisms [38, 50, 55, 2] can reproduce higher fidelity haptics and render both tactile and kinesthetic feedback. While such approaches can produce large forces, they are not suitable for mobile scenarios due to their mechanical constraints. Glove-based exoskeletons [13, 6, 18, 12] and tilt platforms [46, 5, 27] are more portable and less intrusive than large-force haptic feedback. However, they have been designed for tethered VR settings, sometimes require external tracking, and are not trivially translated to wearable scenarios.

Mobile Haptic Feedback

Due to size constraints, mobile devices cannot provide large actuation forces. Electrostatic friction can be leveraged to render tactile feedback directly on [3, 44] or around [7, 36] hand-held displays. Others have focused on more direct form of stimuli, placing actuators on or around finger tips [29, 57]. More frequently various forms of vibro-tactile actuation such as voice-coils, eccentric weight motors, and solenoids are integrated into smartwatches [33, 34, 41, 15, 49], styli [30, 32] and belt-type wearables [54]. Several papers have studied the properties and placement of such actuators. Carcedo et al. [9] found that three wrist mounted vibration motors is the ideal number for communicating spatio-temporal patterns. On the back of the wrist, linear actuators modified with a 5 mm plastic tip performed better in terms of accuracy and information transfer in pattern recognition tests [31]. Lee et al. [33] created a set of 24 patterns finding that pulsed vibrations are more easily distinguished than steady vibration. Vibro-tactile actuation has also been demonstrated across a number of contexts, including walking, running, and cycling [25, 10], as well as on different body parts including the arm, thigh, and waist [1]. This work informed our prototype design and we study placement and actuation patterns of our novel actuation mechanism under similar conditions.

Both vibro-tactile and electrostatic actuation can only provide a limited sense of localization which necessitates to encode information into patterns [1, 33, 34]. Furthermore, electrostatic actuation is currently limited to flat surfaces and displays and cannot be easily made flexible.

Tactile Displays

State of the art tactile displays convey dense tactile information using an array of mechanically or electrically actuated pins that stimulate different parts of a finger tip (e.g., [52, 45, 56]) or hand (e.g, [23, 17]). The Exeter touch array display [52] used piezo actuators to move small pins in a 1.5 cm square, while the Lumen interface [45] employed a coarse array of illuminated rods. Focusing on tangible interaction, piston-crank mechanisms [23, 17] and air-flow [22] have been employed to actuate rods and form larger tactile displays. While conveying rich tactile information, such solutions require large and heavy components and complex mechanics, making them unsuitable for wearable or mobile scenarios.

More portable solutions have been proposed recently. Khurelbaatar et al. [26] introduce a small electro-tactile display formed by 61 electrodes with 1.2 mm diameter mounted on the back of a mobile phone. HapticEdge [24] proposes to augment the side of a phone's screen with a one-dimensional tactile array formed of mechanically actuated rods. Such approaches illustrate the potential of haptic mobile interactions, however, due to their mechanical requirements, current solutions are still rigid, add bulk to mobile devices and cannot be easily adopted for wearable setups.

Braille displays

Another class of devices that convey tactile feedbacks are Braille displays (e.g., [47]). Typical systems use cantilevered piezo-actuators that support vertical pins at their free end. However, similarly to tactile displays these are rigid and bulky. EM solutions [4, 53, 51] are appealing in view of their speed, but have traditionally not been practical for pins with pitches below 5 mm due to magnetic forces scaling down with size. Furthermore, power consumption and magnet-magnet interactions have been major challenges for arrays. Current EM-based displays employ hand-wound coils, which allow for good performance, but cannot be scaled up to larger number of actuators, unlike approaches using PCBs. State of the art flexible tactile displays have much smaller actuator count and much larger actuator spacing than their rigid counterpart. Current solution can either achieve limited stroke and force [29] or have high power consumption [40]. We tackle these issues by introducing a novel shielding approach, a novel fabrication technique and a fast and energy efficient actuation mechanism. These improvements result in a small device that can convey the feel of soft deformation while keeping the force generation capabilities of hard materials.

MagTics OVERVIEW

We first discuss the working principle and fabrication process of the proposed haptic feedback mechanism. We then illustrate a number of application scenarios.

Principle of Operation

At the heart of our approach lie latching electromagnetic (EM) actuators that move the pins which in turn are felt by the user. The overall flexibility of MagTics derives from the integration of rigid actuator cells into a soft and flexible sleeve. The holders are 3D printed using a soft (elastic modulus: 1 MPa) material to mechanically interconnect the rigid elements (elastic modulus: 1 GPa), enabling a very large range of configurations that need not to be planar. In Figure 2 we show a cross-section of the four in-line actuator configurations used in this work. Each actuator cell consists of a rigid hollow cylinder, in which a permanent magnet moves up and down between two stable positions, created by flexible actuation coils and thin ferromagnetic latching plates. Haptic pins attached to the top and bottom side of the magnets generate a haptic sensation by rising above the device surface.

