Can a Smartwatch Move Your Fingers? Compact and Practical Electrical Muscle Stimulation in a Smartwatch

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Figure 1: (a) The conventional way to actuate the wrist & fingers via electrical muscle stimulation (EMS) requires electrodes on the forearm—while this provides good accuracy, it makes EMS less practical. Instead, (b) we propose moving all electrodes to the wrist and packing them in the smartwatch band. We found that cross-sectional stimulation at the wrist can render thumb extension, index extension & flexion, middle flexion, pinky flexion, and wrist flexion. We demonstrate that this compact form factor enables a *practical* application of EMS, allowing our participants to feel comfortable with wearing muscle stimulation in social settings, such as buying a coffee at a public café during the study. We believe this (c) opens new applications for EMS.

ABSTRACT

Smartwatches gained popularity in the mainstream, making them into today's de-facto wearables. Despite advancements in sensing, haptics on smartwatches is still restricted to tactile feedback (e.g., vibration). Most smartwatch-sized actuators cannot render strong force-feedback. Simultaneously, electrical muscle stimulation (EMS) promises compact force-feedback but, to actuate fingers requires users to wear many electrodes on their forearms. While forearm electrodes provide good accuracy, they detract EMS from being a *practical* force-feedback interface. To address this, we propose *moving the electrodes to the wrist*—conveniently packing them in the backside of a smartwatch. In our first study, we found that by cross-sectionally stimulating the wrist in 1,728 trials, we can actuate thumb extension, index extension & flexion, middle flexion, pinky flexion, and wrist flexion. Following, we engineered a compact EMS that integrates directly into a smartwatch's wristband (with a custom stimulator, electrodes, demultiplexers, and communication). In our second study, we found that participants could calibrate our device by themselves ~ 50% faster than with conventional EMS. Furthermore, all participants preferred the experience of this device, especially for its social acceptability & practicality. We believe that our approach opens new applications for smartwatch-based interactions, such as haptic assistance during everyday tasks.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Electrical muscle stimulation; Smartwatch; Force feedback

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1 INTRODUCTION

In recent decades, smartwatches and other wrist-worn devices (e.g., fitness trackers) have risen to become one of the most mainstream interactive devices—wrist-worn devices can be considered today's de-facto wearables. As such, ample research efforts have been dedicated to enhancing their input & output capabilities.

While an abundance of sensors has been used to add new input modalities to smartwatches (e.g., sensing finger poses [54] or arm poses [6]), this abundance is *not* paralleled in haptics for smartwatches. In fact, the haptic modalities commonly found on smartwatches are typically tactile sensations (mostly vibration [31], skin-stretch [16], or pressure [51]). This is caused by a lack of haptic actuators that would be compatible with the size of a typical smartwatch and could render the strong forces needed for finger actuation and wrist force-feedback.

To generate such strong forces, researchers typically use mechanical actuators (e.g., motors [55] or pneumatic actuators [59]). However, these conventional methods for realizing force-feedback cannot easily be contained inside the form factor of a smartwatch (also, these actuators require large batteries, which further enlarges their form factor).

An emerging approach is electrical muscle stimulation (EMS), which promises miniaturization of force-feedback since its electrodes and battery are typically smaller than the components needed for mechanical actuators [32]. Unfortunately, virtually all EMS systems that actuate the fingers or the wrist place the electrodes on the forearm [19, 34, 35, 64] or back-of-hand [62]. While this is anatomically intuitive (wrist and most finger muscles reside in the forearm), this limits the practicality of EMS—most users do not typically wear electrodes in their forearm day-to-day.

Instead, in this paper, we explore & evaluate EMS at locations where users today wear a smartwatch—around the *wrist* (Figure 1). First, we explored an actuation strategy that allows for best results when electrodes are placed *only* around the wrist. We found that stimulating cross-sectionally (i.e., a pair is formed by diametrically opposing electrodes) enabled a wider range of finger actuation than the side-by-side electrode placement (typical of most interactive EMS systems). Then, we characterized possible finger & wrist actuations when electrodes are at the wrist (including at different distances to the hand and during different hand poses). We found that our approach can render thumb extension, index extension & flexion, middle flexion, pinky flexion, and wrist flexion—all from the vantage point of the wrist. These results helped inform the engineering of our wrist-EMS device, a compact muscle stimulator that integrates directly into a smartwatch's wristband, with its custom EMS stimulator, 12 electrodes, demultiplexers, battery, and wireless communication.

