Interactive Benefits from Switching Electrical to Magnetic Muscle Stimulation

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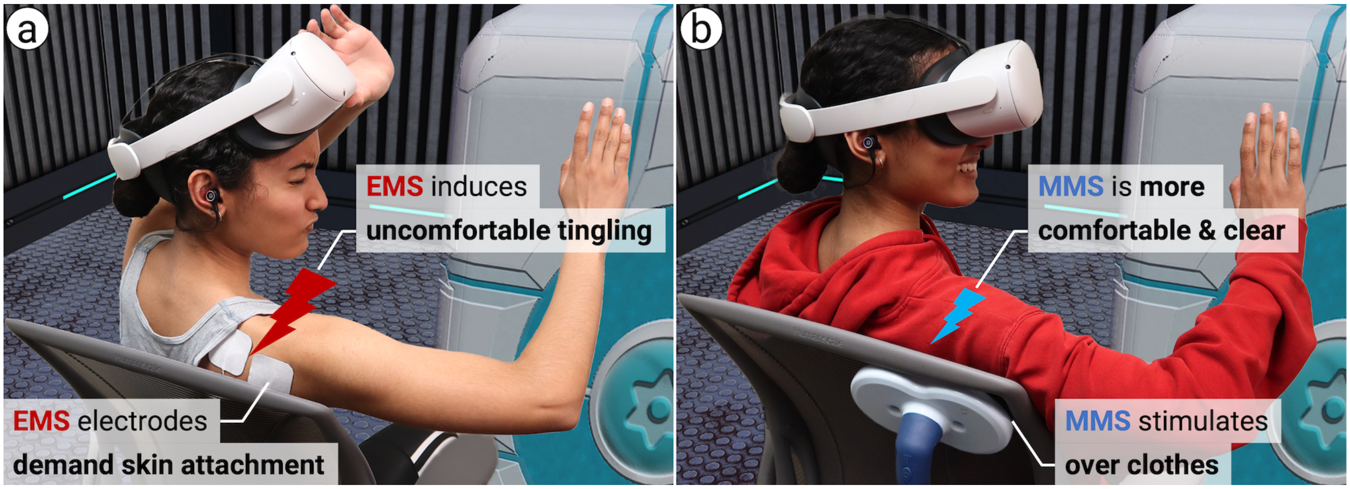

Figure 1. We examine the benefits of switching from electrical (EMS) to magnetic muscle stimulation (MMS). While much ink has been spilled about the advantages of EMS, not much work has investigated circumventing its key limitations: (a) electrical impulses cause an uncomfortable "tingling" sensation; EMS relies on pre-gelled electrodes, which require direct contact with the user's skin, and dry up quickly. To tackle these limitations, we study (b) force-feedback based on magnetic muscle stimulation, which we found to reduce uncomfortable tingling and enable stimulation over the clothes (VR scene replicated from [42] to contrast EMS and MMS).

ABSTRACT

Electrical muscle stimulation (EMS) became a popular method for force-feedback without mechanical-actuators. While much has been written about the advantages of EMS, not much work has investigated circumventing its key limitations: (1) as impulses traverse the skin, they cause an uncomfortable "tingling"; (2) impulses are delivered via gelled-electrodes, which not only require direct skin contact (must be worn under clothes); but, also (3) dry up after a few hours. To tackle these, we explore switching from electrical to magnetic muscle stimulation (MMS), via electromagnetic fields generated by coils. The first advantage is that MMS coils do not require direct skin contact and can actuate up to 5 cm away (Study#1)—this enables applications not possible with EMS, such as stimulation over the clothes and without ever replacing electrodes. Second, and more important, MMS results in ~50 % less discomfort caused by tingling than EMS (Study#2). We found that reducing this tingling discomfort has two downstream effects for interactive systems: (1) participants rated MMS force-feedback as more realistic than that of EMS (Study#3); and (2) participants could more accurately perceive the pose actuated by the interactive system (Study#4). Finally, we demonstrated applications where our proposed switch from EMS to MMS improves user experience, including for VR feedback, gaming, and pose-control.

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Keywords
Magnetic Stimulation, Muscles, Force Feedback, Haptics.

INTRODUCTION

Stimulating a user's muscles using electrical currents has become a popular method for achieving force-feedback in interactive experiences without requiring mechanical actuators. Over the last decade, this technique, known as electrical muscle stimulation (EMS), has revitalized the use of force-feedback in new contexts due to its portability.

However, while much has been written about the advantages of EMS as an interface capable of actuating the user's body, not much rigorous work has proposed technical alternatives that address most of its key limitations. While some work has been done on improving the accuracy of movements induced by means of EMS recently [24, 25, 54, 68], other key factors that drastically affect the user's experience have been left unturned. We identify outstanding and unsolved limitations of EMS and trace their root cause to the EMS' need for *electrodes*. We summarize the three most important of the five issues we analyzed: **(1) EMS induces an uncomfortable tingling sensation:** in conventional EMS, before an electrical impulse can stimulate the muscle fibers (which contract to generate the desired effect), it conducts via an electrode and traverses skin receptors, generating an unwanted and uncomfortable tactile sensation often described as “tingling” [29, 55, 58], or “buzzing” [37]; **(2) EMS must be worn under clothes:** users need to attach the interface on exposed skin or under their clothes (i.e., this is why most EMS interfaces depict users with rolled-up sleeves [9, 41, 53] or even short pants [23, 57])—this prevents this type of actuation technique to be used in more walk-up scenarios, in which there is no time to attach interfaces under clothes. **(3) EMS electrodes dry up:** conventional EMS utilizes *pre-gelled* electrodes (already meant to minimize the tingling), but these electrodes dry up over time and typically are only good for a few hours.

To tackle these and other limitations, we explore switching from electrical to **magnetic** muscle stimulation (MMS), which uses electromagnetic fields generated by coils instead of electrical impulses via electrodes (Figure 1). The first key advantage is that MMS coils do not require direct contact with the user’s skin and, unlike the electrodes of EMS, can actuate a muscle and provide force-feedback up to 5 cm away (as validated in our Study#1). This is transformative as it enables applications not possible with EMS, such as muscle stimulation over clothes or through a furniture piece, or applications that actuate users in a walk-up setting without needing to replace sticky-pad electrodes.

Second, and more importantly, we found that force-feeback using MMS exhibits ~50% less skin-tingling sensation than that of EMS (as validated in our Study#2). Critically, we found that reducing this uncomfortable tingling has two key downstream effects for interactive systems: (1) users were able to more accurately perceive the pose of their body when actuated by the interactive system (as validated in our Study#3); and, (2) users rated MMS force-feedback as more realistic than that of EMS (as validated in our Study#4).

In light of these benefits, we present the first set of interactive MMS applications, exemplifying cases previously difficult to realize via EMS. We hope these examples will inspire researchers to extend MMS to new interactive domains.