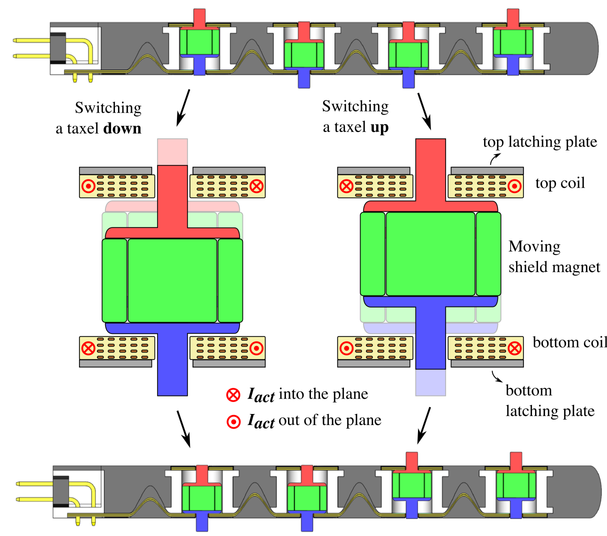

Figure 2. Schematic cross-section of MagTics. The EM actuators are confined to 3D printed hollow cylinders, that are mechanically connected by a 3D printed rubber-like material. Inside each actuator (see center of the figure), a laterally shielded magnet moves vertically between two stable positions (up and down). Short current pulses (10 - 20 ms and up to 6 A) applied to the coils in the top and bottom flexible printed circuits generate magnetic field gradients that switch the taxel state. The coils and the electrical connection between them are fabricated with flex PCB technology. The bistability is generated by two soft magnetic thin plates (latching plates), that hold the taxel either up or down without any power consumption. The tactile stimuli is generated by cylindrical pins, attached to both faces of the moving cylinder and allowing to perceive an haptic sensation on both sides of the strip.

One of the key features of the EM actuator is its bistable nature. A taxel will remain in either the up or down state, consuming no power, until either a new current pulse is applied, or until the user pushes the pin, toggling the taxel to the new state. The bistability is achieved without springs, by using soft magnetic latching plates placed on both ends of the actuator stack (see Fig. 2). The latching plates attract the magnet, one towards the up state and the other towards the down state. The smaller the gap between the magnet and the latching plate, the stronger the magnetic attraction force. Therefore, when a magnet is nearer to one of the two borders, the attraction force of the closest latching plate holds the taxel on that stable position. Bistability allows persistent patterns to be displayed without drawing power.

An electrical current pulse of 10 to 20 ms is used to switch a taxel from one state to the other. As described in Figure 2, the top and bottom coils are operated simultaneously, but with opposite current direction, so as to generate a net force on the magnet. To switch a taxel from up to down, the top coil generates a magnetic field gradient that pushes the magnet away from the up position, and the bottom coil pulls it towards the down state. By reversing the direction of the current, the taxel can be switched to the other stable position. The actuation coils are carefully designed to optimize the switching force while minimizing the power consumption of each taxel during its refresh. For the coil optimization we followed the guidelines proposed by [61]. Our actuation cells are completely symmetric between the up and down states. The effect of gravity is negligible, as the weight of each magnet is only about 5% of the actuation and latching forces. So one can flip the strip upside down and the haptic effect remains the same.

The moving element of each EM actuator is formed by a magnetic cylinder with haptic pins bonded to the top and bottom faces. Assembling arrays of densely packed EM actuators can be challenging when using unshielded moving magnets. Individual magnets will naturally align with the magnetic field generated by other units due to cross-talk forces. To overcome this issue we employ a lightweight magnetic shielding, inspired by [60]. In that case, a pot-magnet configuration (i.e., only one magnet face unshielded) is proposed to avoid magnetic cross-talk between neighbor taxels in a 4x4 rigid array of tactile pins. However, such solution does not implement latching and uses a more complex fabrication process based on elastomeric membranes to hold magnets in place. In this work instead, the moving element is directly placed in the hollow 3D printed guide, making the fabrication much simpler and robust.

Our shielded magnet is formed by a neodymium permanent magnet embedded within a cylindrical shell made of low-carbon steel, a soft magnetic material that can be easily magnetised or demagnetised, keeping both poles of the permanent magnet unshielded. As a result, the magnetic field generated by the permanent magnet is focused into the top and bottom faces, i.e., in the region of the actuation coils and the latching plates, while the lateral magnetic flux in the central region is confined within the shielding material. The lateral magnetic shielding reduces the interaction between neighbouring actuators like in the pot-magnet case, avoiding the cross-talk between taxels and allowing many independent actuators to be placed close to each other.

Fabrication and Assembly

We now detail how the main actuator elements, i.e., the magnetic latching, the flex PCB actuation coils and the laterally shielded magnets are integrated into flexible and wearable haptic feedback devices.

Figure 3 and the accompanying video illustrate this process. The overall size of the device is given by the 3D printed multi-material strip, with soft flexible regions (black) linking rigid wells. A flex-PCB runs along the length of the strip, and wraps around it, bringing current coils to the top and bottom of each rigid well. Each well holds one EM actuator, consisting, from bottom to top, of: heat-sink, latching plate, PCB coil, magnet with lateral shielding, PCB coil, latching plate and heat-sink (see Fig. 2 and 3). Coils, heat-sink and latching plates all have central holes to allow pin motion. The coils consist of 4-layers of spiral conductors, obtained by stacking two flex PCBs with two conductive layers each.

