Haptic Source-effector: Full-body Haptics via Non-invasive Brain Stimulation

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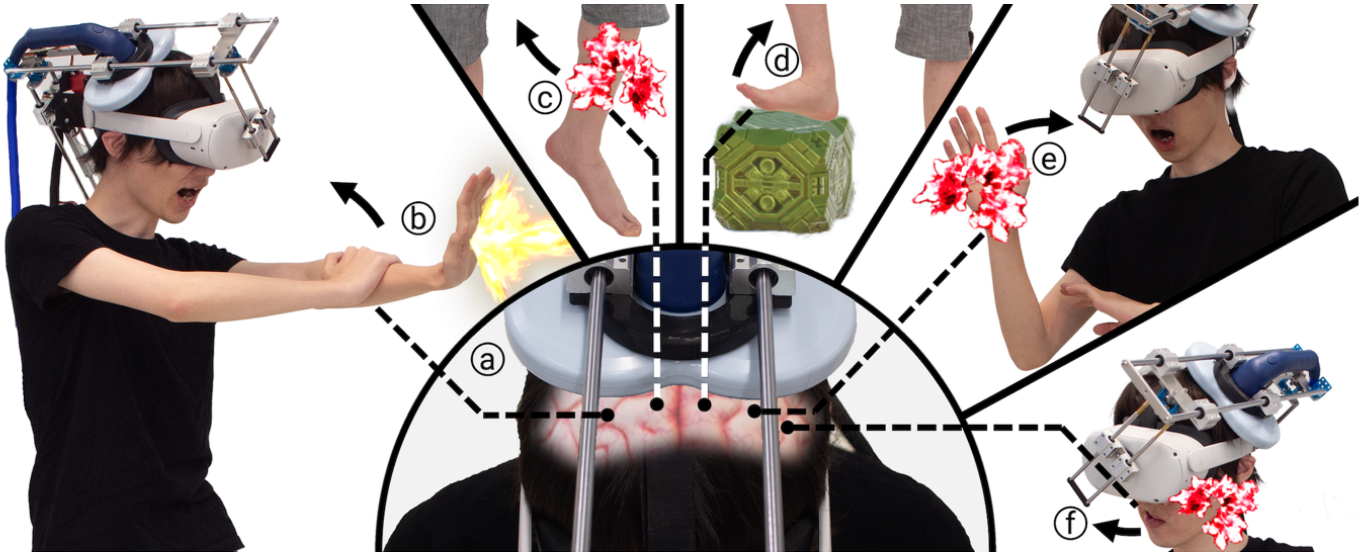

Figure 1: We propose & explore a novel concept in which a single on-body actuator renders haptics to multiple body parts—even as distant as one's foot or one's hand—by stimulating the user's brain (a). We implemented this by mechanically moving a coil across the user's scalp. As the coil sits on specific regions of the user's sensorimotor cortex it uses electromagnetic pulses to non-invasively & safely create haptic sensations, e.g., touch and/or forces. For instance, (b) recoil of throwing a projectile, (c) impact on the leg, (d) force of stomping on a box, (e), impact of a projectile on one's hand, or (f) an explosion close to the jaw.

ABSTRACT

We propose a novel concept for haptics in which one centralized on-body actuator renders haptic effects on multiple body parts by stimulating the brain, i.e., the source of the nervous system—we call this a haptic source-effector, as opposed to the traditional wearables' approach of attaching one actuator per body part (end-effectors). We implement our concept via transcranial-magnetic-stimulation (TMS)—a non-invasive technique from neuroscience/medicine in which electromagnetic pulses safely stimulate brain areas. Our approach renders ~15 touch/force-feedback sensations throughout the body (e.g., hands, arms, legs, feet, and jaw—which we found in our first user study), all by stimulating the user's sensorimotor cortex with a single magnetic coil moved mechanically across the scalp. In our second user study, we probed into participants' experiences while using our haptic display in VR. Finally, as the first implementation of full-body haptics based on non-invasive brain stimulation, we discuss the roadmap to extend its interactive opportunities.

CCS CONCEPTS

• **Human-centered computing** → Haptic devices; • **Hardware** → Emerging interfaces.

KEYWORDS

Transcranial Magnetic Stimulation, Electrical Muscle Stimulation, Haptics

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1 INTRODUCTION

Enabling users to leverage all their senses while immersed in interactive experiences has been one of the driving visions in Human-Computer Interaction—as Sutherland put it "[the interface] should

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serve as many senses as possible" [80]. To this date, an immense body of work in haptics has engineered specialized actuators to deliver skin sensations to the user's body (e.g., contact [75], texture [10, 96], pressure [37]).

The overwhelming majority of haptic devices are engineered using the same principle, i.e., an actuator is mounted atop the part of the skin that is meant to be stimulated, e.g., finger-worn haptic devices deliver tactile cues to the fingerpad [37, 55, 75], foot-worn devices deliver tactile cues to the soles [79, 93], head-worn devices deliver tactile cues to the face [15, 65], and so forth—this approach can also be referred to as haptic *end-effector* [42], a term borrowed from robotics literature, where it denotes how the actuator is attached at the very *endpoint* of a robotic extremity. Similarly, in this context, a haptic end-effector denotes how the actuator is attached at the very *endpoint* of the user's nervous system, e.g., a vibration motor attached atop the tactile receptors at one's fingertips [31]. Users feel haptic sensations delivered by end-effectors via the following process: (1) mechanical stimuli are translated to electrical impulses (by mechanoreceptors at the endpoint), (2) electrical signals propagate via the peripheral nervous system (via neurons from limbs to the spinal cord), and, finally, (3) signals are processed in the ***source*** location where all the neurons flow (i.e., the brain, in particular, the somatosensory cortex).

This end-effector approach has been successful in that devices can deliver precise temporal and spatial cues. However, few examples of these devices lend themselves well to *full-body* haptic experiences, which reveals a research question to which our field has not found new answers: how might we *scale up* haptic devices given that the current approach requires *many* devices to render sensations on *many* locations of the user's body?

Thus, to propose a new approach, we take the inverse conceptual turn. Instead of placing haptic end-effectors on the endpoints of the user's nervous system, we propose delivering full-body haptics via a single haptic device that directly stimulates the user's brain areas responsible for creating haptic sensations—we call this a *source*-effector.

To create the first instantiation of this concept, we turned to transcranial magnetic stimulation (TMS)—a technique from medicine that allows for safe & non-invasive brain stimulation. To translate the TMS technique into readily usable knowledge for human-computer interaction, we (1) characterized, by means of a user study, which areas of the body TMS can elicit haptic sensations; then, (2) engineered a haptic device that sits atop the user's head and is able to position the TMS coil at strategic locations to generate haptic sensations (i.e., either touch or touch & force) in nine locations of the users' body: hands, arms, legs, feet, and jaw, as shown in Figure 1—all by stimulating the user's sensorimotor cortex with a single magnetic-coil moved mechanically across the scalp; furthermore, (3) we characterized, by means of a second user study, the user experience created by our device in a virtual reality application; finally, (4) we mapped out the possible evolution of this concept, including its hardware challenges.

Finally, we see this approach as the first step towards exploring new methods to scale haptic feedback to multiple body areas without encumbering users' bodies. Naturally, as a first step in this direction, our current implementation using transcranial magnetic stimulation is not without shortcomings. We will discuss these in detail later as we believe they are crucial for identifying the next research challenges to be tackled. However, we believe that our work provides technical insights that will inspire researchers to explore new approaches for haptics.

2 RELATED WORK

Our work is built primarily on approaches towards full-body haptic feedback, which we organize by their conceptual takes on delivering haptic sensations: to the *endpoint* (e.g., attaching a haptic end-effector to the palm, or even sending an air) or to a *midpoint* (e.g., electrically stimulating nerves in the arm to create touch on the palm). We discuss the differences between these approaches and our source-effector. Finally, since our approach is one of the very few that makes use of transcranial magnetic stimulation (TMS) in an interactive context, we briefly review the working principle behind this non-invasive brain stimulation technique.