Finally, it is important to note that we do not consider MMS as a way to completely replace existing EMS applications; rather, we view it as a new option for force-feedback stimulation that enables muscle actuation in interactive contexts where EMS tends to fail, such as walk-up-use interfaces (e.g., game arcades, museums, public kiosks, etc.).

BACKGROUND & RELATED WORK

Our work is built on electrical muscle stimulation (EMS) and magnetic stimulation. First, we analyze EMS’ limitations. Then, we discuss the principles of magnetic stimulation that offer a promise towards addressing EMS’ shortcomings.

Electrical Muscle Stimulation

While force-feedback is useful in many interactive experiences by directly guiding the user’s body or adding haptic realism in an immersive experience, such devices typically require mechanical actuators that are heavy, thus encumbering the user’s movement. Electrical muscle stimulation (EMS) is a more recent alternative to this long-standing challenge of actuating limbs. EMS uses electrodes attached to the skin near or atop a muscle. Passing a current through those electrodes causes the muscle fibers to contract and, in turn, actuate the user’s muscle [37]. While EMS originated in the field of medical rehabilitation [75], many see it as a promising interface to miniaturize force-feedback today [43]. As such, EMS has been adopted in a variety of force-feedback applications: adding realism to immersive experiences [24, 38, 42]; guiding the user’s limb movement [40, 57, 69, 70]; conveying information via proprioceptive sensations for eyes-free interactions [41, 53]; or even enhancing the user’s abilities [29, 30, 62].

Our Analysis of the Limitations of EMS

While EMS has been used as an alternative to mechanical force-feedback devices for its attractive form factor, researchers have rarely investigated its limitations, with most of the work focusing only on improving the lack of accuracy [24, 25, 54, 68] or agency [29], but not improving the lack of comfort, its reliance on electrodes, etc. In this section, we shed light on five additional limitations of EMS.

1. EMS induces an uncomfortable tingling sensation. In conventional EMS, electrical impulses must travel through electrodes attached to the user's skin to reach deep into their muscles. This presents a significant limitation because, before the electrical impulse can stimulate muscle fibers (which ultimately contract to generate the desired effect), it inevitably traverses skin receptors [28], producing an unwanted and uncomfortable tactile sensation often described as "tingling" [29, 43, 55, 58], or “buzzing” [37]. This has been known since the early days of EMS as an interface: “Triggering of [skin] receptors might also have caused the feelings of pain or *buzzing* (…) sometimes noticed by the users” as put by Kruijff et al. [37] in their first seminal study on the interactive use of EMS. The authors also found that "two users reacted negatively (...) and had the most problems with user comfort" [37]. It is known that this is not just a limitation of EMS but of most electrical-based stimulation techniques, in the seminal work of Francini et al. in 1979, they describe that as the intensity of skin-based electrical stimulation increases, it “evokes three different sensations with consecutive sensory thresholds: tactile sensation, tingling, and pain” [14, 72]. As noted by Kruijff et al.’s participants, we argue this is a major limitation to users’ experiences that warrants novel solutions. As we will find later, via our Study#2, switching from electrical to magnetic stimulation dramatically reduces tingling by 50 %.

2. EMS demands exposed skin. EMS requires that the electrodes are attached directly to the user’s skin. This implies that users need to expose their skin to the interface or wear the interface under their own clothes—this is why most EMS interfaces depict their users with rolled-up sleeves [9, 41, 53] or even short pants [23, 57]. This needs to direct contact with the user’s skin prevents this type of actuation technique to be used in more walk-up interfaces [63], in which there is no time to attach interfaces under clothes.

3. EMS electrodes dry up. Moreover, these electrodes are usually *pre-gelled* to ensure the comfort of the stimulation as their impedance matches that of the user's skin (i.e., they are already designed to minimize the tingling). As Tachi, Kajimoto, and Kanno put it, "[the gel is a] means for alleviating a sensation experienced by the wearer as a result of the stimulation (…) The conductive gel layer has a resistance value equivalent to that of the [outermost layer] of the skin" [67]. Unfortunately, like with any hydrogel, these pre-gelled electrodes dry up over time and are typically only good for a few hours [3]. As Tamaki et al. reported in their seminal paper, "dry (…) pads cause pain when the contact area is small" [69]. Alternatively, it is also possible to deliver the stimulation via dry electrodes [58], or even integrate them into garments to improve wearability [34, 52]. However, dry electrodes are not optimized to match the skin impedance [59] and will elicit more uncomfortable tingling or even pain [69]. As such, most interactive EMS is limited to gel-based electrodes.

4. Electrodes are adhesives = no quick detachment. These gel-based electrodes are essentially adhesives, making it difficult to detach them; we preliminary measured that a fresh electrode from *Syrtenty* required 4.2 N to detach from the skin. This makes it challenging to envision EMS in a walk-up-use interface, in which the user rapidly experiences force-feedback and leaves after (e.g., EMS in a public space).

5. Electrodes are often limited to a per-user basis. Lastly, as the user's dead skin cells and other organisms adhere to the electrodes upon the detachment, re-using the same electrodes across users raises hygienic concerns. Thus, most EMS demonstrations are limited to a per-user basis. While EMS installations for the public have been performed at conferences and museums, they typically require new electrodes per user, or a disclaimer about the shared-electrode hygiene (e.g., the EMS artwork *ad infinitum* [2]).

Showcasing EMS' limitations via case studies. Let us exemplify these limitations in interactive systems that use EMS. For instance, Lopes et al's "VR wall" (Figure 2a), the user feels the desired force but, unfortunately, is accompanied by an uncomfortable tingling that distracts them from the experience, as one of their participants put it: "EMS tingles and hence reveals the source of the force" [42]—this depicts how our first limitation (tingling) decreases the effectiveness of this work (reduced realism). Moreover, the users of these "VR walls" wore tank-top shirts allowing experimenters to reach the skin on the shoulder muscles and attach the electrodes—this depicts our second limitation (no use over clothes). Extending EMS to walk-up scenarios reveals even more challenges: public EMS installations such as the artwork "*ad infinitum*" (Figure 2b), require that an audience member first rolls-up their sleeves, otherwise electrodes will not attach to their muscles—this, again, depicts how EMS limitations prevent walk-up use. Moreover, EMS demonstrations and art installations require monitoring from a technician, who regularly replaces electrodes as they dry up and lose conductivity—this, again, limits the applicability of EMS. Also, in such installations, audiences might be informed via disclaimers if the electrodes are used across multiple users—this, again, illustrates a limitation with the electrode's need for direct contact (hygiene in public use). Finally, because of the adhesive nature of electrodes, these need to be detached with a considerable amount of force, typically a technician or, in the case of the aforementioned artwork, a motorized system of levers—this further emphasizes how the reliance on electrodes prevents EMS from being more widely applied to contexts, such as art installations, products, or public spaces that might require "walk-up use" interactions.