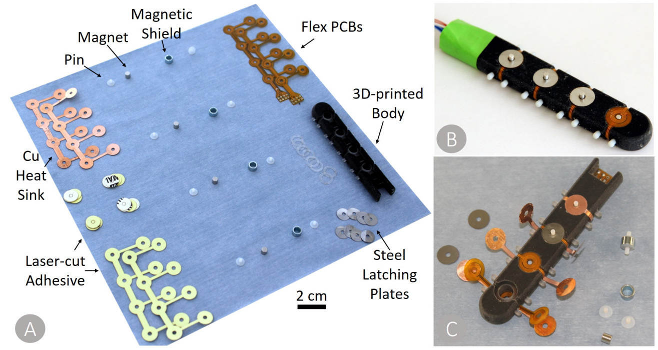

Figure 3. MagTics' components and assembly. A) All elements prior to assembly. B) MagTics with each taxel at a different assembly state. The PCB is routed along the bottom of the device (thus providing the bottom coils), and wrapped around the sides of the device, bringing the top coil into position. A steel latching plate is bonded on the coils, followed by a thin copper heat sink. C) A completed device, with the rightmost taxel lacking a latching plate to reveal the coils.

Implementation

The 3D printed strip was produced on a StrataSys Objet Connex printer, using VeroWhite or VeroClear materials for the rigid parts and TangoBlack material for the flexible elements. The taxels are separated by a 17 mm pitch, while their stroke is 2 mm, with actuation pins on both top and bottom side of the device. When using EM-based actuators there is a trade-off between the generated forces and actuator pitch, as the forces scale down with the magnets volume. MagTics' pitch allows to perceive stimuli in both high-acuity areas (e.g., finger) and location with higher sensitivity threshold (e.g., up. arm). The PCBs have two layers of 35 μm thick copper on polyimide foil, giving 200 μm of PCB thickness. Each spiral layer has four turns, 254 μm track / 150 μm clearance and internal radius of 1.6 mm. The pins that protrude from top or bottom (depending on taxel state) are also 3D printed in VeroWhite material. The latching plates are 50 μm thick low-carbon steel, laser cut to 10 mm diameter. There is a trade-off when choosing the plate thickness: thicker plates lead to larger latching force but higher power consumption during switching. The coil PCBs, latching plate and heat sink layers are kept in place by using a thin thermal adhesive, to maximize heat dissipation from the inner layers to the external heat sink. The shielded magnets consist of 4 mm diameter Neodymium permanent magnets inserted in shielding cylinders of low-carbon steel with 6 mm external diameter, and glued in place using Loctite adhesive. The same adhesive is used to attach the pins to the top and bottom of the magnets.

The taxels have a holding force between 160 and 200 mN, resulting in two main advantages. First, previous work [35, 16, 28] has reported detection thresholds of 4-27 mN for vibrating taxels and 25-40 mN for static tactile displays. Our haptic feedback mechanism produces forces 5 times larger than these thresholds, allowing the taxels to latch even when the

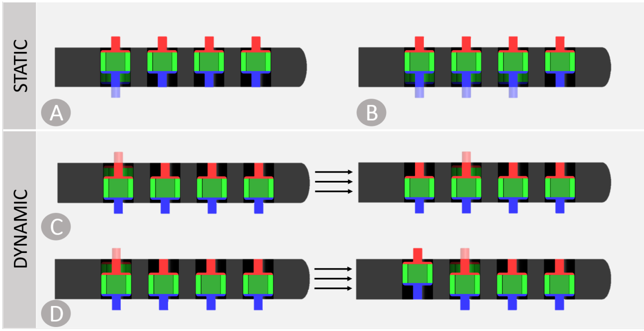

Figure 4. MagTics affords two main class of actuation modes. *Static*. (A) Single Pin: an individual taxel moves from up (red) to down (blue transparency). (B) Numeric: consecutive taxels move from up to down to render the number three. *Dynamic*. (C) Single Pin Directional: following one direction, a taxel moves from down to up, to eventually return to its original position. (D) Numeric Directional: following one direction, a taxel moves from down to up and eventually keeps its position.

skin is pressing against them. Second, higher forces enable shorter actuation periods during which the stimuli is still perceivable [20]. The taxels' stroke is 2 mm, and can be easily changed by printing the actuators with a different thickness. For reliable switching, current pulses of 10 to 20 ms are used. Currently, we operate our prototype at 24 V, with peak power of approximately 140 W during the short actuation pulses. Hence, with a notification rate of one every 20 seconds, the average required power is of 140 mW per taxel.

Control Electronics

A custom driver board was developed to generate current pulses with millisecond resolution in the desired direction and with individual-taxel addressing. The board is controlled by a Raspberry Pi 3 over an I2C bus, using our custom low-level library written in Python. Our prototype is cabled with wires of length of 0.7–1.5 m, with one meter of cable contributing only 13% to the total resistance. However, we are currently working on a wireless and portable version of the driver board which will feature Bluetooth communication. Our library operates on single taxels, offering a simple interface for the application layer. All the applications presented in this paper, as well as the experimental interface, have been written in Python. The VR scenario used an additional rendering and tracking module developed in Unity 5.