Importantly, given that our goal was to explore if placing the electrodes on the wrist, rather than on the forearm, improved the practicality of EMS, we conducted a study where participants were asked to calibrate the EMS *by themselves* (with no experimenter assistance) and asked to wear our wrist-EMS *in public*. We found that the participants could calibrate our wrist-EMS device by themselves $\sim$ 50% faster than with forearm-EMS. Moreover, all participants favored the experience of using our device, especially for its social acceptability & practicality (e.g., the study involved public interactions, such as at a café).

Finally, we believe that our approach opens up completely new *everyday* interactions with smartwatches, such as actuating one's hand to display walking directions, wrist-based drumming assistance, and haptic exercise coaching.

2 BACKGROUND AND RELATED WORK

Our work builds primarily on the field of wearable haptics, in particular, wrist-worn devices and muscle stimulation.

2.1 Increasing the Expressivity of Wrist-worn Devices

Since wrist-worn devices gained mainstream popularity, a lot of research in HCI has proposed & explored new avenues to increase their input and output expressivity (e.g., number of I/O modalities, accuracy of the I/O, etc.).

These advances are most notable in wearable sensing, with an abundant number of sensors used specifically because their small size fits easily inside the form factor of wrist-worn devices (e.g., smartwatches). Some canonical examples of sensors used to enhance the input capability of wrist-worn include: capacitive sensing [2], accelerometers [4, 5, 70], IR sensors [14, 29, 47], ambient light sensors [15], and microphones [13].

One extremely popular area for wrist-based sensing is pose detection, which enables the wrist-worn device to leverage the user's wrist and fingers pose as an input modality. There are countless examples of technical approaches specifically tailored for pose detection at the wrist, such as capturing the electrical characteristics [71, 72] or acoustic interference [17] inside the arm. Others implemented high-frequent electromagnetic signal generators and receivers for object recognition [30] and hand pose recognition [23]. Unfortunately, while pose-sensing is well established, the reverse is not the case—pose actuation for smartwatches is a relatively understudied area due to its technical challenges.

2.2 A Lack of Output Expressivity in Wrist-worn Devices

Indeed, output modalities for wrist-worn devices are less abundant and usually limited to visuals, sound, or vibrations. While many areas of HCI have seen a strong resurgence of haptics (e.g., in VR/AR [12, 56, 68]), this is not as pronounced in wrist-worn devices—likely because of the unique challenge of fitting actuators in a small device, worn at such a visible location as is the case for someone's wrist. Some haptic areas have been successful with miniature actuators that fit inside a wrist-worn device, such as skin-dragging [16], thermal [49, 60], and squeezing [8, 51, 60]—just to cite a few. While the previous devices were designed to create sensations at the wrist, some aimed to create sensations in other skin areas by applying electro-tactile stimulation to the wrist [48]. As this line of work shares our interest in electrical stimulation, we turn additional attention to it next.

2.3 Electro-tactile Stimulation on the Wrist

Pena et al. demonstrated that coarse tactile sensations can be evoked at the palm via low-intensity electrical pulses without moving the fingers [50]. Taking this further, Ogihara et al. induced tactile sensations by stimulating multiple skin areas around the wrist [48]. Moreover, Duente et al. integrated two electrodes at the back of a mock-up smartwatch for rendering electro-tactile feedback at the wrist [10]. All these works share a sentiment with ours regarding the desire to explore electrical stimulation on the wrist—however, these are all tactile sensations, none of these prior works demonstrated that these approaches could render any force-feedback.

2.4 Realizing Force-feedback in Wrist-worn Devices

To generate the magnitude of forces needed to physically move the user's wrist or fingers, researchers typically employ bulky mechanical actuators in force-feedback devices (e.g., motors [55], exoskeletons [1, 55], robotic arms [40, 41], pneumatics [59]). However, these conventional methods for achieving force-feedback do not scale down gracefully: if one scales down the mechanical actuators, the output force is greatly compromised (i.e., no longer strong enough to move fingers/wrists); conversely, if one does not scale down the mechanical actuators, these will not fit inside the typical form-factor of a wrist-worn device.

On the other hand, researchers have explored using illusions of motion to move the wrist, namely, hanger reflex, which makes a user rotate their arm, based on skin-stretch at the wrist joint [42, 44], which can also be promoted via vibrations [43]. While such illusions are exciting, none of them can actuate the fingers.

2.5 EMS Miniaturizes Force-feedback Devices

A recent approach to realize force-feedback in interactive applications is electrical muscle stimulation (EMS). It creates forces by contracting the muscles using electrical impulses applied to the skin via electrodes. While the technique originated in the field of rehabilitation [61], many now view it as a promising interface for force-feedback, as the electrodes and battery are smaller than those components required by mechanical actuators [32].