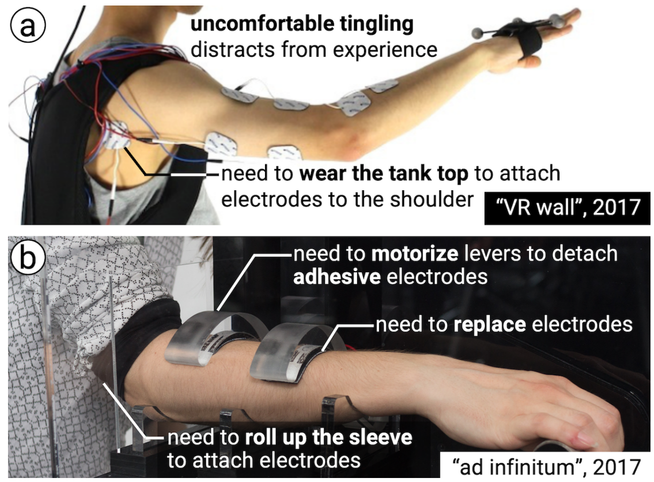

Figure 2. Two use-cases to exemplify how the electrodes in EMS bring five additional limitations. (Figures from [42] and [2]).

Magnetic Stimulation

Similar to electrical stimulation, magnetic stimulation is a technique that originated from medicine/neuroscience [18]. Unlike its electrical counterpart, magnetic stimulators do not directly provide an electrical current to the user's body; instead, a magnetic stimulator uses a coil to produce a changing magnetic field. Because this magnetic field is oscillating rapidly, it creates an electrical current (known as *eddy currents*). The difference is that this current originates in a spatial area around the coil by a magnetic field, not by electrodes that produce high current density at their surface. As such, this current appears inside the target body region and does not require conduction from the source to the target by means of cables or electrodes—it is magnetic [21].

Use in brain stimulation. The primary use of magnetic stimulation is for the most popular technique for non-invasive brain stimulation as it directly stimulates neurons under the skull [21]. First confirmed by Barker et al. in 1985 [4] and known as *transcranial magnetic stimulation* (TMS). It uses coils placed atop the patient's skull to stimulate the brain neurons without needing to operate (or open-up parts of) the skull. It is frequently used as a tool to map brain functions to cortical areas, e.g., motor control [74], vision [6], language processing [13], working memory [50], and more. TMS has also been used as therapy for improving motor function in Parkinson's patients [39], reducing epileptic seizures [15], and as a depression treatment [19].

Use in rehabilitation. While magnetic stimulation finds its primary use as TMS, stimulating muscles via coils atop—known for repetitive peripheral magnetic stimulation (rPMS) [61]—has also been applied for muscle rehabilitation [5, 49]. Szecsi et al. reported that rPMS induced less pain compared to EMS during leg rehabilitation of patients with paresis [66]—a muscular weakness caused typically by nerve damage or neurological conditions. Abe et al. also observed the pain reduction in the wrist extensor muscle of healthy subjects [1]. In light of this, neuroscientists have pursued this stimulation for various clinical applications, including leg rehabilitation [65], shoulder rehabilitation [16], finger rehabilitation [64], or even swallowing rehabilitation for post-stroke patients [47, 48]. Building on prior efforts in rehabilitation, our work demonstrates the *potential of MMS in interactive systems*. We analyze what new types of interactions are possible when we remove EMS electrodes, as well as characterize the reduction of tingling sensation for healthy participants (not explored in prior work). We found that this reduction in tingling has two downstream implications for interactive systems: (1) clearer proprioceptive (i.e., pose) sensation; and (2) haptic realism of force-feedback compared to EMS.

Use in interactive systems. Although magnetic stimulation has gained recognition in rehabilitation, its presence in human-computer interaction remains limited. To our knowledge, the sole instance of this is by Kim et al., who used magnetic fields to stimulate hand nerves for *tactile sensations* [32, 33]—not muscles. Our work explores the benefits that interactive systems can reap by switching from electrical to magnetic muscle stimulation.

CONTRIBUTION, BENEFITS, AND LIMITATIONS

Our key contribution is that we propose that many interactive systems could benefit from a switch from electrical to magnetic muscle stimulation (MMS). We found, by means of four user studies, four benefits of MMS over EMS: (1) MMS does not require electrodes or physical contact with the skin and can stimulate over the user's clothing—eliminating the issues with electrodes such as their adhesiveness and need for replacement; (2) MMS reduces uncomfortable tingling sensations by 50%; (3) MMS provides higher perceived realism of force-feedback in VR; and (4) MMS enables the user to more clearly perceive poses that were actuated by the stimulation.

MMS is not without limitations, which we believe are important to discuss in light of this being the first exploration of MMS in interactive systems. First, as with any electrical stimulation, MMS requires calibration (e.g., intensity and placement, just as with EMS). Second, the coil generates a loud sound, while EMS is soundless. Third, a coil is heavier than electrodes (1.1 kg), which leads us to mostly recommend MMS for stationary applications as depicted in most of our examples; however, it is worth noting that despite wearing the coil's full weight, participants in our study preferred MMS to EMS for the realism of VR force-feedback. Fourth, the size and power consumption of the stimulator do not rival the small form factor of EMS (i.e., we used a stationary medical-grade magnetic stimulator, powered from AC outlet, not battery). Later, we discuss these limitations in detail and suggest potential directions for each.

Finally, we reflect on the nature of our proposal for using magnetic muscle stimulation as force-feedback. This technique is not new—it originates from neuroscience as a method to stimulate the brain. However, the value of our proposal lies in its *translation* as a tool for force-feeback, coupled with our investigation of the benefits it brings to human computer interaction. In fact, similar translational efforts have previously advanced our field. For instance, the *PossessedHand* [69] translated a 50-year-old medical tool (i.e., electrical muscle stimulation) into our field, leading to a growth in force-feedback research. Likewise, our efforts are the first to translate magnetic muscle stimulation from the medical realm into new knowledge for interactive systems.

OVERVIEW OF STUDIES

In the subsequent sections, we present a series of four user studies designed to explore the interactive advantages resulting from the transition from EMS to MMS. The following is an overview of the critical insights gleaned from these investigations: in **Study#1** we found that MMS stimulated participants' muscles up to 5 cm away; in **Study#2** we found that MMS reduced the tingling sensation by about 50% compared to EMS; in **Study#3** we found that MMS rendered more realistic force-feedback in VR than EMS; and, in **Study#4** we found that participants could better recognize the pose output of the MMS actuation than of EMS. All four studies were approved by our Institution Review Board (IRB21-0055).