APPLICATION SCENARIOS

MagTics's novel latching mechanism allows for bidirectional actuation of taxels, which in turn either stimulate the skin or objects underneath the unit or form a 1D tactile array. As such, our prototype can afford two main types of actuation modes: *Static* and *Dynamic* (Fig. 4). The former includes modes in which one or more taxels are actuated simultaneously such as *Single Pin*, *Numeric* and *Shape* modes (Fig. 4, A-B). The latter entails modes that change over time, making full use of the device surface and number of taxels. These include *Single Pin Directional* and *Numeric Directional* modes (Fig. 4, C-D). While only directly supporting discrete states, our actuators can afford a wide range of patterns via combinations of spatio-temporal actuation modes. For instance, different perceived force amplitudes may be simulated by dynamically varying the actuation period, or increasingly shorter pulses can be used to convey a sense of urgency. Hence, when combined, the supported actuation modes create an extensive set of actuation patterns and output modalities.

On-body Notifications

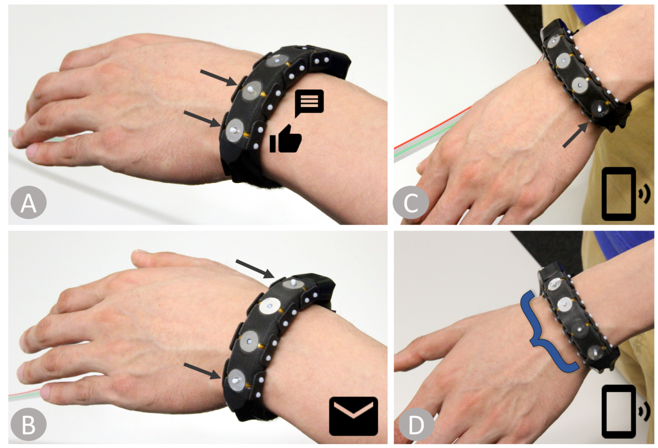

Figure 5. Our wristband prototype with bi-directional actuation. A) Individual taxels are actuated to signal application notifications (here a social network notification and a text message). B) A U-shaped pattern notifies of new email. C–D) In the event of an incoming call, the Numeric Directional mode is actuated (C, start and D, end of notification).

Given its thin form factor and flexibility, MagTics can be used to render *precisely localized* haptic feedback. To illustrate this, we have implemented a fully functional notification wristband (see Fig. 5 and video figure), where location, as well as actuation modes are used to differentiate events. Such a band could be used to integrate rich haptic feedback into future smartwatches.

This setup allows for direct on-skin notification via different actuation patterns. For instance, the *location* of a pin may be linked with a specific application, such that an incoming text message may trigger a single pin switch (Fig. 5, A). Similarly, the *shape* of a pattern may signal different event types such that an incoming email which can be associated with a U-shaped pattern (Fig. 5, B). Events that *extend in time* can also be rendered. For example a phone call could trigger a wave-like dynamic pattern (Fig. 5, C–D), which could then also be modulated by a caller-specific property. Because MagTics actuates taxels bidirectionally, on-skin notification can be combined with long-term reminders by holding the pattern on the visible side of the wristband. This passive tactile modality allows users to distinguish notifications by *touching* them, easily retrieving information when they need it rather then when it first arrives. This can be beneficial in mobile scenarios where users are focused on mentally demanding activities, for example during sports or while riding a bike.

Further, we have implemented a simple exercise application (Fig. 6 and video). In this scenario a user wearing a flexible strip on their biceps receives hands and eyes-free instructions

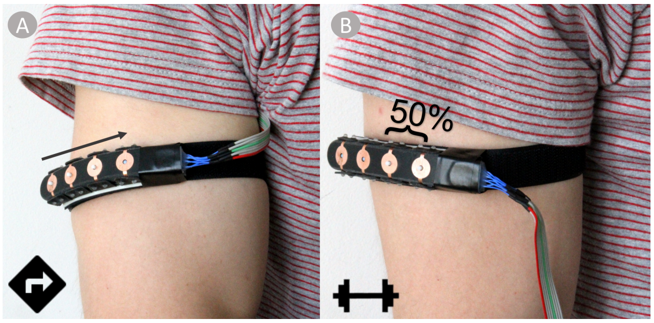

Figure 6. MagTics may assist during exercise with on-arm notifications. A) A user receives directional notification on their arm. B) Users may monitor the percentage of training completed via tactile feedback.

during the workout. Directional notifications could be delivered by using the Single Pin Directional actuation mode (Fig. 6, A). Similarly, a preset cadence may be rendered on the arm by actuating all the taxels simultaneously at a certain frequency such that a jogger could adjust their speed accordingly. Training-related data that express quantities and require temporal persistence, such as heart rate, caloric intake or percentage of training completed may also be conveyed by actuating numeric patterns (Fig. 6, B).

Augmenting Existing Objects

Figure 7. MagTics can be used to augment existing objects and input devices. A–B): A standard mouse gets augmented with output capabilities to enhance desktop productivity. C–D): Everyday objects, such as water bottles and coffee mugs, turn into notification proxies.

MagTics can also be used to augmented existing objects and input interfaces (Fig. 7 and video). The device can simply be mounted onto devices to add haptic feedback capabilities. By mounting MagTics on a mouse users may get different haptic stimuli from different graphical elements. For example, while browsing the web a specific taxel is actuated to render a physical version of the hyperlink (see Fig. 7, A and B). Also position aware UI elements, such as drop-down menus, can be augmented analogously. As a user scrolls through the menus items, MagTics renders a bump travelling down the strip and as such providing physical awareness of the relative position in the menu. Feedback on numerical quantities can also be rendered such as to indicate the number of hits when searching within a webpage.