Indeed, EMS has been leveraged to actuate wrist and fingers in many interactive contexts, ranging from offering haptics for immersive experiences [37, 62] to serving as a novel information output modality [21, 38]—just to cite a few. However, while many interactive EMS systems exist in laboratory settings, the technique has not yet proven practical for wider applications, such as for everyday interactions.

2.6 Factors that Limit the Practicality of EMS

If the reader has not used EMS before, let us illustrate what it entails to reliably actuate a muscle: (1) the user places electrodes on a skin area of interest to target a muscle, which requires knowledge of musculature under the skin; (2) the user sends electrical impulses via the stimulator, gradually increasing the intensity and observing the result—a muscle contraction and target limb's movement; and (3) if the contraction is not achieved or robust (e.g., the user might rotate their limb or body to check if this deteriorates the quality of the observed actuation), the user revisits step (1) and, again, starts placing electrodes in a new area of interest.

These steps illustrate two challenges that undermine the practicality of EMS: (1) the need for manual calibration, which requires users to tweak the stimulation parameters [9]; and (2) the need for many electrode locations, which requires users to either try stimulating many skin areas or wear sleeves that cover their skin with many of electrodes, so that at least some electrodes reach the correct areas [24]. Unsurprisingly, much HCI research in EMS emphasizes these as serious limitations, for instance: "It is difficult to fasten the [electrodes] and set the stimulation levels correctly on a user's forearm" [64]; "the placement of the electrodes and the calibration process of the EMS signal parameters are challenging" [52]; or "time for calibration can quickly become impractical" [25].

Fortunately, researchers are already exploring automatic calibrations of EMS by simultaneously monitoring muscle response and control the stimulation accordingly, for instance, through electromyography (EMG) [25] or motion tracking [67]. Therefore, we expect less manual calibration will be required in the future, which might reduce the first practical issue with EMS.

2.7 The Need for Many Electrode Locations is Impractical

However, the need for many electrode locations still causes impracticality in EMS. Currently, most interactive systems that use EMS require users to either place multiple electrodes in anatomically correct skin areas [19, 21, 22, 27, 36, 38]. A smaller number of emergent systems aims to improve this by having users wear garments covering a large skin area with high-density distributions of electrodes, so that at least some electrodes reach the correct areas [24, 25, 52]. In both cases, users still end up with large EMS systems that cover their forearm—*this does not blend well with everyday interactions* nor with *any existing devices*—in other words, the EMS is yet another device that the users must attach to their body and does not integrate directly in any existing devices they might be *already* wearing.

2.8 EMS for the Wrist and Fingers Uses Forearm Electrodes

Nearly all EMS systems that actuate the fingers/wrist place the electrodes on the forearm [19, 34, 35, 64] (and only more recently, some in the back-of-hand [62]). This heavy focus on placing electrodes in this area is anatomically intuitive since the wrist muscles and most finger muscles reside in the forearm. Indeed, placing at least one electrode on the forearm is not just intuitive but also necessary, according to Bao et al.'s study, which examined the entire skin from the wrist up to the elbow for EMS finger actuation [3]. However, not only is the forearm impractical since users do not wear any other devices in this area (with which the EMS could easily be integrated), but the forearm also increases the number of possible electrode locations—further making its calibration less practical. Recently, some researchers have explored new areas to achieve finger movements, such as the back of the hand [62]. However, while they are promising in flexing individual fingers, they cannot extend fingers, and, more importantly, much like the forearm-EMS, users are not wearing any devices in the back of their hands—making this form factor also very impractical for everyday use of EMS.

2.9 Social Acceptability of EMS-based Interactive Systems

While most EMS applications remain as research prototypes, in recent years, there have been some instances of commercializing EMS. For instance, *UnlimitedHand* [63] is an EMS device that packs electrodes and a stimulator; still, users have to wear it on the forearm. *Teslasuit* [39] has even extended EMS to a full-body suit, yet it requires users to switch their clothing entirely to use the device. Again, none of these strived to integrate EMS with existing devices. Indeed, to deploy EMS to a larger range of interactive contexts, it is crucial to consider and design EMS for social acceptability, as Faltaous et al. outlined in their review of EMS systems [11]. On this note, Shahu et al. investigated how users accept or deny using EMS depending on the application scenarios, where they found that "long-term exposure to the EMS technology has been severely questioned and critiqued" by users [57, 58]. Moreover, Knibbe et al.'s sleeve-type EMS also emphasized social acceptability and aesthetics [24]; these authors iterated on their prototype, changing not only the electrode arrangement but also materials and appearance so that the device could be more acceptable for future daily interactions, reflecting on comments from their participants [24].