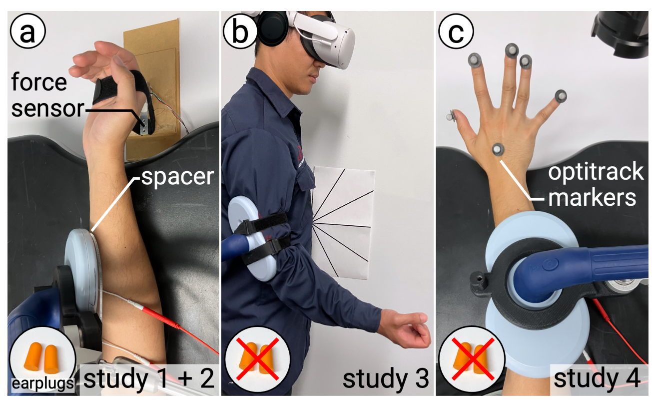

Figure 3. Overview of our study setups. In Study#1, we had an additional spacer to adjust the coil distance (e.g., 20 mm), and the EMS electrodes were not present as this study focused solely on MMS. In all EMS conditions, we used 1.5-inch pre-gelled electrodes and biphasic stimulation, a method commonly employed in previous work (e.g., [42]), to mitigate skin tingling.

USER STUDY #1: HOW FAR MMS CAN STIMULATE?

Our first study characterized the relationship between the force generated by MMS and the coil's distance to the skin.

Participants. We recruited ten participants from our institution (3 identified as female, 6 male, 1 as non-binary; 23.8±2.3 years old; all right-handed). None had any form of motor impairments. Each study session took ~10 minutes.

Apparatus. Participants sat with their dominant arm resting on a tabletop (Figure 3a). This provided a similar setup to prior work that characterized forces generated by EMS [44]. We used a medically compliant magnetic stimulator (Magstim Super Rapid[2]) with a butterfly coil (Magstim D70[2]) connected to it. We used five different spacers (20, 30, 40, 50, and 60 mm) to control the distance. The coil was placed above the participant's forearm muscle (flexor carpi radialis) over the spacer with the support of an armrest. The participants wore earplugs. We also attached a 3 mm acrylic plate to the MMS coil to approximate the thickness of clothes. We used a 5-kg load cell with a HX711 amplifier sampled by an Arduino to measure the force.

Procedure. We calibrated the MMS so that the participants' wrist flexor was actuated. Then, we set the stimulation to a one-second duration, 1200 mT intensity (recommended maximum intensity for this stimulator [45]), at 20 Hz (as in [64]), while ensuring that the stimulation was pain-free for participants at the 20 mm distance. Each participant completed 10 trials (2 repetitions for 5 distances), resulting in a total stimulation duration of ~10 sec. Trials began at the 20 mm condition, incrementally increased by 10 mm, up to 60 mm; then, decreased step-by-step back to 20 mm. In each trial, we applied magnetic muscle stimulation and logged the maximum force value measured during stimulation.

Results. As shown in Figure 4, the amount of generated force via MMS measured the averages of 2507 g (M=24.6 N; SD=13.1) at 20 mm, 1514 g (M=14.8 N; SD=10.6) at 30 mm, 588 g (M=5.8 N; SD=7.4) at 40 mm, 92 g (M=0.9 N; SD=1.8) at 50 mm, and 4 g (M=0.04 N; SD=0.08) at 60 mm. As expected the decay of a magnetic field is sharp, yet we observed that MMS still produced ~1N of force at 50 mm, which can trigger hand movement [69]. As such, we deemed this as the maximum distance for force-feedback generation.

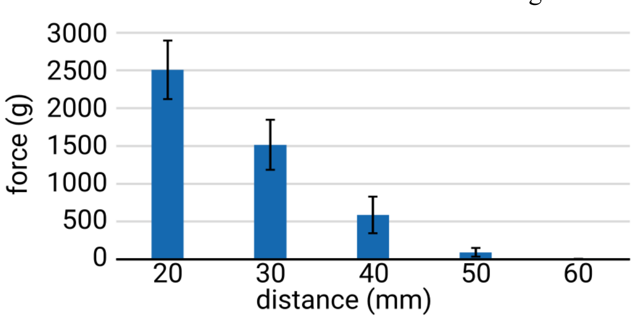

Figure 4. The force-distance relationship found in Study 1.

USER STUDY #2: REDUCING TINGLING VIA MMS

Our second user study characterized the comparison of MMS and EMS regarding the skin-tingling sensation. Although prior research in the rehabilitation field has shown that MMS generates less pain in the leg [66] or wrist extensor [1] muscles, our study is the first in focusing to evaluate the tingling sensation still arises during pain-free operations—the most common condition for such interactive systems. Our hypothesis was that MMS would induce less tingling than EMS. As such, our study design is based on these prior works [1, 66].

Participants. We recruited the same ten participants from Study#1. Each study session took about 30 minutes and the participants received $10 USD as compensation.

Conditions. Participants experienced muscle actuation of their wrists in two conditions: **MMS** or **EMS**. We chose to stimulate the wrist flexor muscle since it is one of the most popular targets for EMS, which enables us to understand how MMS might facilitate grasping/touching-type of interactions.

Apparatus. We used the same apparatus as in our previous study (Figure 3a) with the addition of a medically-compliant EMS stimulator (HASOMED Rehamove3). For the MMS condition, the coil was kept 3 mm away from the skin via the same spacer from Study#1, which replicates the thickness of clothing.

Calibration. We first calibrated the maximum intensities of MMS and EMS that ensured pain-free operation while logging their resulting forces in the same way as Study#1. For each, starting from the minimum, we applied one second of stimulation and increased its intensity by the unit amount. Both stimulations were at 30 Hz—considered to be a lower bound for EMS to reliably contract muscles [12]. We made the increase upon the participant's agreement so that they were pain-free; otherwise, we defined the intensity before the increase to be an upper bound. Once we reached the upper bound, we logged the stimulation intensity and the generated force at that level. After calibrating all participants, we found an average intensity of 526 mT (SD=148) for MMS, and 9.5 mA (SD=2.6) for EMS.

MMS-EMS equalization on the resulting force. As MMS and EMS operate on different stimulation modalities (i.e., direct current and electromagnetism), the MMS stimulator controls the stimulation intensity via the strength of magnetic fields (with a unit of 12 mT), while the EMS stimulator controls the current amount (with a unit of 1mA). As such, after the calibration, we had to equalize the MMS intensities to those of EMS on the amounts of resulting force in order to compare them for the tingling sensations. The earlier calibration informed which of the two had the larger upper-bound force. Since the force range based on the smaller upper bound is always included in that of the larger one, we used 25%, 50%, and 75% of the smaller upper bound as target force levels. Then, for each stimulation technique, we calibrated its intensity so that the output force was closest to the target force amounts using the staircase method.

Procedure. In each trial, participants rated and compared the MMS and EMS stimuli at the calibrated intensities. After each stimulation, the participant rated their perceived amount of tingling on a 7-point Likert scale (1: least, 7: most). Then, only after feeling both stimuli, they rated the tingling amount for each using a visual-analog scale, i.e., which stimulation tingled more and by how much. We repeated this process for six trials (three force levels × two repetitions). Note that the presentation orders of the stimuli and the force levels were randomized.