2.1 Full-body Haptic Feedback by Stimulating the Endpoint

N:N haptics (N actuators, N locations): The most popular way to realize full-body haptics has been to attach an actuator per location where a sensation should be felt—hence N:N haptics. Some of the first explorations of this approach date back to the 1990s, when researchers used 10 vibrotactile actuators placed at the hands, feet, legs, and head [97]. Later, Lindeman et al. took this further with 16 vibrators, even including solenoids and fans [47]. Because attaching/removing individual actuators on many parts of one's body is extremely time-consuming for the user and requires many fixation points that encumber the user (e.g., straps), researchers opt to integrate these vibrotactile actuators in haptic suits—both [97] and [47] are canonical examples of haptic suits, while many more exist in research [19, 40] and even in industry (e.g., bHaptics [60]). This haptic-suit approach improves wearability & comfort by trading it off with design flexibility (e.g., it is harder to reconfigure the location of the devices depending on body size, individual preferences, goals of the application, and so forth).

1:N haptics (1 actuator, N locations): Counter to the previous approach, an emergent and more experimental way to deliver haptics to the endpoint, is to use a *single* actuator. In these systems, there is only one actuator but the user feels sensations in multiple locations—hence 1:N haptics. One way to enable this is to utilize the air around the user: as demonstrated by *AIREAL*, an air vortex that stimulates the skin up to 1 m away [77]. This approach has been then extended to present tactile sensations at the head, shoulders, and legs [29, 81]. Another approach is to attach a single haptic actuator to an endpoint but then move it mechanically to reach different limbs. For instance, *Calico* is an on-cloth robotic platform that moves a small end-effector across the user's clothes, providing vibrations from arms to legs [73]. As emergent techniques, these are not without limitations. In the case of air vortexes, these require line of sight, intensity decays over distance, and have a limited interactive volume, etc. Conversely, moving wearables on the body is relatively slow and can require rails added to one's clothing, etc. Most importantly, all of these techniques *cannot deliver force feedback*—these provide only tactile cues (e.g., soft puffs of air or vibrations). That said, these devices conceptually align with our goal, i.e., building a *centralized* haptic device capable of delivering haptics to multiple locations. In addition, these are flexible in adding new points of sensation easily (i.e., pointing the air cannon or moving the on-body robot). Thus, we are inspired by these centralized devices, yet seek to explore a novel approach that breaks away from having to stimulate the endpoint.

2.2 Haptic Feedback by Stimulating the Midpoint (Peripheral Nerves)

An approach, which we draw inspiration from, is to create sensations in a target area, but using actuators attached to another patch of skin that communicate via peripheral nerves. These techniques typically work by electrically stimulating nerves to induce sensations ”remotely” at the endpoint of this nerve. This can take the form of touch-feedback (electro-tactile) or force-feedback stimulation (electrical muscle stimulation).

Tactile sensations from the midpoint. One way to create tactile sensations without attaching a haptic end-effector to the endpoint is to stimulate the nerve that leads to it—this is known as inducing a *referred sensation*, i.e., “somatosensory feelings that are perceived to emanate from a body part other than, but in association with, the body part being stimulated” [53]. While this was initially only explored in prosthetics to provide tactile feedback to the prosthetic hands or feet of amputees [14, 48, 64], it has also been adapted to enable users to feel tactile sensations in their hands or fingerpads without attaching electrodes directly to these areas; instead, electrodes are placed on the wrist to create sensations in the hand [63, 66], or other strategic locations more proximal to the peripheral nerves such as the back-side of the hand [86], palm, [1] or base of the fingers [99, 100] to induce sensations in the fingerpads.

Force feedback from the midpoint. Similar to this, with electrical muscle stimulation (EMS), it is possible to create force feedback without requiring mechanical actuators (e.g., motors or exoskeletons). Electrical impulses are sent to electrodes placed atop a muscle (midpoint), which in turn cause a movement on the limb (endpoint). For example, stimulating the forearm can cause the fingers [83, 84] or the wrist to move [36, 49]. Similarly, stimulating the neck can move the head [85], or even stimulating the calf [32] or thigh [68] can move the foot.

Pushing past the midpoint. While we take inspiration from these techniques, we ask the natural question: how would an interactive system look like if we moved past the midpoint? The logical consequence of this is to actuate the *source* of the nervous system, i.e., the user's brain, to generate sensations even at larger distances and from a *centralized* haptic device. To find a suitable method to stimulate the brain, we turn to the field of neuroscience where a number of brain stimulation techniques are used in research & therapeutics. There are several established techniques to achieve this, however, they range in their applicability outside of the medical domain. First, invasive techniques involve implanting electrodes in the brain, via a surgical procedure. Given this stringent requirement of implantation, this technique (known as intracortical microstimulation [11]) is typically used for extreme medical cases, such as researching prosthetics with tactile feedback for amputees [24]. On the other side of the spectrum stand non-invasive techniques, which trade off accuracy for safety and wide applicability. One such non-invasive technique that has been extensively explored for the last decades is transcranial magnetic stimulation (TMS) [30]. Before we turn into the details of this technique, we note that TMS is not the only non-invasive brain stimulation approach; others include transcranial direct-current stimulation [62] or transcranial focused ultrasound stimulation (tFUS) [44]. With regards to tDCS, it is a neuromodulation technique that uses small electrical currents delivered via electrodes on the scalp; as a modulation technique, it typically does not have the accuracy nor amplitude to induce haptic sensations and is used for neuropsychiatric conditions [61]. On the other hand, tFUS is a nascent stimulation technique that uses focused ultrasound, delivered by a transducer placed atop the scalp [12]. While tFUS might eventually resolve some limitations of TMS (which we will discuss later in detail, e.g., device weight), its safety protocols and guidelines are still under development, unlike those of TMS, which have been established for decades [71]. Therefore, we decided to implement our concept using TMS.

2.3 Transcranial Magnetic Stimulation

Transcranial Magnetic Stimulation (TMS). TMS is a technique that originated in medicine/neuroscience [27], in which a magnetic coil placed atop the user's head produces a magnetic field that oscillates rapidly. This, in turn, creates electrical currents, known as *eddy currents*, inside the brain [30], without the need for implanted cables or electrodes [24] (as with other brain stimulation techniques)—it is thus, *non-invasive*.

TMS in neuroscience as a tool to understand brain function. TMS has been popularized as a tool for neuroscience since first demonstrated by Barker et al. in 1985 [5]. It is frequently used to map brain functions to cortical areas, e.g., motor control [95], vision [9], language processing [23], working memory [57], and more.

TMS as a medical intervention/treatment. TMS has also been extensively used as therapy for improving motor function in Parkinson's patients [43], reducing epileptic seizures [26], and as a depression treatment [28].

Peripheral magnetic stimulation (e.g., muscles or touch). While magnetic stimulation finds its primary use in stimulating the brain, it can also be used for peripheral nerves, placing its coil atop muscles (similar to EMS) or skin (similar to electro-tactile). While the latter (tactile) is rather rare, it has been used for creating tactile sensations in mid-air without the need for direct contact [38, 39]. The former (magnetic muscle stimulation), has been used for muscle rehabilitation [8], gaiting [82], and even swallowing [56]. Moreover, recently, it has also been used for interactive force-feedback [87]. It is worth noting that, unlike TMS, these magnetic skin/muscle actuation systems create sensations by stimulating the periphery—these are still midpoint approaches.