3 OUR APPROACH: ALL ELECTRODES AT THE WRIST

We propose a novel form factor for EMS devices by integrating the electrodes in a device—the smartwatch—that users are already familiar with and that provides a useful vantage point for electrically actuating wrists and fingers. Our proposal moves *all* electrodes to the wrist, standing in contrast to the conventional EMS approaches for actuating wrist/fingers, which place electrodes on the forearm.

At first glance, our proposal sounds counterintuitive since most finger/wrist muscles are largest under the forearm—however, as depicted in Figure 2, some muscles are accessible from the wrist. For example, the index finger extensor (*extensor indicis*) passes close to the skin surface, around the back of the wrist. As we will see in our Study#1, we found more muscles to also be accessible, such as the thumb (*extensor pollicis longus*), the index finger (*flexor digitorum superficialis*), and the wrist (*flexor carpi ulnaris*).

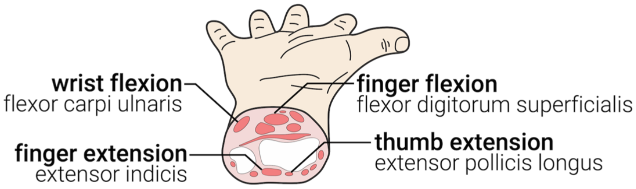

Figure 2: A cross-section of the wrist reveals our working principle: despite being far from most finger muscles, the wrist still provides access to some fingers and wrist muscles.

At this point, the reader might expect that we would apply the typical EMS electrode placement strategy employed in the forearm (and virtually all other locations) to the wrist, i.e., placing two electrodes side by side atop the muscle, as depicted in Figure 3 (a). However, as depicted in Figure 3 (b), we found that using this typical electrode placement does not work reliably if applied to the wrist—it would, in fact, require a ground electrode on the elbow, as used by [3, 69], overturning all the practicality we gained from moving the electrodes to the user's wrist.

Instead, as shown in Figure 3 (c), we found that *cross-sectionally stimulating the wrist* (i.e., a pair is formed by diametrically opposing electrodes) resulted in a wider range of finger actuations that better mimic some of the results of forearm-EMS. This is because the electrode-to-electrode distance is now larger, which creates a deeper current path inside the wrist [18, 65]. Finally, it is this final electrode configuration and its accompanying stimulation strategy that enables our EMS to be easily integrated into a device—the smartwatch—that many users are already familiar with.

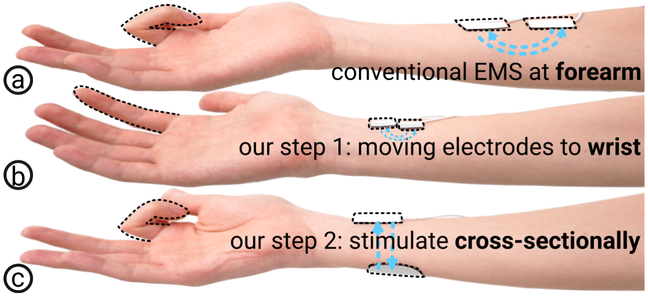

Figure 3: (a) Conventionally, electrodes are placed in the forearm. (b) Naïvely, moving electrodes to the wrist does not actuate the finger robustly, as the current path is too shallow to reach to the muscles. (c) We found that via a pair of electrodes across the sides of the wrist ensures that the current reaches the muscles and actuates the finger.

4 CONTRIBUTIONS, BENEFITS, AND LIMITATIONS

Our contribution unveils a novel stimulation technique and form factor for EMS, extending EMS interactions beyond laboratory settings. We achieved this by *conveniently* integrating EMS into smartwatches—a wearable device that users are *already familiar with* and provides a suitable vantage point for stimulating wrists and muscles. A key innovation that made this integration possible is our novel cross-sectional EMS, which enables a compact device at the wrist to provide thumb extension, index extension & flexion, middle flexion, pinky flexion, and wrist flexion.

This approach has four key benefits: (1) it provides an extremely compact form factor for simple EMS actuations of some fingers and the wrist—as validated in our Study#1; (2) it reduces calibration time, even when users are new to EMS calibration—our Study#2 found that it reduces calibration by 50% compared to a highly-improved version of the conventional forearm EMS; (3) it provides new avenues for social acceptability of EMS, given that no electrodes are visible on the forearm, since they are tucked under the smartwatch—none of the participants in our Study#2 felt uncomfortable when it came to public-facing interactions; and, finally (4) our approach, conceptually, closes the loop on a popular area of smartwatch research—pose sensing—with our approach, *a single smartwatch* can now perform *both* pose sensing and pose actuation.