Results. Firstly, through our calibration, we found, at their maximum intensities, MMS produced more force (M=23.9 N; SD=12.1) than EMS (M=13.5 N; SD=12.3), which was confirmed using a paired t-test ($p<0.01$). More importantly, the participants rated MMS' tingling less than that of EMS as depicted in Figure 5a. We conducted a two-way repeated measures ANOVA and found the main effects for stimulation techniques ($F(1, 9)=14{,}71$, $p=0.004$, $\eta_p^2=0.62$), force levels ($F(2, 18)=9.42$, $p=0.002$, $\eta_p^2=0.51$), and interaction ($F(2, 18)=8.30$, $p=0.003$, $\eta_p^2=0.48$). As we found interaction, we performed a post-hoc test with Bonferroni corrections on the main effect of stimulation techniques and found significant differences for the simple main effect in all force levels, which showed that MMS was less tingling than EMS: 25% ($p<0.05$), 50% ($p<0.05$); and 75% ($p<0.05$). To analyze visual-analog scale results, we followed prior work [51] and calculated the quotients of MMS' and EMS' visual-analog scale scores, i.e., the portion of EMS tingling that corresponds to that of MMS: M=58.4 % (SD=46.7) at 25 %; 44.4 % (SD=43.4) at 50 %; and 50.5 % (SD=55.8) at 75 % (Figure 5b). These results overall suggest that MMS reduced the tingling sensation by about 50% compared to EMS.

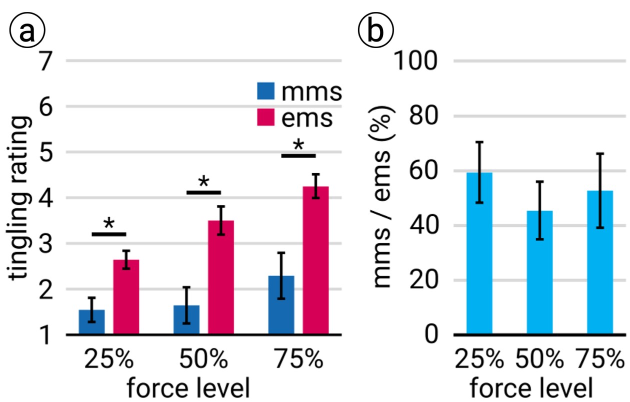

Figure 5. The Likert-scale rating (a) and the ratio (mms/ems) of the perceived amounts of skin-tingling sensations (b). For both tingling rating and tingling ratio, *less depicts a superior result.*

USER STUDY #3: MMS VS. EMS ON REALISM

Our third user study explored how MMS' reduction in tingling might lead to an increase in realism during force-feedback with tasks inspired by [42]. Our hypothesis was that a VR application making use of MMS-based force-feedback would be perceived as more realistic than the same application using EMS-based force-feedback.

Participants. We recruited 12 participants (5 identified as female, 7 as male; 21.7 ±2.1 years old, all right-handed), of which three were recruited from the pool of our first study. The study took ~30 min, including ~15 mins inside of the VR experiences. Participants received $10 USD compensation.

Tasks. Participants performed two VR tasks (depicted later in Figure 11) using their dominant arm: **box-task**: pushing three cargo boxes aside; **lever-task:** turning on an electrical generator by pulling a lever three times. During the box-task, we stimulated the bicep muscle to simulate the resistive force experienced when pushing a heavy object (as in [42]). In the lever-task, we stimulated the participant's tricep muscle to emulate the resistance of the lever (as in [42]).

Apparatus. Participants stood in a 1.5 × 1.5 m open space, wearing a Meta Quest 2 headset (Figure 3b). Participants wore either an MMS coil or EMS electrodes connected to their respective stimulators. While the EMS electrodes were attached directly to the skin after rolling up participants' sleeves, the MMS coil was placed over clothing and secured using velcro straps. Participants also wore headphones to provide sound effects, such as the box dragging on the floor or the mechanical detents of the lever, without the use of earplugs or white noise to mask any acoustic noise from the MMS.

Procedure. Prior to actual trials, we calibrated MMS and EMS so that both actuated the participant's bicep and tricep muscles by 30 degrees over one second of stimulation (Figure 3b), with the zero-degree angle defined where the participant's forearm was parallel to the ground and the upper arm was perpendicular to the ground. After the calibration, each participant performed four trials (2 conditions × 2 tasks), with the presentation order of the simulation techniques counter-balanced. After each trial, participants were asked to rate haptic realism using a 7-point Likert scale. After completing both tasks in one condition, participants also rated the overall haptic realism of that condition. The procedure was then repeated for the remaining stimulation condition. At the end of the study session, we collected preferred conditions and open-ended feedback by asking participants about their experiences.

Results. The participants rated MMS' force-feedback more realistic than that of EMS (i.e., box, lever, and overall) as depicted in Figure 6. We conducted a two-way repeated measures ANOVA and found the main effect for stimulation condition ($F(1, 11)=13.5$, $p=0.004$, $\eta_p^2=0.55$). We did not find main effects for tasks ($F(2, 22)=3.5$, $p=0.08$, Greenhouse Geisser corrected for sphericity, $\eta_p^2=0.24$) nor interaction ($F(2, 22)=0.24$, $p=0.78$, $\eta_p^2=0.02$).

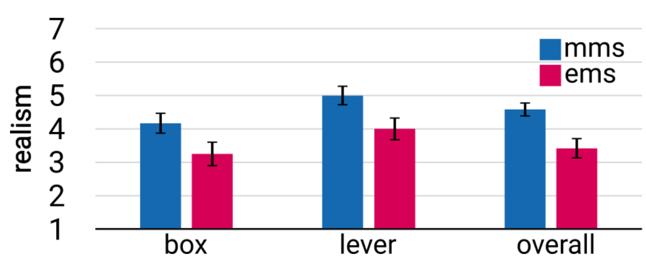

Figure 6. Participants' VR realism rating for MMS and EMS.

Qualitative feedback. All 12 participants preferred MMS to EMS. Eleven out of the 12 participants attributed their preference to MMS from having "less tingling", "numbing", or "sharp", "strong skin sensations" or "jerky vibrations". For example, P2 stated "[MMS] was very comfortable. There was no tingling" (P2), while P6 stated "[MMS's] tingling is not as intense as electrodes". P9 stated "EMS felt a little bit jerky vibrating" (P9). P12 stated "[MMS's] pulse feels like smooth" (P12). Additionally, four participants reported that the tingling sensation induced by EMS decreased the realism of the experience, with P3 stating, "[EMS's] sharp, painful stimulation aspects hold me away from the realism". The only participant who did not directly mention a difference in tingling still stated "EMS makes a more unwanted movement like a vibration, MMS was much more clean[er]" (P8).