TMS in interactive systems. Although it is known that TMS applied to the motor cortex induces limb movement [95] and/or touch sensations in the hand [25], its presence in human-computer interaction remains limited. Recently, Bassolino et al. demonstrated that TMS to the motor cortex improves the sense of embodiment in a VR rubber hand illusion [6]. While this implies the utility of haptic feedback via TMS, to our knowledge, there have been no

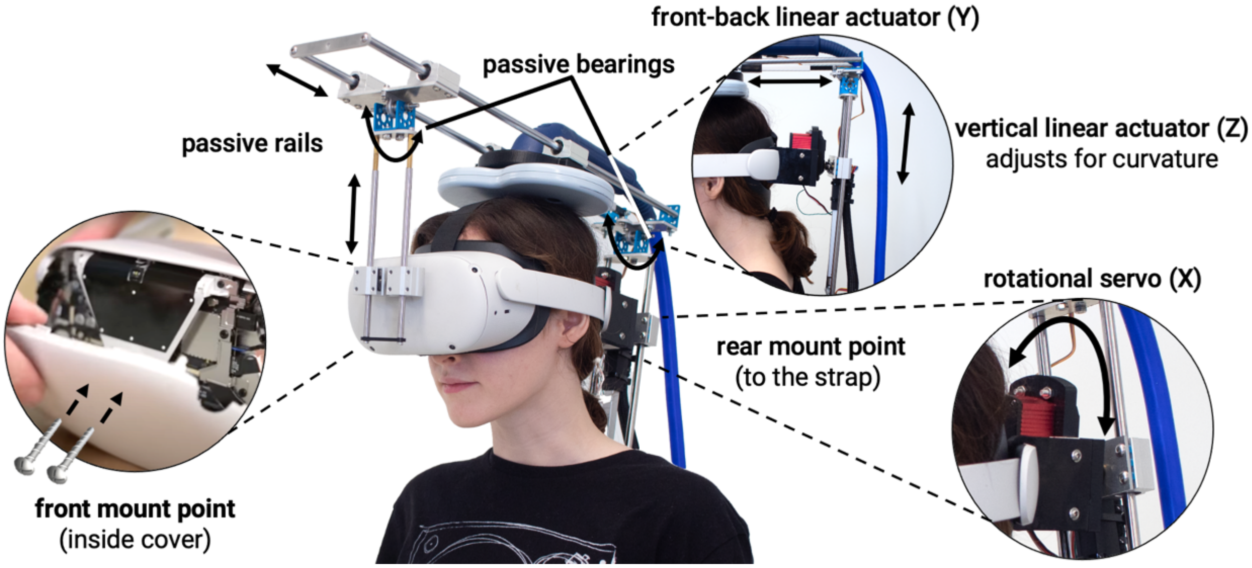

Figure 2: Overview of our mechanical actuator to interactively displace the TMS coil over key areas of the user's brain.

interactive devices that leverage TMS to extend haptics to the user's full body.

3 IMPLEMENTING SOURCE-EFFECTOR VIA TMS

To help readers replicate our design, we now provide the necessary technical details (hardware & software), alongside a discussion of important safety considerations for any future interactive system based on TMS. Furthermore, to accelerate replication, we provide all the source code & hardware of our implementation[1]

Design rationale. As the first instantiation of the concept of a head-worn centralized haptic device, we focused on understanding the *range of sensations & locations* that can be created using TMS rather than optimizing for form-factor or ergonomics. As such, we opted to implement a versatile design that could move a powerful medical-grade TMS coil. This gave us maximum flexibility in our findings, as the coil has excellent stimulation depth; in other words, using smaller coils would result in a smaller device, but would not allow us to learn the full range of haptics that TMS can unleash. Now that we know the range of haptics that can be generated via TMS (Study#1) and the afforded user experiences (Study#2), we are poised to also explore new design trade-offs. These include the potential use of multiple smaller coils rather than moving a single powerful coil, which we will discuss later.

3.1 Hardware Implementation

We engineered the actuation system shown in Figure 2, capable of moving a TMS coil (Magstim D702 butterfly coil) around the user's head, which is connected to a medical-grade magnetic stimulator (Magstim Super Rapid2).

Robotic platform. The key component in our hardware implementation is a robotic gantry that mechanically moves the TMS coil across key areas of the user's scalp. Our design is inspired by a traditional X-Y-Z gantry system commonly found in CNC machines [51], but with key modifications that allow it to: (1) most importantly, conform to the curvature of the scalp around the pitch axis (i.e., front/back), which is estimated to be ~18 degrees for the sensorimotor cortex area, based on our measurement from a standard head shape dataset [46]; (2) accommodate different heads, including different curvatures and sizes; (3) actuate with sufficient force to move a medical-grade TMS coil (~1 kg); (4) actuate with steps smaller than 8.5 mm, as determined by our Study#1; and, finally, (5) provide a structure that can be either directly mounted to a VR headset or suspended from the ceiling (as in [52, 78]). To satisfy these requirements we engineered the actuation system shown in Figure 2.

Actuators. We feature three actuators, respectively, to move the coil in the X- (ear-to-ear translation), Y- (nose-to-back translation), and Z- (height away from the scalp) axes. Since the X-axis exhibits most curvature as the coil moves towards the ear, we actuate it via a servo motor (Feetech FT5335M; maximum torque=392N·cm) with a built-in encoder, this offers a reliable, fairly compact, strong way to actuate the coil—as the coil moves closer to the ear it exerts more torque force to the servo lever. As we found in our technical evaluation, we can move the servo reliably & repeatably at 4.2 mm steps. For the Z-axis (height away from the scalp) we employ a linear actuator (Actuonix L16-P; gear ratio=63:1; maximum load=100N) with a built-in encoder, mounted directly to the lever of the aforementioned servo. Finally, for the Y-axis (as the coil moves from nose to back) we also use a linear motor (Actuonix P8-P; gear ratio=165:1; maximum load=110N) with a built-in encoder. The Y-axis is mounted to the endpoint of the Z-axis actuator and, ultimately, holds the coil via a custom metallic adaptor. As we found

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[1] https://lab.plopes.org/#source-effector

in our technical evaluation, we can move the Y- and Z- actuators reliably & repeatably at 1.9 mm and 2.6 mm steps respectively. So far, what we described is a typical gantry (with carefully chosen actuators that are strong enough to move the TMS coil), however, with the standard design with fixed *perpendicular* axes, we would not be able to account for the head's curvature. This would require at least adding more actuators to tilt the coil. Instead, to avoid more actuators, we opted to build a structure with passive mechanisms. In the following, we describe the structural elements that make this possible.

Structural elements. To account for curvature, the Z-axis needs to be lifted as the coil traverses the head. One option, that we explored in the early phase of the engineering, was to let the coil hang entirely at the end of the Y-axis, with no further structure to support it. This is similar to some CNC machines that optimize for space and do not feature two rails per degree of freedom (e.g., EasyThreed X1). However, we noted this increased the slack and backlash due to the coil's weight. As such, we added a mount on the faceplate of the VR headset (Meta Quest 2), which is depicted in Figure 2. The faceplate was drilled and secured to our custom mount using M4 screws and a ball bearing. To enable movement with the new mount point, we incorporated a passive mechanism comprised of linear rails and bearings (Figure 2). This design allows the Z-axis linear actuation to tilt the coil around the pitch axis, adapting to the nose-to-back curvature of the scalp. Lastly, the secondary mount attaches to the back of the VR headset's strap using a custom 3D-printed bracket.

Alternative designs. Many other designs are certainly possible and ours depicts one possibility. For instance, one could add a hemispheric rail connecting the sides of the VR headset's strap to a passive rail, thus guiding the coil with greater precision. However, after experimenting with this, we noted that this also has drawbacks: (1) it prevents the headset's strap-size adjustment from working, rendering our system fixed in size unlike our current design (i.e., the rails properly slide as the user adjusts the headset for their size); and (2) It restricts the coil's movement to a single line over the cortex, eliminating the possibility of diagonal movement. Additionally, it is important to note that our evaluation showed our system has already achieved sufficient accuracy to stimulate the sensations found in Study#1.

3.2 Software Implementation

To control our medical-grade TMS stimulator, we implemented a custom middleware via MagPy Python Toolbox [54], which routed serial communication to the stimulator and received Open Sound Control (OSC) commands. Our main applications for both studies ran on Unity3D, which dispatched OSC commands to our custom middleware for TMS, and serial commands to a SAMD21-XIAO microcontroller connected to the motors and encoders. For tracking the hands and feet, we used HTC VIVE 3.0 Trackers attached to the user's extremities, and integrated their tracking information into Quest 2's headset tracking using Open VR Space Calibrator [45].

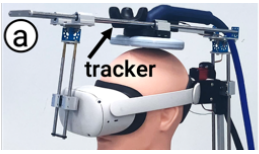
Stimulation flow. When a VR experience requests feedback, the following process triggers the stimulation: the Unity3D application communicates the required stimulation intensity to the Python middleware via OSC, which is then conveyed to the stimulator as a serial command using MagPy. As a result, the stimulator charges its capacitor arrays at the requested intensity. In parallel, the Unity3D application also sends serial commands to the motor controller to move the coil to a target area. Once the coil has reached the position and five seconds have elapsed since the previous stimulation (see *3.3 Safety*), the Unity3D application sends another OSC command to our middleware to trigger the TMS stimulation using three consecutive 300-μs biphasic cosine cycle pulses [50], each separated by a 50-millisecond interval. Finally, the resulting current flow through the coil creates the oscillating magnetic field, delivering the stimulation to the target brain region.