Moreover, given its flexibility and thin form factor, MagTics can be easily wrapped around a wide range of surfaces to turn passive objects into interactive devices (Figure 7 and video). For example, nudging a user to drink their daily water intake (Fig. 7, C) or to notify about incoming calls and voice mails while away from the office (Fig. 7, D).

Haptic Feedback in Virtual Reality

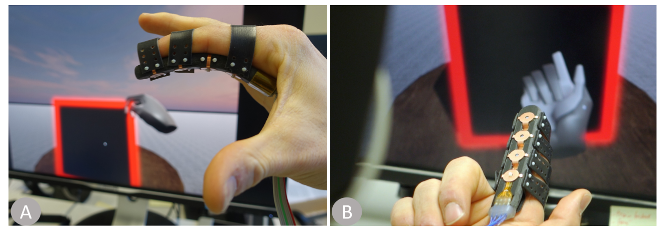

Figure 8. Tactile haptic feedback in VR. Contact with virtual objects triggers localized tactile feedback giving a coarse sensation of the object's size and shape.

Finally, we have implemented a simple tactile feedback mechanism for VR. Fig. 8 shows the device worn on a finger to enable "feeling" of virtual objects. We map each of the taxels to one of the four segments of the index finger to accurately render collisions with the virtual object. As the real hand moves through the scene the taxels corresponding to the colliding bone are actuated. On-finger mounting could also be employed to add touch feedback to virtual keyboards, enabling eyes-free typing in VR. When multiple strips are mounted together a similar mechanism could be employed for on-palm tactile feedback (see Fig. 11). In future work denser arrangements of our mechanism could be used to obtain full hand coverage or even an entire haptic glove.

EVALUATION

To characterize MagTics and inform the design of its future applications, we conducted a user evaluation of our prototype. The flexible design and functional properties of MagTics allow its use in new contexts, and in particular across different body locations which may display differing tactile acuity [58] or spatial resolution to perceive different vibro-tactile patterns. We note that our device can render two main classes of actuation modes (static and dynamic, see Fig 4) and that these can encode localized and spatio-temporal information respectively. Furthermore, as our device supports a wide band of actuation periods (i.e., frequencies) it is also important to narrow this range down to those timings that are perceived and discerned easily by users. More precisely we seek to answer the following research questions:

- **RQ1**: Which body locations perform best in terms of (A) *haptic sensitivity*, (B) *comfort*, and (C) *discernibility*?
- **RQ2**: Which duration and actuation period ranges are perceived and discerned well?
- **RQ3**: Amongst the top locations, how does placement influence accuracy in terms of static (single pin, numeric) and dynamic modes?

Location	Accuracy (%)		Sensitivity (A)	Comfort (B)	Discernibility (C)	Best Period (sec)
	Binary	Dynamic				
Ankle	69.00 (± 12.50)	86.00 (± 12.50)	5.0 (5.00-5.75)	3.0 (3.00-5.25)	5.5 (4.25-6.00)	0.5 – 0.1
Upper-Arm	72.16 (± 17.16)	**100.00** (± 0.00)	**6.0** (5.25-6.00)	6.0 (3.75-6.00)	5.0 (4.25-5.75)	0.5 – 0.1
Center-Chest	58.33 (± 22.83)	97.16 (± 6.66)	5.0 (5.00-5.75)	2.0 (2.00-3.50)	4.0 (4.25-5.75)	0.25 – 0.05
Index finger	**83.33** (± 18.16)	**100.00** (± 0.00)	**6.0** (6.00-6.75)	4.5 (3.25-5.00)	**6.0** (5.25-6.00)	0.25 – 0.05
Palm	72.16 (± 08.50)	97.16 (± 6.66)	5.5 (5.00-6.00)	3.5 (2.25-5.50)	5.0 (4.25-5.00)	0.5 – 0.1
Outer-wrist	77.66 (± 17.16)	94.33 (± 8.50)	**6.0** (6.00-6.75)	**6.5** (3.75-7.00)	**6.0** (4.25-7.00)	0.25 – 0.05

Table 1. Exploratory study results. We measured performance in terms of accuracy for stimulus detection (mean in col. 2–3, std. dev. in parenthesis), and Likert scores for the subjective responses (median in col. 4–6, interquartile ranges in parenthesis.). Q1–Q3 rated using a 7-points Likert scale (1 = strongly disagree and 7 = strongly agree). In bold best performing (in either metric) locations.

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. Six areas on the body were selected, following previous studies [37] and common wearables application domains such as sports*, on-body notifications and VR. These included: outer-wrist, index finger, palm (i.e., base of fingers), center-chest, ankle and upper-arm. While other areas have been considered previously, we preferred curved surfaces and those with direct contact with the skin. We tested actuation periods of 1.0, 0.5, 0.25, 0.1, 0.05 and 0.01 seconds.

Six healthy participants (M=29.2; SD=3.3; 2 female) took part in the study. Upon being introduced to the device and on how to wear it each participant was also instructed on the task. Subsequently, a familiarization pattern that actuated each taxel twice and in ascending order was rendered. The experiment was divided into two sections: First, focusing on static actuation (i.e., single pin actuation, Fig. 4, A), while the second section focused on dynamics (i.e., single pin directional, Fig. 4, C). In both cases, we actuated a random taxel or used a random direction twice with randomly selected period from the testing range.