USER STUDY #4: CLARITY OF THE ACTUATED POSE

In our fourth user study, we continued examining how the MMS' reduced tingling might provide additional interactive benefits. In particular, we examined how it might let participants better recognize their body's pose when actuated by MMS compared to EMS. This leads to a benefit in applications where the user's body poses act as values output by interactive systems, e.g., gestural IO or proprioceptive interactions [41]—a user can perceive the output more accurately. To this end, we evaluated how well participants could *recreate* their hand pose after having been stimulated by MMS or EMS—using the study design from [41]. Our hypothesis was that the participants would have smaller errors between the actuated and recreated poses in MMS.

Participants. We recruited 12 participants (2 identified as female, 9 as male, 1 as non-binary; 25.0±3.0 years old; all right-handed), of which five were recruited from our prior studies (two from Study#1 and three from Study#3). The study took ~30 min and participants received $10 USD.

Task. We used the EMS-pose task design from [41]: we stimulated the participant's wrist extensor using MMS or EMS. After the stimulation, we asked the participants to *voluntarily* recreate the pose induced by the stimulation. We chose this muscle as it has minimal risk of the fingers touching each other or the palm upon an actuation, which would introduce tactile sense as a confounding factor in task performance. We then evaluated the error between the actuated and recreated pose for each stimulation technique.

Apparatus. As depicted in Figure 3c, participants sat at a desk with their dominant hands resting on a desktop. We used the same stimulators as Study#1-3. An MMS coil and EMS electrodes were placed atop the wrist extensor muscle (extensor carpi radialis) with the support of an armrest. Throughout the trials, we blindfolded the participants in order to let them recognize the pose, solely relying on their proprioceptive sense, (same as [41]). The participants did not wear earplugs nor hear white noise since shutting off the acoustic noise of MMS could bias task performance in favor of MMS. Note that the noise of MMS is independent of the wrist pose so it was not effective as a cue for this task. For optical tracking, we used an Optitrack Flex 3 system, with a total of six markers attached to each of the fingernails and the back of the hand.

Procedure. Prior to the trials, we calibrated MMS and EMS so as to actuate the participant's wrist by 45 degrees (measured by the tracking system), following the same calibration protocol from Study#3. Each participant performed six trials (2 stimulation conditions × 3 repetitions) with the presentation order of the simulation techniques randomized. In each trial, after a random waiting period, the participant received either MMS or EMS, which was automatically shut off once their wrist angle had reached 45 degrees. We instructed the participant to memorize their hand pose right before it turned off. Then, participants waited five seconds and, at an audible tone, they recreated the previously sensed pose. To confirm their pose was finalized they pressed a key on a keyboard with their non-dominant hand. We calculated the total error between the marker positions recorded at the moment stimulation stopped and those recorded when the participant confirmed their pose.

Results. As shown in Figure 7, we found that participants had smaller total errors in recreating the pose rendered by MMS (M=18.8 cm; SD=6.2) than EMS (M=25.9 cm; SD=12.5) as confirmed by a paired t-test ($p<0.01$). We also observed a smaller mean error for the back of the hand for MMS (M=1.8 cm; SD=1.3) than EMS (M=2.3 cm; SD=1.5).

Figure 7. Total error in pose recreation with MMS and EMS.

APPLICATIONS

Now that we have confirmed the benefits obtained by transitioning from EMS to MMS, we showcase how these benefits improve EMS-based applications, or even enable applications that were previously challenging with EMS.

A Pose-Based I/O Interface (e.g., a video scrubber)

We demonstrate how MMS enables a new rendition of the I/O pose-control previously shown with EMS (e.g., [41]). The key is that, as found in our Study#4, MMS likely enables users to more clearly recognize the output of the interactive application as it actuates their pose. Figure 8 depicts how the user scrubs through a video they are watching using pose-control: (a,b) the user sitting on a couch rests their arm on the armrest that has an MMS coil inside; (c) the user activates the system by performing a pinching gesture; (d) our system immediately takes over and renders the current playback position of the video by actuating the user's wrist; and (e) now, by moving the wrist voluntarily left/right, the user scrubs the video (e.g., rewinds by moving their wrist to the left). When finished, the user makes the pinch gesture again to exit the interaction. Note that we purposefully drew an outline of the arm on the surface of the armrest to let the user better understand which area allows for stimulation (Figure 8a). While this is obviously optional and not always needed (e.g., our next applications do not use this method), it also lets users better align themselves on demand with the coil's location.

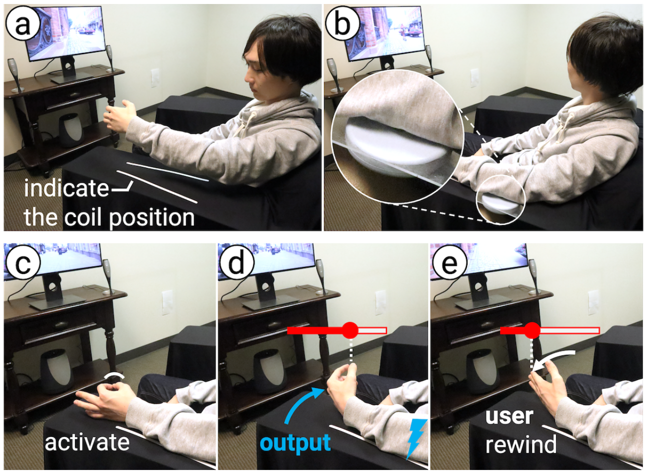

Figure 8. Our video-scrubbing tool based on MMS can extend EMS-based I/O interaction by improving the clarity of its output and installing the system into the furniture piece.

Envisioning Muscle Actuation in Public Spaces

This application envisions how MMS might enable applications previously challenging with EMS, namely deployment of muscle actuation in a publicly available interface (i.e., walk-up-use, quick interactions, many users). Figure 9 envisions the use of MMS-based force-feedback in a bus: (a) the passenger places their hand on a handrail but is not firmly holding it. However, (b) when the bus starts driving, an MMS coil is actuated, causing the passenger to involuntarily grab the handle, reminding them of this safety behavior. (c) Depicts how this finger flexion is achieved using a back-of-hand stimulation [68] since the coil is placed in the wall, parallel to the back of the hand muscles. (d) To detect acceleration and trigger the coil, our proof-of-concept implementation uses an IMU sensor.