3.3 Safety

Risks of TMS. Like any other electrical or brain stimulation technique, TMS is not without its associated risks. These are primarily local skin-tingling at the scalp or magnetic interference with implanted devices, which can be avoided through user screening and the proper selection of stimulation parameters [71]. Moreover, according to a set of safety & ethics guidelines for TMS released in 2021 [70], as long as TMS is applied to subjects without epilepsy, no lasting adverse events (e.g., seizures) have been reported. This claim is further supported by a comprehensive review of TMS, including long-term use of up to 26 months [22]. TMS is also an FDA (Food and Drug Administration) approved technique for therapeutic purposes [18]. The minimal risk of TMS is ensured by properly screening the population and limiting stimulation within the known safety range.

User screening. In adherence to the safety guidelines [70, 71], we strictly applied the following user eligibility criteria. First, we did not recruit participants with medical conditions that could increase the risks associated with TMS (i.e., epilepsy, or history of seizures). Second, in line with the safety guidelines for fMRI [20], we did not recruit participants with implanted devices (e.g., pacemakers, metal implants) to prevent unintended interactions with the electromagnetic field generated by the coil. We also ensured ethical compliance by obtaining informed consent from participants prior to using our device—overall, these screening criteria are mostly analogous to those for EMS [41].

Stimulation parameters. Rossi et al.'s guidelines provide a range of stimulation parameters that ensure minimal risks during TMS [71]. These specify the maximum stimulation duration and the necessary break period between stimulations as a function of the stimulation frequency. For instance, for a 20 Hz stimulation, the guidelines prescribe a safe continuous stimulation up to 400 ms (i.e., 8 consecutive pulses). Following this guideline, we use the stimulation parameter of three consecutive pulses with 50 ms intervals—a conservative & safe approach using less than half of the maximum pulse count that is deemed safe. Moreover, for these stimulation parameters, Rossi et al. further recommend adding a five-second break between stimulation sequences. As such, our software apparatus does not allow the TMS stimulation to be reactivated unless five seconds have elapsed prior to the preceding stimulation. This additional safety was also incorporated into our VR experience used in Study#2, by adjusting aspects such as the timing of the enemy's attacks or charge-up duration for the user's projectile launcher.



b

direction	left		right		front		back	
distance	40 mm	80 mm	40 mm	80 mm	15 mm	30 mm	15 mm	30 mm
mean error	1.8 mm	0.8 mm	2.1 mm	1.0 mm	1.0 mm	1.5 mm	1.9 mm	1.6 mm
SD	0.5 mm	0.4 mm	0.6 mm	0.4 mm	0.3 mm	0.3 mm	0.3 mm	0.3 mm

Figure 3: (a) Measurement setup for the actuation characterization. (b) Mean errors and standard deviations (SD) for all targets.

Runtime safety. For runtime safety, we implemented an emergency stop function in our Unity application, which immediately shuts off both the TMS stimulation (hardware switch) and motor power (hardware switch).

4 TECHNICAL EVALUATION

We conducted two technical characterizations: **(1) device characterization** (i.e., end-to-end latency, noise, weight), and **(2) actuation characterization** (i.e., accuracy in moving the coil on the user's scalp).

4.1 Device Characterization

End-to-end latency. We measured an end-to-end latency of 16 ms using a 240fps camera that also recorded sound—this is a complete round-trip, from an event in Unity3D to the audible sound of a TMS pulse. For simplification, the coil was already at the target, we will later characterize the actuation speed delay while moving the coil.

Operating noise. We measured the sound generated by our TMS using a decibel meter (AS824) placed at the height of a user's ear (ten repetitions). We measured an average peak of 79.8 dB at the average TMS intensity used in Study#2 (actuating the leg, which requires the most amplitude). In comparison, haptic devices such as propeller-based tend to be louder (e.g., [72] produces up to 95.3dB). Also, propeller-based devices actuate for several seconds or even stay on for minutes, instead, our TMS produces sounds for only 150 ms.

Device weight. The total weight of the device is 3.1 kg (measured with a Camry Digital Scale, 50g resolution), which consists of 1.1 kg from the effective weight of the TMS coil when worn and connected to the stimulator and 2.0 kg from our mechanical actuators, rails, and attachments.

4.2 Coil Actuation Characterization

As we will see in our Study#1, we observed that the shortest distance between adjacent locations on participants' scalps that correspond to haptics on different limbs, was approximately 17 mm. Consequently, we required an actuator that meets this level of precision, ideally with a resolution of at least half that distance, i.e., 8.5 mm.

Measurement setup. All the evaluation in this section was conducted with a HTC VIVE 3.0 tracker (with a tracking accuracy of 0.3 mm [7]) attached to the coil of our complete system worn by a mannequin head (Figure 3a). We used our Unity3D application to control the motors while recording the tracker's position. Note that the positional difference between the tracker and the center of the coil was compensated via an offset applied in the Unity3D spatial coordinates.

Range of motion. We characterized the range of motion for each motor axis. We found that the rotation of the servo motor (X-axis) spans 24 cm across the head. The actuation range of the Y-axis linear actuator equates to 7.4 cm across the head, and the Z-axis linear actuator's range corresponds to a 24-degree tilt of the coil in the pitch axis.

Minimum step-size. We characterized the step-sizes that the coil can robustly move on the scalp using its servos and linear actuators, which we found to be: 4.2 mm, 1.9 mm, and 2.6 mm for the X-, Y-, and Z-axes respectively.

Actuation consistency. The most important factor is the ability to consistently replicate target coil positions multiple times after calibration, i.e., measuring the motors' drift. For this test, we instructed the system to actuate to eight known targets in the four cardinal directions at two distances that were pre-defined. In these measurements, the coil was first set to the initial position where the center of the coil coincided with the center of the mannequin's scalp. Then, the coil was actuated at the speed employed in our Study#2 (50mm/s on X-axis, 8mm/s on Y-axis, and 18mm/s on Z-axis), After stopping, we calculated the error. We repeated this 10 times for each target to obtain a variability, as a metric of robustness. Figure 3 (b) shows our results. We found that the average error across the targets was 1.4 mm (SD=0.7) on the X-axis (left/right) and 1.5 mm (SD=0.4) on the Y-axis (front/back). Consequently, this actuation consistency, along with the minimum step sizes, confirmed that our system surpasses the required precision of 8.5 mm.

Actuation latency. We measured the time that our actuation system would require in a worst-case scenario, where the coil needs to travel from the jaw location on the left side to its counterpart on the right. Drawing from the average unit distance between different stimulation targets on the scalp as determined in our Study#1, we set the distance for this case to be 13.6 cm. We found it takes 3.2 seconds for our system to cover this furthest distance.

5 CONTRIBUTION, BENEFITS & LIMITATIONS

Our key contribution is a novel interface concept, haptic source-effector, which we explore as an alternative direction to scaling haptic interfaces to be able to render full-body sensations from a centralized on-body device.

Our approach has four key benefits: (1) **One actuator for full-body haptics**: unlike haptic systems created by a constellation of many devices, our implementation has only one centralized point of contact with the user's brain; this is beneficial in that it demonstrates a path forward to scaling haptics without the complexities associated with wearing many actuators. **(2) Easily reconfigurable**: as our TMS coil moves over the user's scalp, it gains access to eliciting tactile/force sensations across many parts of the user's body, thus the device can *reconfigure* by moving to a new stimulation location of the user's brain—contrast the distance that an actuator would have to be moved if swapped from hands to feet (source-effector's movement on the scalp is 50-times smaller than that). **(3) Freeing up the body:** because source-effector only sits on the head, it frees up the rest of the body from hardware—no need to wear end-effectors which would otherwise limit the user's ability to feel sensations in their hands or feet; **(4) Force & touch:** since any sensory information takes the form of electrical currents passing through neurons in the brain, our approach renders *both* touch & forces—two different modalities that conventionally require two different types of actuators (e.g., vibrotactile motors and force-based exoskeletons).