We repeated this procedure for all the testing periods, pausing 10 seconds in between trials. After each static stimulus, we asked the participants to a) identify which taxel had been actuated and b) report on how many times they felt the taxel touching their skin. Similarly, after each dynamic stimulus participants were asked to confirm its direction. For both modes, we asked participants if they considered the speed of the stimulus appropriate for a notification, as opposed to excessively slow or fast. Finally, participants were asked to answer questions related to the area sensitivity (A: *"I could easily feel the pin poking on my skin."*), comfort (B: *"I would use the device to receive notification in this area."*) and discernibility (C: *"It was easy to tell which pin was raised and touched my skin."*) using a 7-point Likert scale. Participants were given 3 minutes rest in between locations. Pink noise was used throughout the experiment to mask audio cues.

Table 1 summarizes the study results. **Index finger**, **outer-wrist** and **upper-arm** are the locations that exhibit the highest accuracy for both static and dynamic actuation modes. Similarly, participants ranked these three locations as the most comfortable (wrist), sensitive (all) and with the highest discernibility (finger and wrist). These results are in line with the anecdotal findings we collected. Almost all participants commented that they would prefer using the device on the wrist (*"I'd love to have this on my watch"*), and that the finger conveyed the strongest haptic sensation. Similarly, several participants felt uncomfortable receiving haptic feedback on the upper-chest (*"It is weird to have something poking at my chest"*), and considered the ankle location unpractical (*"Notifications can easily get missed while walking"*). Across all locations, the **0.5 – 0.05** seconds actuation interval was rated as the best and the most appropriate for a notification.

Main Study

Following the above results we narrow down the main experiment to include only the *index finger*, *outer-wrist* and *upper-arm*, using an actuation period of 0.25 seconds.

Participants

Twelve healthy subjects (M=27.75; SD=2.63; 4 female) were recruited for our study. Participants performed the same tasks wearing our device in all three body locations and with a fixed actuation period.

Task, Stimuli and Apparatus

During each trial, an actuation mode was rendered by the device at the specified period. Each stimulus was played twice to ensure that participant perceived it. A trial finished when the participant pressed any button on a keyboard, after which participants were prompted to log their answer, classifying the stimuli. Participants were instructed to press the button only after they had recognized and identified the actuation mode. A 10-15 second break between trials and a 45 seconds break in-between actuation mode blocks allowed for sufficient rest. We tested two static and one dynamic actuation mode. The static modes included a *Single Pin* switch and a *Numeric* pattern (see Fig. 4, A and B). As dynamic mode we used the *Single Pin Directional* (see Fig. 4, C). For the first two modes, participants were asked to report which and how many taxels had been actuated, respectively. For the dynamic mode, participants were asked to report on the stimulus direction. As a fourth test, we randomly selected modes from the previous three stimuli, and required participant to report which mode they felt.

*AthleteIQ. *Voice of the Athlete Survey. Wearable Devices In the Active Lifestyle Market*. **https://goo.gl/bTdmCw**. Last accessed: 10.03.2017.

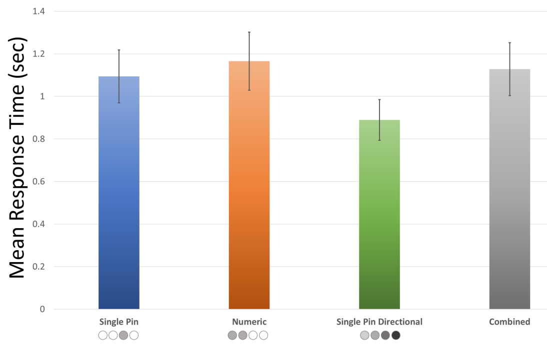

Figure 9. Average response time depending on Actuation Mode.

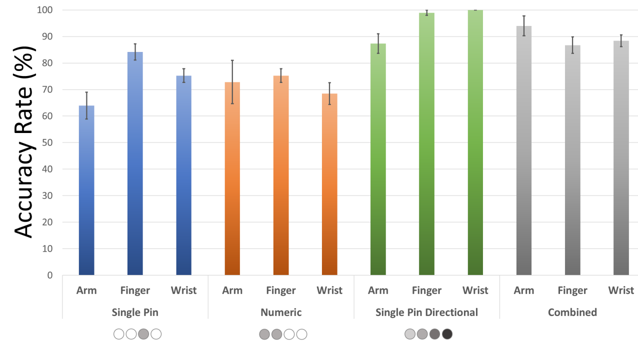

Figure 10. Accuracy rate grouped by Location and Actuation Mode.

Procedure

The experiment was divided into four sections with three sections for the two static modes and the dynamic mode, while the last section comprised of a randomly selected mix of the previous three modes. Each section started with a training block previewing one of the stimuli. After training, participants completed repetitions of four test blocks of four stimuli repetitions. Presentation was randomized. For each location, participants were asked to rate their perceived difficulty in distinguishing modes and recognition performance using a 7 point Likert-Scale. Upon completion of the entire experiment, participants filled in a post-experiment questionnaire and indicated their subjective ranking of the actuation modes. We also recorded suggestions for possible applications of our device and informal comments.