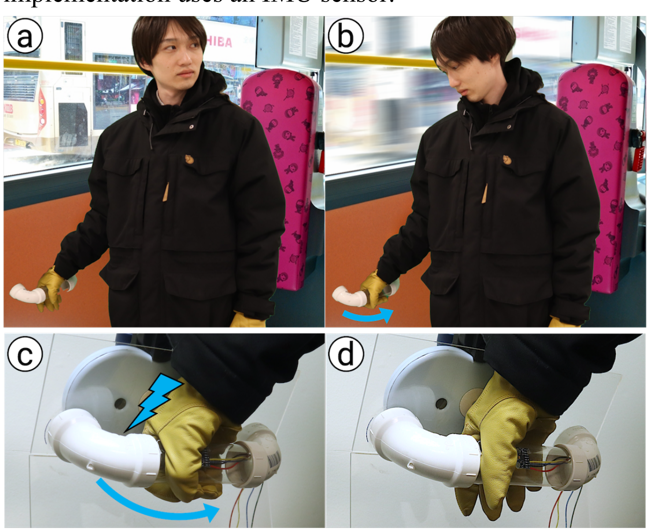

Figure 9. (a, b) Envisionment of MMS in a bus handle where its handle automatically actuates the passenger's grab when the bus starts/stops/shakes. (c, d) Proof-of-concept prototype that activates MMS based on IMU sensor data inside the handrail.

Stimulating the User's Back in a Driving Simulator

While EMS has been explored for force-feedback, very few systems provide force to a user's back [31]. This is likely due to the difficulty in attaching electrodes to the back. Figure 10 depicts a driving simulator where MMS enables force-feedback applied to the user's back without the need for any electrodes, instead, the coils are on the chair. As the user experiences inertia while the car turns left/right, in response, the corresponding MMS coil outputs stimuli to actuate the user's back muscles (latissimus dorsi) even through the fabric of the chair. Actuating this dorsal muscle causes the user's body to tilt. We use a second coil (Magstim AirFilm) and multiplex the connection to a single magnetic stimulator.

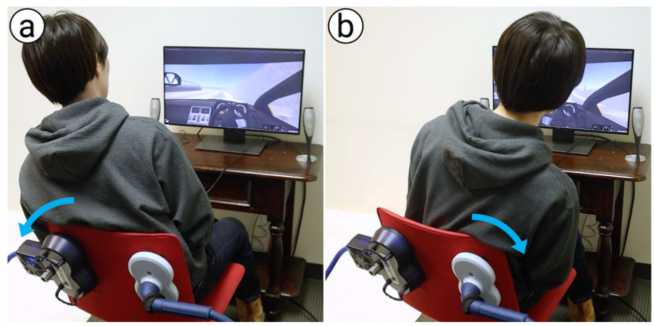

Figure 10. Muscle actuation through the fabric of the chair. As the car turns (a) left or (b) right, users feel force-feedback.

MMS as Wearable Force-Feedback

While we demonstrated stationary coils embedded in objects, it is also possible to have users wear coils over their clothing. We show this by replicating the EMS VR force-feedback application of [42], but *without* the need for the tank-top since MMS stimulates over clothing—this is the application used in our Study#3 and depicted in Figure 11: (a) when users push the cargo box they feel a resistive force; then, when users pull the lever to turn on the electrical generator, they feel resistance. While we recommend that most MMS applications use stationary coils, it is worth noting that participants from Study#3 all preferred this condition to EMS even after 15 minutes of wearing the heavy coil.

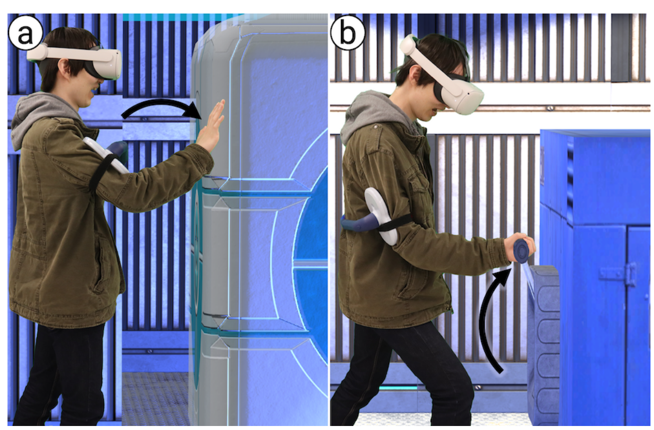

Figure 11. MMS for VR feedback (box replicated from [42]).

SOFTWARE IMPLEMENTATION

In our user studies and applications, we implemented the control of a medical-grade magnetic stimulator (Magstim Super Rapid[2]) using the *MagPy Python Toolbox* [46]. Our middleware routed serial communication to the stimulator and received commands from our Unity applications via Open Sound Control (OSC). Regarding tracking, we employed Meta Quest's hand/pose tracking for the VR and video-scrubbing applications. For the video-scrubbing application, the headset was mounted on a tripod located behind the couch (inspired by [22]). We made all the source codes and materials publicly available[1].

DISCUSSION ON LIMITATIONS & GUIDELINES

In this section, we note the limitations of current MMS stimulation common to most magnetic stimulators, in which we elaborate on potential directions to address them. Based on this, we further discuss guidelines for interactive MMS.

Current Hardware Limitations

Acoustic noise. Rapidly oscillating magnetic fields create coil vibrations due to magnetostriction, producing pressure waves that result in a clicking sound. In prior work, this acoustic noise was measured at ~65 dB (similar to the loudness of a human conversation) at the lower bound of stimulation intensity (~370 mT) that actuates the fingers [17, 36]. We also measured the noise using a decibel meter (AS824), positioned 50 cm away from the coil, while increasing the intensity to 540 mT (the average upper-bound intensity observed in Study#2's calibration). We observed a peak amplitude of 80.7 dB, which is similar to that of propeller-based haptic devices (e.g., 83 dB [27]). Consequently, it is advisable to reduce the level of perceived noise either by utilizing sound effects to mask the noise (as in our VR applications), or by implementing MMS in environments that are already noisy. Ultimately, addressing noise is required to enable MMS in applications where users are engaged in sound-sensitive activities (e.g., listening to music, etc.). Peterchev et al. demonstrated a coil prototype for brain stimulation that reduced noise by 19 dB, showing that engineering the coil casing can decrease noise by shifting its dominant frequency outside the human audible range [56]—as these authors state, further optimization of coils and pulse shapes could lead to greater noise reduction.

Coil form-factor. To produce magnetic fields, MMS coils are significantly larger than electrodes. The coil used in our work (Magstim D70[2]) measures 18×11×2 cm and weighs 1.95 kg with its 2 m cable. When worn by a user with the cable connected to the stimulator, its effective weight is 1.1 kg. While participants in our Study#3 preferred MMS to EMS even while wearing the coil, we believe that a 1.1 kg weight may negatively impact experiences in prolonged use and do not recommend it for most deployments of interactive MMS. Improving the coil form factor is paramount to enable more wearability. One approach is tweaking coil geometries. The butterfly-shaped coil we used consists of two loops, whereas a single-loop coil can reduce the size by about half [11]. One could even use a smaller coil designed for smaller mammals [71]. Although these alternative coil designs compromise the depth of the stimulation [11], they might still effectively reach most surface muscles.