Limitations. We acknowledge that our current implementation of source-effector based on TMS has its limitations and every benefit has associated caveats. First, while our concept is novel in that a single point of instrumentation can realize haptics in many body locations, this instrumentation is currently heavy. Second, this point of instrumentation leaves plenty to be optimized for in terms of comfort (not only total weight but distribution of weight too). Third, while this haptic actuator is unique in its ability to reconfigure to stimulate new body locations, the fundamental limits of TMS dictate the expressivity of this approach—like any other technique based on stimulating neurons, TMS is also non-selective, i.e., electrical eddy currents traverse through many neurons at once, which limits induced sensations (i.e., touch & forces, but not thermal), limits spatial fidelity (i.e., we cannot stimulate small brain areas and those corresponding to high thresholds such as the torso), and modality isolation (e.g., force-feedback occurs with touch). Moreover, we discuss more detailed limitations in our roadmap as we believe that these point to a set of challenges worth pursuing to further unlock TMS' interactive potential.

Finally, we reflect on the nature of our proposal: the TMS technique we employed is not new—it originates from neuroscience and medicine as a method to understand our brain function. However, the value of our proposal also lies in the translation of this medical tool as a new way for full-body haptics. In fact, similar translational efforts have previously advanced our field, e.g., the *PossessedHand* [69] translated a 50-year-old medical tool (i.e., EMS) into our field, leading to a growth in force-feedback research. Likewise, our effort is the first to translate transcranial magnetic stimulation from the realm of neuroscience into new knowledge for designing brain-haptic systems.

6 STUDY#1: GENERATING HAPTIC SENSATIONS ACROSS THE BODY WITH BRAIN STIMULATION

In our first study, we focused on characterizing the range of our source-effector concept when implemented by means of medical-grade transcranial magnetic stimulation (TMS), by measuring: (1) *in what locations can haptic sensations be created using TMS?* and, (2) *what types of haptic sensations can TMS create?*

As such, a TMS-trained experimenter stimulated the nine predefined locations on the right hemisphere of participants' sensorimotor cortex using TMS, while participants reported where they felt sensations and the strongest point of tactile sensation, as well as observing any resulting limb movements—this study design was based on traditional neuroscientific methods used by prior work to investigate motor responses to TMS [13, 95], as well as perceived locations [74, 94] or qualities [2, 76] of electro-tactile stimulation. The study was approved by our Institutional Review Board (IRB21-0055).

6.1 Study Design

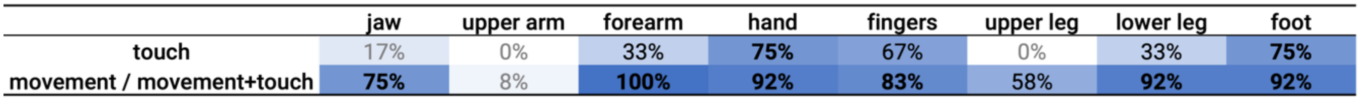
Participants. We recruited 12 participants from our institution (7 identified as male, 5 as female, average age = 23.2 years, SD = 2.2). All participants were right-handed. The participants were compensated with $30 USD.

Apparatus. We used a medically compliant magnetic stimulator (Magstim Super Rapid^2) with a butterfly coil (Magstim D70^2). The participant sat in a reclined chair, wearing earplugs and a white fabric cap on their scalp, which allowed the experimenter to mark the stimulation locations prior to actual trials. For reporting elicited touch sensations, we provided participants with an iPad and Apple pencil running our GUI application. This enabled them to draw the perceived sensation area on front/back views of a human model. They reported the quality of the sensation by selecting from the following six keywords: "tapping", "vibrating", "tingling", "pressing", "skin-stretching", and "thermal". For evaluating force feedback from TMS, we video-recorded participants throughout the study and post-annotated any involuntary joint movements via TMS that occurred during each trial.

Stimulation. We stimulated the right hemisphere of the sensorimotor cortex (corresponding to the left side of the body [35]) with three consecutive 320 μs TMS pulses separated by 50 ms, resulting in a stimulation of ~150 ms. While we opted to only stimulate the right side of the brain to avoid fatigue, the results will be generalizable to the left side. In fact, we purposefully picked this side because it allowed us to measure the worst-case scenario since the other side (dominant side) of the brain is known more sensitive to TMS [92].

Defining the stimulation locations. We identified two locations on the participant's scalp that yielded minimum stimulation intensities to elicit observable limb movement (i.e., motor threshold) for the hand and foot. For this, the experimenter moved the coil following the grid-search method used by Franza et al. [25], while adjusting the intensity based on Awiszus' method [3]. After setting the hand and foot locations, we defined the final nine locations on a line between them. These were equidistant at one-sixth of the distance between the hand and foot locations.

Procedure. We started trials at the foot location. For each location, the intensity was set to 10% below the hand's motor threshold. The amplitude of TMS stimulation was reported in percentage (100% is the stimulator's maximum). During a trial, the experimenter stimulated the target location. Afterward, the participant reported the strongest point and area of a perceived touch as well as a keyword (or if nothing was felt). Then, the experimenter increased the intensity by 5% while ensuring the participant's comfort & consent, and moved to the next trial. This process continued until the participant reported the same location and same quality of sensations for two consecutive trials, or the intensity reached the maximum (i.e., 100%). At that point, the procedure advanced to the next location.



	jaw	upper arm	forearm	hand	fingers	upper leg	lower leg	foot
touch	17%	0%	33%	**75%**	67%	0%	33%	**75%**
movement / movement+touch	**75%**	8%	**100%**	**92%**	**83%**	58%	**92%**	**92%**

Figure 4: Overview of results depicting the locations where we were able to induce touch and/or movement in participants.

Analysis. After each study session, we organized the participants' responses regarding touch sensations based on where the strongest point of the sensation was. We also annotated each trial to indicate which of the following body parts moved: "none", "jaw", "upper arm", "forearm", "hand" (i.e., the palm), "fingers", "upper leg" (i.e., the thigh), "lower leg", and "foot". To focus exclusively on clear and meaningful force feedback situations, we adhered strictly to the following two rather conservative criteria: (1) when multiple parts of the same limb moved, it was counted as the movement of the part closer to the torso, which is typically the largest/coarsest (e.g., if both forearm and fingers moved, it was annotated as forearm)—thus, in our analysis, "foot movement" means *only* the foot moved, and so forth; (2) movements that occurred when the strongest touch sensations were felt outside the relevant body part (e.g., a trial with hand movement, but strongest sensation in the forearm) were counted as "none".

6.2 Results

Overview. Figure 4 depicts an overview summarizing the body locations where we were able to induce touch and/or movement in participants. Overall, these results suggest that we were able to induce **touch sensations without body movement in *two locations*** (hand & foot), and **involuntary body movement accompanied with or without touch *in six locations*** (fingers, hand, forearm, lower leg, foot, and jaw). Moreover, it is worth noting that we only actuated the right hemisphere of their cortex corresponding to the non-dominant hand side of the body for the sake of participants' time (study durations of up to 1.5 hours). On this note, neuroscience research suggests that it is more challenging to induce somatosensory responses in the side we actuated (non-dominant) via TMS [92]—thus, these results are expected to generalize even better to the other side. When accounting for both sides of the user's body, this brings the haptic sensations that can be induced by TMS to a **total of 15 sensations** with a single actuator: four touch sensations and eleven force-feedback sensations. Note that we regarded jaw movement as one sensation. In the following, we analyze each modality (i.e., touch / force-feedback) in more detail.