Design

A within-subject design was used with two independent variables: *Location* $\{$*Outer Wrist, Index Finger, and Upper Arm*$\}$ and *Actuation Modes* $\{$*Single Pin, Numeric, Single Pin Directional, and Combined*$\}$. The order of body-locations was counter-balanced using a Latin Squares design, while actuation modes were presented in order. As dependent variables, we measured *accuracy* and *response time* for each trial. The experiment included: 12 participants $\times$ 3 body locations $\times$ 13 stimuli [4 single pin + 4 numeric + 2 single pin directional + 3 combined] $\times$ 5 repetitions [1 training blocks + 4 test blocks] = 2340 trials. Duration was about 50 minutes per subject.

Results

Data from the training blocks were excluded from the analysis of the results. Occasionally overheating and frequent actuation can cause the device pins to malfunction, and therefore some participants reported a lack of haptic stimulus for a particular trial. We removed those trials (4.4%) from the analysis leaving a total of 104 trials. We ran a two-way repeated-measures ANOVA with two within subject factors (*Location* and *Modes*). We applied Greenhouse-Geisser sphericity correction when needed, and pairwise t-tests with Bonferroni correction for post-hoc comparisons. All effects are reported as significant at $p < .05$.

Response Time

Reaction time was low on average with a global average response time of 1.06 sec (see Fig. 9). ANOVA reveals a significant main effect of *Modes* on execution time ($F_{3,33} = 5.077, p = 0.005$). *Single Pin Directional* was the fastest ($M = .89\ s$), followed by *Single Pin* ($M = 1.09\ s$), *Combined* ($M = 1.12\ s$) and *Numeric* ($M = 1.13\ s$). Pairwise comparison revealed a significant difference between *Single Pin Directional* and all other patterns, specifically: *Single Pin* ($p = .05$), *Numeric* ($p = .004$) and *Combined* ($p = .027$).

Accuracy

Perception accuracy was also high with an overall accuracy of 81.5% (see Fig. 10). ANOVA results show a significant main effect of *Modes* on accuracy ($F_{3,33} = 33.28, p < 0.001$), with *Single Pin Directional* being the most accurate ($M = 95.4\%$), followed by *Combined* ($M = 89.7\%$), *Single Pin* ($M = 74.4\%$) and *Numeric* ($M = 66.5\%$). We also observed a significant *Location* $\times$ *Modes* interaction effect ($F_{2.63,29} = 5.304, p < 0.001$), indicating that accuracy per actuation mode depends on the device location. To unpack this interaction further we analyze main effects of *Mode* at each level of *Location*. The simple effect of *Location* on *Single Pin* was significant ($F_{2,22} = 6.88, p = 0.005$), with *Finger* ($M = 84.13\%$) significantly more accurate than *Arm* ($M = 63.94\%, p = 0.025$). Similarly, *Location* had a significant simple effect on *Single Pin Directional* ($F_{1.11,12.29} = 6.886, p = 0.006$), with *Finger* ($M = 98.95\%$) being significantly more accurate than *Arm* ($M = 87.31\%, p = 0.024$).

DISCUSSION

Quantitative Results

With these results in place we can now answer our research questions. Trying to identify the most suitable body locations for placement (**RQ1**) we narrowed down the initial six locations to three. User feedbacks showed a positive reception for *Wrist*, which was considered as the most comfortable and sensitive area on the body. Although during our main study we did not observe a significant effect of *Location* neither on time nor on accuracy, we note that throughout the experiment *Finger* performed consistently better than the other two locations. This finding is in line with existing literature [58], for which the index finger has a higher tactile acuity than both the outer-wrist and upper-arm. This aspect is corroborated by the observed interaction effect of *Location* $\times$ *Pattern* on accuracy. Further analysis revealed that, when significant, the effect of *Location* on individual patterns always showed significant better results for the *Finger* condition.

By addressing **RQ2** we identified the 0.05–0.5 seconds interval as the best actuation period. Being able to use a large dynamic range of actuation periods is also beneficial when conveying dynamic haptic feedback. For example, shorter pulses can convey a sense of urgency [48]. Further, our results compare favorably to previous vibro-tactile studies, for which much longer actuation periods in the range of 0.5 seconds have found to be optimal [34, 1].

Our results in terms of **RQ3** reveal a significant effect of *Mode* on both time and accuracy, with the modes encoding both spatial and temporal information (i.e., *Dynamic*) performing consistently better than modes which rely only on pin localization. Single pin and numeric modes achieve results in line with similar vibro-tactile studies on localizing stimuli while employing a smaller pitch (1.7 vs 2.5cm) [8, 1]. This indicates that both the dynamic and localized haptic feedback can indeed be beneficial.

The relatively high accuracy of static patterns in areas such as the finger, enables the ability to directly communicate a numerical value without any encoding which is typically necessary with vibro-tactile approaches [10]. This is valuable in scenarios where the attention span may be too limited to decipher long pulsed patterns (e.g., sports), and provides further evidence for our claim that the proposed actuation mechanism helps in localizing haptic feedback spatially.

Finally, our response time results are in line with some of the lowest previously reported (e.g., [11]) and shorter than others (e.g., 2-4 s [9]). Further, we note that *Combined* patterns also performed well, indicating that different actuation modes could be combined to create an expanded set of notifications.