Stimulator form-factor & power. MMS stimulators are much larger than EMS stimulators. For instance, the stimulator that energizes our coil (Magstim Super Rapid[2]) measures 46×38×31 cm and is typically used for stationary applications. This is mostly because MMS stimulators are comprised of an array of high-voltage capacitors and a power supply. To produce these magnetic fields, the capacitor arrays consume 4600 W at peak stimulation—approximately the energy required to drive two hairdryers. This is in stark contrast to EMS' low power consumption. As such, we currently recommend MMS as a tethered device. However, advances in engineering are likely to change this. Sauvage et al. designed a compact magnetic brain stimulator measuring 11×27×29 cm and weighing 9 kg, which operates on a small 24 V DC power supply [7]. This is capable of generating magnetic fields of 700 mT at 1 Hz. Since MMS typically requires less than 540 mT, it appears feasible to miniaturize the hardware and enable it to operate on a 24 V LiPo battery.

Coil-alignment. Much as with EMS, MMS requires the actuator to be aligned with the target muscle. Given the aforementioned size limitations with current MMS stimulators, we recommend placing the coil in strategic locations where the user's body will align naturally (e.g., embedding the coil in the seat of a chair or in the handle of a door). Obviously, when the coil is installed on an object, the target muscle needs to be within a certain area around the center of the coil for the stimulation to be effective. Based on our Study#1 results, we recommend the maximum distances between the coil and target muscles as follows: 3 cm for VR/gaming to render 10N~; and 4~5 cm for applications requiring less force (e.g., pose). This means that users cannot move away from the coil during the stimulation, a restriction similar to other walk-up-use haptics (e.g., seat vibrations [26]). Figure 12 illustrates how deviations in alignment influence the resulting muscle contraction, using the wrist flexor muscle as an example. In this example, the arm can be positioned 2 cm in either direction of the center of the coil while still producing the intended wrist flexion. Deviations larger than that start affecting the actuation. Note that, in this observation, the coil output was fixed at 540 mT (the average intensity observed in Study#2's calibration)—increasing the coil output to its maximum is likely to widen the area more. As demonstrated in our pose-based I/O application, one way to assist the alignment is to visually represent the coil's position. All in all, further research is needed for a more case-specific discussion with respect to different muscles or other types of instrumented surfaces.

[1] https://lab.plopes.org/#MMS

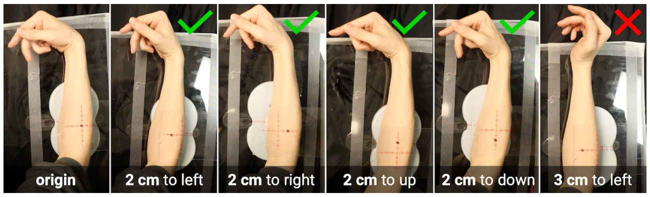

Figure 12. An example and measurement of how deviation in coil alignment could impact the resulting wrist movements.

Moreover, while we recommend that most interactive deployments of MMS should make use of stationary coils, we also acknowledge that other options are possible, with different tradeoffs and complexity, such as: attaching the coil to the user's body (e.g., as in our VR study by means of Velcro straps); or even, automatically aligning the coil with the target muscle by *motorizing* the coil. Figure 13 depicts two examples in which the MMS coil is mechanically moved into position: (a) depicts the simpler instance in which an X-Y gantry is used to move the coil—this is useful in applications on surfaces, such as actuating the user's finger on a tabletop; (b) depicts a more involved mechanical approach, in which a robotic arm moves the coil—this is useful in applications where users have some degree of mobility (e.g., VR). While we still tend to think that MMS lends itself best for stationary applications without the need for any mechanical actuators, we denote that the addition of a mechanical actuator does not compromise the benefits of MMS. First, the mechanical actuator only needs to have sufficient force to move the coil (~2 kgf). This is lighter than the force typically required for a mechanical actuator to move a human body [73] (an average human arm without exerting any voluntary force is still ~4.5 kgf [8]). As such the actuator needed for MMS alignment would be smaller than an active force-feedback motor. More importantly, mechanically moving the MMS coil still reaps more benefits of MMS, i.e., no direct contact or attachment is needed with the user's body. Instead, if one would use a gantry or robotic arm to actuate the user's body directly (as with mechanical force-feedback devices), one would require to attach or connect the user's body to the mechanical actuator.

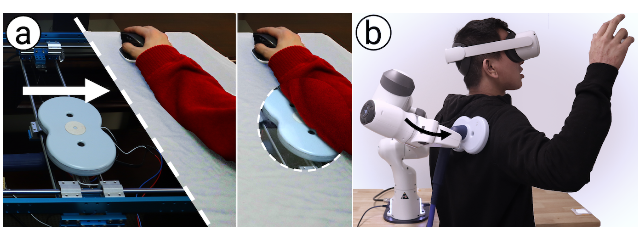

Figure 13. An alternative to strategic coil placement is to motorize the coil, e.g., using (a) X-Y gantry or (b) robotic arm.

Safety Guidelines

Establishing safety guidelines for interactive MMS is crucial for wider deployment. A large portion of safety guidelines of EMS [35] may apply to MMS as both pass electrical currents to muscles (e.g., they both require calibration, etc). Moreover, due to its use of an electromagnetic field, MMS also shares some of the safety guidelines of fMRI [10] and TMS [60], i.e., remove any ferromagnetic materials from the stimulation range (e.g., implants, or metallic accessories such as jewelry) and maintain some distance from electronic devices (e.g., smart watches) to prevent unintended interactions. Moreover, as an interactive system, it is advisable to ensure that users are in control of the MMS stimulation and that the stimulation stops whenever it is against the users' intention. Such a function can be implemented by an emergency stop switch [20], or by incorporating motion sensing measures [40, 41].

CONCLUSION

We explored how switching from electrical (EMS) to magnetic muscle stimulation (MMS) brings interactive benefits and addresses the key limitations of EMS. Unlike its electrical counterpart, MMS offers novel advantages: it does not require direct skin contact and causes approximately 50% less discomfort due to tingling sensations. Our studies have shown that MMS can actuate muscles up to 5 cm away, enabling applications that are not possible with EMS, such as over-the-clothes stimulation and without ever replenishing electrodes. Additionally, we found that participants rated MMS force-feedback as more realistic than EMS and could more accurately perceive actuated poses. Finally, we showcased a range of applications unique to MMS (e.g., walk-up-use interfaces, such as force-feedback on a publicly used bus) and outlined a roadmap of future challenges to expand its applicability in interactive contexts.

In sum, by significantly reducing the tingling discomfort and removing electrodes from the skin, we believe MMS has the potential to improve many interactive force-feedback experiences previously realized by means of EMS. As such, we humbly believe that our work will inspire researchers to consider MMS as a new tool for force-feedback.

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