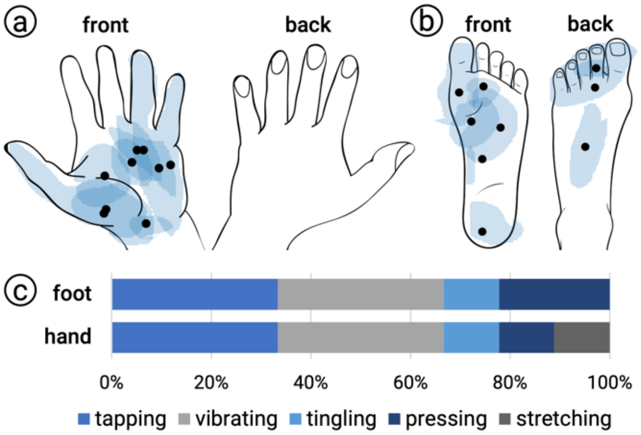
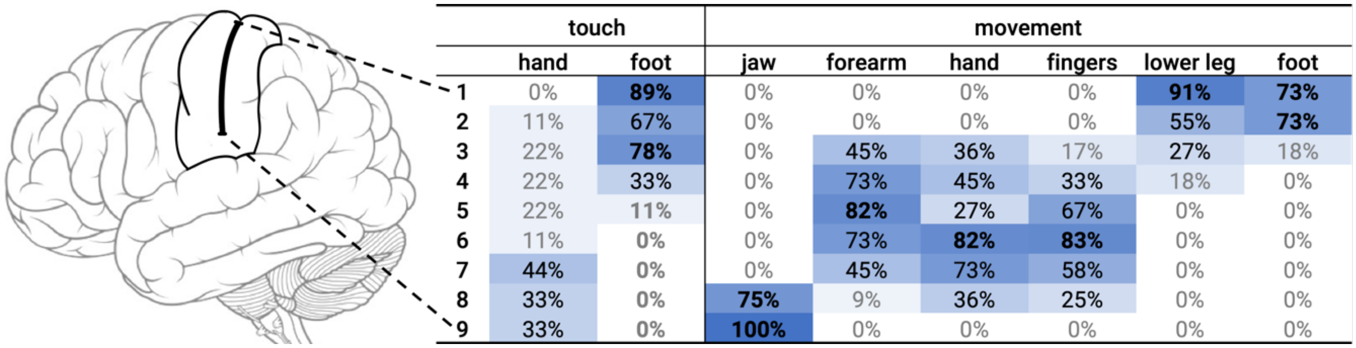


Figure 5: (a, b) Extracted raw data of where the participants felt touch sensations in the hand and foot. (c) Quality of the sensations.

Touch. Results suggest that we were able to induce, by means of TMS, touch sensations (i.e., only tactile in isolation of any noticeable movements) in two unique locations: hand and foot, which were both experienced by 75% of the participants (i.e., nine participants). The next most promising area was found to be touch on any of the four fingers, experienced by 67% of participants, which we did not find to meet our criteria. Now, we turn to where in the hand or foot these touch sensations occurred. For this purpose, for each of the nine participants who reported sensations in these areas, we plotted raw data from one trial where they felt the strongest touch sensation in these areas. As shown in Figure 5 (a, b), TMS could induce the sensations on the front side of the hand or the either side of the foot, meaning no simultaneous sensations were observed in other areas. Moreover, we found that these tactile sensations had spectrum of quality with the majority being described as "tapping" (33%) or "vibrating" (33%), and less often as "tingling" (11%), "pressing" (11%, 22%) or stretching (11%, 0%)—as depicted in Figure 5 (c).

Force-feedback. As shown in Figure 4, our results suggest that we were able to induce, by means of TMS, force-feedback sensations (i.e., noticeable involuntary movements) in six unique locations: jaw (75%), forearm (100%), hand (92%), fingers (83%), lower-leg (92%), and foot (92%), which were all experienced by >75% of the participants. In fact, most of the actuated limbs were observed in almost all participants (>90%) except for the jaw (75%) and fingers (83%). The next most promising candidate would be the upper leg (58%), which we did not find to meet our criteria. Furthermore, all these force-feedback sensations were associated with touch at the same location (e.g., if the hand was actuated involuntarily, there was touch felt & reported on the hand), except for the jaw movements. Jaw movements were observed to be isolated from touch sensations (i.e., only movement was observed). Moreover, while the jaw movement was likely also unilateral (i.e., it moved the left side of the jaw more than the right) its effect was perceived by participants as one single movement, i.e., jaw clenching on both sides; hence, we only consider this as a single haptic sensation.

Correspondence to the brain areas. Next, we analyze which locations of the sensorimotor cortex were more effective in creating haptic sensations. Figure 6 depicts the brain region that we targeted, with a line emphasizing the principal axis of the sensorimotor cortex, which was defined for each participant prior to trials. From



	touch		movement					
	hand	foot	jaw	forearm	hand	fingers	lower leg	foot
1	0%	**89%**	0%	0%	0%	0%	**91%**	**73%**
2	11%	67%	0%	0%	0%	0%	55%	**73%**
3	22%	**78%**	0%	45%	36%	17%	27%	18%
4	22%	33%	0%	73%	45%	33%	18%	0%
5	22%	11%	0%	**82%**	27%	67%	0%	0%
6	11%	0%	0%	73%	**82%**	**83%**	0%	0%
7	44%	0%	0%	45%	73%	58%	0%	0%
8	33%	0%	**75%**	9%	36%	25%	0%	0%
9	33%	0%	**100%**	0%	0%	0%	0%	0%

Figure 6: A heatmap of stimulation locations of the sensorimotor cortex corresponding to evoked touch sensations & movements.

here, we depict the effectiveness of each stimulation location in creating touch or movement at nine equally separated positions on the main axis. In defining these positions, we found that the average unit distance between each location was 8.3 mm (SD=0.9; min=7; max=10). This suggest that only position 2 was redundant with 1, and the remainder were useful for haptics. Moreover, the two nearest adjacent locations that successfully stimulated limbs were separated by ~17 mm (x2 average unit distance). This indicates that interactive systems operating a TMS coil should maintain a positional precision of at least ~8.5 mm, which we used as our design specification.

Stimulation thresholds. Finally, with respect to inducing haptic sensations by means of TMS, we investigated at what intensity haptic effects occurred. Figure 7 shows a breakdown of the intensity at which touch sensations and/or movement were first observed on average. Overall, haptic effects occurred within the range of 60~85%. Results also suggest that body parts closer to the torso consistently required higher stimulation intensities (e.g., the forearm required more than the hand), indicating that the extremities are easier to stimulate. Additionally, touch sensations always occurred at lower intensities than movements, which aligns with Franza et al's findings on TMS studies of the hand [25].

	touch		movement					
	hand	foot	jaw	forearm	hand	fingers	lower leg	foot
mean	62%	65%	63%	79%	74%	71%	86%	83%
SD	10%	7%	8%	11%	6%	9%	8%	8%

Figure 7: A summary of the minimum stimulation intensities observed to induce touch sensations & movements.

Study conclusions. Overall, our results imply that, when considering both sides of a user's body, TMS can produce a total of 15 haptic sensations using just one actuator: touch sensations at each of the four extremities and force feedback at eleven locations spanning across the jaw and the four limbs. Finally, building on our findings, we designed an interactive experience that can render force feedback to the user's hand, forearm, foot, and lower leg on both sides of the body and used it to probe into experiential aspects of our approach.

7 STUDY#2: USER'S EXPERIENCE WITH SOURCE-EFFECTOR

This study was designed so that participants could provide qualitative feedback regarding their experience with this on-of-a-kind device during an actual interactive use. To this end, participants experienced a custom-design VR game that featured several sensations that our device is capable of (from Study#1). VR experience was followed by a semi-structured interview to let participants voice their experiences. This study was approved by our Institutional Review Board (IRB21-0055).

7.1 Apparatus, VR & Haptic Design

Apparatus. Participants wore our complete device and a VR headset (Meta Quest 2), as described in *Implementation*. Their hands and feet were tracked via four HTC VIVE 3.0 Trackers attached with Velcro-straps. Participants wore headphones (Apple Airpods Pro) to hear the VR experience.