Qualitative Results

The above results are also echoed by qualitative feedback which was overwhelmingly positive. Participants felt most confident with the *Finger* condition ($MED = 5$), and ranked it as the least difficult ($MED = 3$). However, *Wrist* was also ranked relatively high ($MED = 4.5$ for performance and $MED = 4$ for difficulty), indicating that fingertips and wrists may be the most preferred locations for haptics enabled wearables. Participants' comments echo this (e.g., *"I can imagine wearing this embedded in my watch"* and *"One could create bike-gloves with added alarms and notifications"*). Furthermore, some suggested applications that would naturally fit wrist mounted devices (e.g., *"This is perfect for discrete notifications"*, *"I could finally have a real life bar while playing games"*, *"When using contactless payment, the device could show your remaining balance on the wrist"* and *"When I am engaged in mentally challenging tasks (e.g., working), the device could remind me [to keep track] of things"*). Interestingly, sports and discrete notifications were mentioned most frequently as potential applications, consistently emphasizing that the device is able to recreate tactile "feelings" (e.g., *"Would be an ideal basketball armband to keep track of points"*).

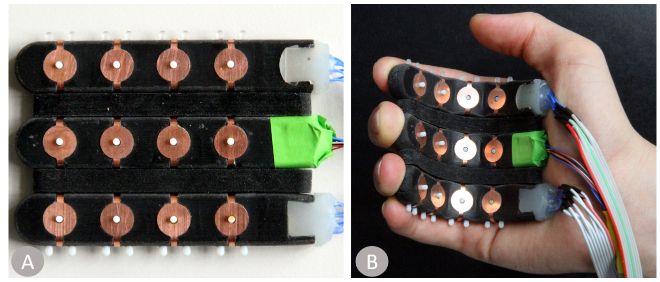

Figure 11. A) Arranging multiple MagTics strips to create a 2D tactile array. B) The two-dimensional arrangement can extend our solution's output outlet, for instance to cover a palm.

In summary, our evaluation indicates that the proposed actuation mechanism is effective, that fingertips and wrists are the preferred and most perceptive locations, and that the high temporal feedback frequency enables more fine-grained and higher bandwidth output than would be possible with vibrotactile actuation.

FUTURE WORK

Our experimental results indicate that MagTics is a promising first step towards rich, soft and flexible wearable haptics. However, there is ample room for future work.

One of the biggest limitation of our current prototype is the excessive Joule heating generated during repetitive taxel actuation. While not a problem in our experiments, the current design is not robust enough for long-term repetitive actuation at high frequency. Similarly, the high instantaneous switching power currently required by our device can limit the portability of the system. To overcome these issues, we are currently designing a second generation of MagTics, working towards further improving the power efficiency and heat dissipation. Specifically, we are planning to adopt more layers in the flex-PCB, and to design a modified soft case to allow for increased air-flow and hence faster cooling. By using a 12 layer system, hence stacking 2 PCBs, we expect the power consumption to drop from 140 W while switching to 30 W, also reducing the heat generation by a factor of 4. Further, the 3D printed shell is not yet durable enough for frequent bending, affecting the long-term reliability of the 3D printed structures. However, our design is amenable to more robust fabrication processes, such as silicone molding, which we plan to explore in future version of our device.

Another long-term goal is to extend our current design to a complete embedded and two-dimensional solution with a much higher actuator density – a challenging direction for future work. In the mean time we explore user experience aspects with composite 2D arrangements of MagTics strips for an enlarged output area (Fig 11). Finally, making the device self-contained via wireless electronics that can drive more independent actuators is another direction of future efforts.

During our exit interviews the tactile feedback capabilities and resulting discrete aspect, together with its ability to draw attention without interrupting other tasks, were the features that drew the most positive reactions. The evaluation results also revealed a number of interesting application scenarios for the proposed technology. For instance, MagTics could be easily integrated into existing wearable devices for sports such as fitness trackers and smartwatches. With further miniaturizations our approach could also be used in smart garments [42] or even VR gloves. Finally, higher actuator density and count would make MagTics an interesting technology for flexible, graphical displays for users with vision impairments.

CONCLUSION

We have presented MagTics, a novel form of wearable and flexible feedback interface that can convey rich haptic and tactile stimuli. Achieving haptic actuation in soft material is a challenging task, which we solve by introducing a novel fabrication technique that combines soft and hard materials with miniaturized magnetic elements driven by flexible PCBs. We also proposed a novel actuation technique that is based on magnetic latching with fast switching and that allows, for the first time, to employ many small EM elements with small pitch and with reduced energy consumption. We have demonstrated through a prototype of our technology and a number of compelling application scenarios how MagTics can be used to provide tactile feedbacks in wearable scenarios.

Finally, a study to characterize our device was performed for a number of body locations and operational parameters. The results showed that MagTics performs best when mounted on finger and wrist, that spatio-temporal actuation modes are the most expressive modality it can afford, and that users would prefer using our device for discrete and tactile notifications during mentally engaging activities.

As wearables become more mainstream richer haptic feedback than vibro-tactile channels becomes increasingly important. MagTics is a step towards this goal, and our hope is that it will foster future research in this direction. To this aim, we are planning to release both the schematics and software to fabricate and run our device as open-source.

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