VR experience. Participants embodied the avatar of a cyborg trying to escape a robotics factory that has malfunctioned, as depicted in Figure 8 (a). However, when they find the escape route blocked by malfunctioning robots that fire at them, —as depicted in Figure 8 (b)— the VR experience commands our haptic device to render *tactile sensation on the affected area* (e.g., the left hand in this case, but both hands and feet are possible). To advance, participants can counteract by charging up their plasma-hand and firing plasma-projectiles to deactivate the robots—as depicted in Figure 8 (c)—when they open the palm of their hands in a firing gesture, the VR experience detects this gesture and prompts our haptic device to render *force-feedback and tactile sensations on the firing hand* (e.g., the right hand in the case, but both hands can fire plasma shots). After this, the user continues to counteract any robots that appear, which can fire shots against any of the user's VR limbs (i.e., the hands or feet). Figure 8 (d) shows the user being shot in their right foot—just before this happens, the VR prompts our haptic device to render *tactile sensation on the right foot.* After a while, the user's plasma-hand stops working, and they need to recharge the energy. They locate a crate on the floor and stomp it with their feet to release its charging energy—as depicted in Figure 8 (e)—just before the stomping releases the energy, the VR commands our haptic device to render *force-feedback and tactile sensation on the*

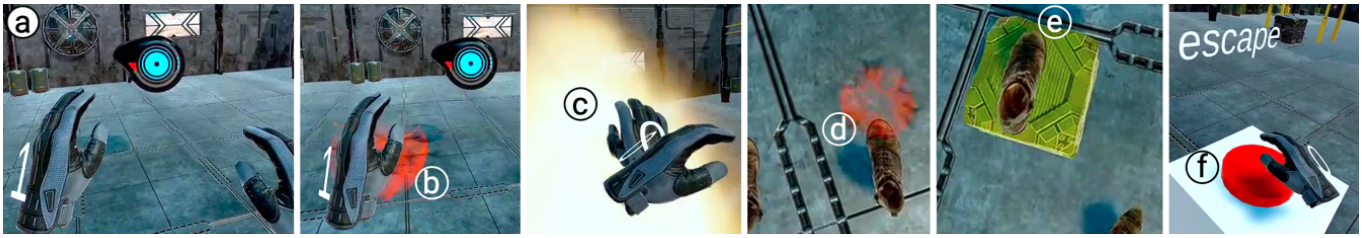


Figure 8: Full-body interactions in our Study#2, including: force-feedback and tactile sensations on both hands and both feet.

left leg. The user keeps fighting until they eventually find a button that opens the exit door—as depicted in Figure 8 (f)—as they are about to press it, the VR requests that our haptic device render *tactile sensation on the right hand*. The user has escaped the factory.

Haptic design. Although our system has some mechanical latency and added safety pauses (see *3.3 Safety*), we tailored our game design to overcome it. For instance, to give the coil time to arrive at the hand (~3.2 seconds if coming from the furthest away), the participant hears a charging sound and sees the hand charging before the plasma shot is fired. This is an example of how haptic designers create VR situations to set up the user's mental model to handle haptic devices that include some latency (e.g., shape-changing devices [34, 90]). Another way to handle latency is to preemptively schedule an event just before it happens, which we leverage when the user is hit by the robots (a popular design used in prior work, e.g., [89] or [17]). Finally, we also took advantage of events not initiated by the user's voluntary actions (e.g., the appearance of the box, the start of enemy firing, spawning new enemies, and so forth). Thus, we only triggered interactive events with haptics after the coil was set atop the target position and/or the completion of the five-second safety interval—a strategy known as queueing.

7.2 Study Design

Participants. We recruited eight participants (five identified as male, three as female, average age = 25.3 years, SD = 3.0) from our institution; three had partaken in our first user study. All participants were right-handed. Moreover, with the participants' consent, we videotaped the study. Participants received $30 USD as compensation.

Procedure. Prior to the VR trial, we calibrated the coil's position and the stimulation intensity to induce the visible movements of the hand, forearm, foot, and lower leg for both sides of the body. We adjusted the coil position with our motor structure while sending commands to motors via GUI sliders on our Unity application. After the calibration, the participant experienced the VR scene. Then we conducted a semi-structured exit interview.

Interview structure. Our semi-structured interview included four phases: **(1) Overall experience**: opener questions about the overall experience with the device; **(2) Open-ended feedback**: we invited participants to provide any comments regarding any aspect of their experience in the entire study; **(3) VR experience**: one question per VR interaction; **(4) Future**: we invited participants to share use-case/features they would like to see. In total this comprised eight questions. Finally, interviews were recorded in audio (with consent) for transcription.

7.3 Results

We analyzed video-recordings from the VR experiences, depicted in Figure 9, as well as responses to our interviews. We identified eight unique topics: (1) surprise, (2) coil, (3) ergonomics, (4) full-body sensations, (5) force feedback, (6) tactile feedback, (7) unexpected sensations, and (8) future form-factors & applications.

Surprise. Six participants (out of eight) expressed surprise: "felt like it's actually happening. Was impressed[!]" (P5), "very surprising" (P2), "surprise that it works, the location of the sensation and motion was correct despite the device being on the head (. . .) hard to imagine that it can work but it does[!]" (P4), and "is on top of your head which you wouldn't expect to be able to move your hands and feet. It was a little counterintuitive[!]" (P7), " it is cool that it is coming directly from your brain. (. . .) [no need to] attach stuff to other parts of your body" (P6), and "It felt natural because there was nothing there, like using my natural hand [versus] using a glove (. . .) bright future! (. . .) a natural feeling and doesn't feel like needles and there is no glue to remove at the end " (P1).

Feeling the coil movement or coil action. Three participants (out of eight) recalled feeling the coil's movement: "you can kind of just ignore the movement, all of the feedback was unexpected. You can't anticipate the sensation in advance" (P4) or "[the coil moving] feels like it's massaging your head, which is good!" (P6) and "the movement of the device could be distracting but the actual sensations were realistic" (P8). Finally, two participants (out of eight) commented on feeling the coil's stimulation "everything else [in VR] distracted from it" (P6) and "felt [haptics] in a specific body area, sometimes it was covered by the sensation on the skull" (P3).

Device's ergonomics. Three participants (out of eight) commented on ergonomics: "a little heavy, but everything else was fine. It was comfortable aside from the weight. It didn't feel uncomfortable when was moving around" (P7), "not really aware of the moving part but was aware of the heaviness (. . .) but it is a lot more adaptable, better than putting 10 different things on body" (P5), "If there is more weight on the front, it would be better" (P6).

Full-body. All eight participants recalled how they felt all sensations successfully, including tactile and forces on their hands, feet, and arms during interactions with firing a projectile, stomping on a box, getting shots on the hands/feet, and pressing the escape button. For instance, "felt sensations on the whole body, which is very convenient. Liked how you only need to calibrate once at

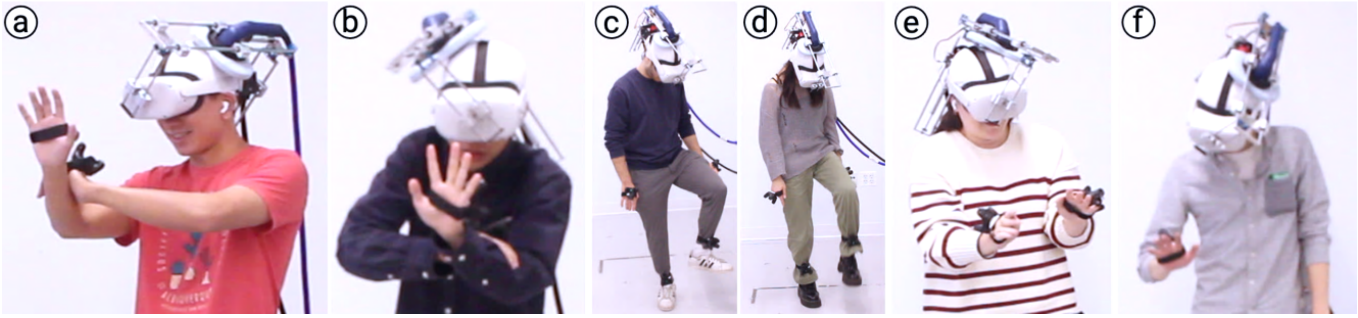


Figure 9: Photos of participants' experiences (reproduced with their consent): feeling the recoil of throwing a projectile (a, b); stomping on a virtual box (c, d); feeling the impact of a projectile on the hand (e); pressing a virtual button with haptics (f).

the beginning and do not need to calibrate again" (P2; note that recalibration could be needed depending on the situation).

Strong force feedback. Seven (out of eight) participants commented on the strength of the force feedback, for instance, "knee joint bounce [proceeds to make "boom" sound], it felt strong (...) like stomping on a rubber ball" (P2, stimulated on leg as they stomped on the box), "felt [a] pushback, cool!" (P1, stimulated on hand as they fired the laser), or "Felt very strong, maybe because it suddenly moves your foot and you need to balance back. surprised by the attack [of the robot]." (P4, stimulated on foot), " really strong, like a kickback (...) kind of like a recoil". (P7)— P1, P4, and P8 went as far as to call the effects felt "very natural". The participant who did not enjoy the haptics mentioned: "All of the haptic sensations made sense (. . .) [I] just didn't like them (. . .) [and then proceeded to explain that they felt] scared of losing balance initially [when feeling foot force feedback]" (P6).

Tactile feedback. All eight participants reported feeling tactile sensations during the VR experience. Two participants (out of eight) commented that these felt less expressive than the force-based sensations, "movement is stronger than tactile" (P2), and "[feeling shot on hand was] less realistic than laser or stomp [both force]" (P3).

Unexpected sensations. One participant reported a sensation that was not force or touch, "the [foot] sensation was very sudden (. . .) may have contributed to the burning sensation, made me realize I got shot" (P2). Also, one participant was surprised by the involuntary actuation, "kind of scary. Interesting because I am not in control" (P1).

Future form-factors & applications. Regarding future applications beyond the VR they experienced, three participants stated, "Learn to play instruments since hands are free (. . .) or handle emergency situations [it] can get your attention very quickly" (P4), "stationary mouse + keyboard games" (P2), and "use with constant forces, liquid, wind, etcetera" (P3). Regarding future form factors, two participants added other ways they would like to experience our device: "many coil arrays so no [need for] motor movement (. . .) [and later added] this could be a structure that carries the coil without placing the weight on the user" (P2) and "maybe move the coil up a couple of centimeters when it is not stimulating" (P1).

8 DISCUSSION & ROADMAP

In this section, we present our reflections and a potential roadmap to further exploring this novel idea.

8.1 Roadmap for Technical Limitations

As one of the very first haptic systems making use of TMS as a centralized haptic actuator, our exploration let us engage & measure several of its current limitations. We believe these current limitations point to significant areas for future research. It is important to note that many in neuroscience/medicine do not push past these limitations because, for most of their practical purposes, these are minor issues (e.g., TMS' audible noises are a minor nuisance during TMS-depression therapy). We argue that incentives to push TMS past its current form factor might have to come from *outside of the medical* space. This is perhaps akin to how researchers & industry in HCI have engineered compact & easy-to-wear EMS stimulators when compared with medical-grade EMS devices. We argue that the translation & exploration of TMS in interactive systems might accelerate & motivate technical advances.

Acoustic noise. Rapidly oscillating magnetic fields create audible coil vibrations. Some advances in noise reduction are possible. For instance, Peterchev et al. demonstrated a TMS coil that effectively reduces its noise by 19 dB—achieved by altering the coil's casing to shift sounds outside the user's hearing range [67].

Coil ergonomics. TMS coils are larger than most types of nerve stimulation (e.g., EMS). While participants in our Study#2 wore our complete system, we believe that this heavyweight may negatively impact experiences of prolonged use and do not recommend these. Improving the coil's form factor is paramount for better wearability. One approach is altering coil geometries (e.g., single-loop coils reduce the size by half [21]). Another approach is using smaller coils designed for small mammals [88], which might still be enough for applications with weak haptics. With all these, there is a tradeoff between size/weight and depth of the stimulation [21].

Stimulator size. Current TMS stimulators are still large, e.g., ours measures 46×38×31 cm. This is because, to produce strong magnetic fields, the capacitor arrays require large power (4600 W at peak—approximately the energy intake of two hairdryers). At the current stage, we recommend TMS tethered to the stimulator, where the user might be free to move around, but limited to the range of the cable. Despite this, advances in engineering are likely to improve this. For instance, Sauvage et al. designed a compact TMS (11×27×29 cm) at 9 kg, which operates on a small 24 V DC power supply [16] and exhibits an output of 700 mT at 1 Hz (i.e., 70% of our stimulator's maximum output).

Alternative mechanical designs. We do not think of our head-worn implementation as the only way to realize source-haptics using TMS. To minimize weight, researchers might explore mounting the coil and the actuation system to the user's chair (e.g., desktop/sited applications) or suspending them via the ceiling (e.g., similar to early VR setups that were heavy, or large free-moving VR arenas). Alternatively, if the stimulation points are predefined for a given application, one could replace the robotic actuators with a fixed mount. Particularly, for single-point stimulation, a coil on a helmet could reduce weight [4]. For multi-point stimulation, a helmet with multiple fixed coils might also be beneficial [59]. All these non-motorized approaches also eliminate the latency associated with our approach's mechanical actuation of the coil. However, this comes at the cost of stimulation resolution, which is limited by the coil's size (e.g., 5 cm steps in [59] vs. our <8.5 mm steps via our actuators).

Limited sensations. While we confirmed that our approach can create a total of 15 haptic sensations including both force & touch, it still has limitations. For instance, the spatial resolution of haptic feedback via TMS is influenced by the size of the coil's focal point (e.g., ~1 cm radius with the butterfly coil we used [91]). While this can be smaller than ~5 mm by optimizing the coil geometry [33], one has to note that a smaller focal point is a tradeoff to the stimulation depth [21]. This poses challenges in rendering focused tactile cues in small skin areas, e.g., multiple tactile points on the fingerpad. At this stage, this is not possible with existing non-invasive stimulation techniques such as TMS (and, instead, necessitates turning to invasive intracortical stimulation [24]). However, it is important to note that the upper bound of TMS' spatial resolution is yet to be fully understood (see *8.2 Stimuli design and understanding*). Additionally, by limiting the stimulation duration (see *3.3 Safety*), our force sensations are impact-like (i.e., applied for a short duration) and not sustained forces. Also, as previously discussed, our touch sensations are less prominent than forces due to the difficulties in stimulating somatosensory neurons, compared to motor neurons.

8.2 Roadmap for the Future of Interactive TMS

Now that we have discussed the challenges brought by our specific implementation using TMS, we turn our attention back to the wider concept of a centralized haptic actuator worn by the user (i.e., a source-effector).

Closing the loop. One possible reason why we observed some of our limitations (e.g., fewer points for touch sensations, or even less strength for touch than forces) might be related to the lack of a closed-loop system. In other words, during calibration, it is easy to accurately determine if a force occurred (i.e., it causes a visible contraction of a muscle) but the same cannot be said for touch. One way that future researchers might tackle this is by attempting to close the loop on the stimulation. This might be done by first scanning participants via MRI to obtain a more precise map of regions that should be stimulated for this *particular* participant [69].

Stimuli design and understanding. While our system can create 15 distinct haptic sensations, this observation is specific to our current actuation resolution (8.5 mm). We hope that our findings facilitate exploration of the upper bound of how many different points across the body TMS can deliver haptics. Possible strategies for this include defining finer grids for coil positioning or implementing the aforementioned MRI-based approach to accurately identify cortical regions. Moreover, broadening the range of haptic sensations—such as different textures or even pressure—is also a promising avenue for future research. One way to approach this is to explore different TMS pulse parameters (e.g., pulse width, frequency, and waveform [58]) and evaluate elicited sensations through psychophysics studies, akin to methods employed in the domain of surface electrical stimulation [2].

Beyond TMS. Finally, we hope our work inspires new implementations of this concept of a source-effector. One promising avenue is via the aforementioned transcranial ultrasound stimulation—despite its still nascent status, it might offer some avenue to mitigate the size of the TMS coils. However, its accuracy & limitations are still being understood [44, 98].

9 CONCLUSION

We proposed, implemented & evaluated a novel concept for haptics in which one *centralized* on-body haptic actuator renders haptic effects on multiple body parts—we called this a haptic source-effector. We implement it by leveraging transcranial magnetic stimulation (TMS). We can render touch/force-feedback in hands, arms, legs, feet, and jaw—without needing to instrument these with individual actuators—which we validated in our first user study. In the source-effector, a single magnetic coil moves mechanically across the scalp. For instance, if the user is meant to feel haptics in their hand, the coil is moved and stimulates the area of their sensorimotor cortex where hand sensations are processed. In our second user study, we probed into participants' experiences while using our haptic display in an interactive VR experience.

Finally, as a first implementation of TMS-based haptics, we thoroughly discussed its limitations and proposed a roadmap to further its use in interactive contexts.

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options for remote participation. While some authors have chosen to present their work in person or bring its physical prototype to the CHI community, they have done so with compassion towards Native Hawaiians and with a heavy heart. We urge that the ACM's process for conference selection should more carefully consider the impact our conferences have on local communities. We especially want to acknowledge Prof. Josiah Hester, a Kānaka Maoli Professor in Computing, who organized comprehensive resources that educated us about the negative impacts of over-tourism and climate degradation in Hawaii[2]. Finally, the decision of some authors to participate in this conference does not represent the views of other members of our lab, who have chosen not to engage with this edition of the CHI conference due to its impact on Native Hawaiians.

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