As with any approach, ours is not without limitations: (1) it cannot actuate all five fingers, since some muscles are harder to reach when all electrodes are at the wrist—this is a tradeoff between practicality and haptic accuracy, yet we believe it is worth exploring the gain in social acceptance and integrated form-factor; (2) much as with conventional EMS, there are other factors that limit its practicality that our proposal does not improve, such as the tingling sensation caused by electrical currents [66]; (3) as with previous EMS, the resulting actuations will slightly vary across hand poses—yet, we specifically measured this in our study and selected the most robust electrode sites that were most invariant to hand poses; and, (4) while our participants found wrist-EMS to be faster to calibrate than forearm-EMS, we have not integrated automatic calibration techniques (e.g., [25, 67]), which would further increase its practicality.

5 INTEGRATING EMS INTO A SMARTWATCH

We provide the technical details here to help readers replicate our device. To accelerate replication, we provide all the source files. Our device, shown in Figure 4, is directly integrated into the watchband of an Android smartwatch (*Samsung*, Galaxy Watch 5). Inside the wristband, we integrated five modular PCBs that realize signal generation, signal amplification, demultiplexing, and wireless communication. Finally, there are 12 electrodes radially placed to the backside of the wristband.

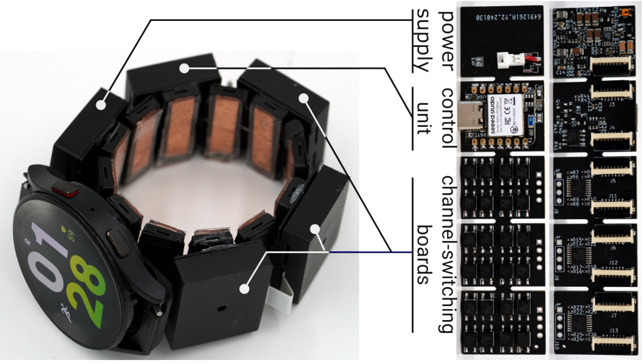

Figure 4: Our wrist-EMS integrated with an Android smartwatch. It comprises twelve electrodes, an expandable watchband, electrodes, and five PCBs that implement power supply, signal generation, and a 12-channel demultiplexer.

5.1 Electrode Array Band Compatible with a Smartwatch

We designed a PLA 3D-printed flexible watchband that expands between 147-360 mm in circumference and ensures electrodes are distributed evenly around the wrist (Figure 5).

Electrodes. Each electrode measures 10 mm × 30 mm, and it is formed by a 3D printed base, copper tape, and a conductive gel sheet (*Yushiro Chemical Industry*, wizard gel). The copper electrode directly connects to our channel switching board (demultiplexer). The addition of conductive gel improves impedance matching, resulting in a more comfortable sensation [53], similar to pre-gelled electrodes.

Figure 5: Our flexible wristband houses twelve electrodes.

PCB interconnects. Atop the wristband, five 240 mm×300 mm×80 mm 3D-printed boxes house each of our modular PCBs. To distribute signals from each module, we employ flexible flat cables.

5.2 EMS Signal Generation

Figure 6 depicts our circuit design. Its goal is to generate an appropriate signal to induce muscle stimulation. Our circuit design is capable of a maximum of 100V at 15mA.

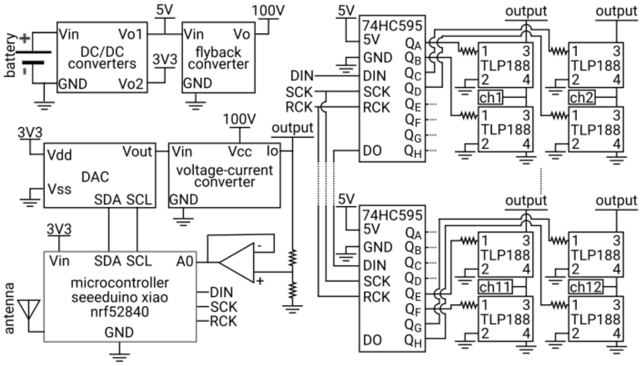

Figure 6: High-level schematics of our device.

Power supplies. Our circuit features three voltage sources: a 3.3 V supply via a DC-DC buck converter from the LiPo battery (3.7 V, 110mAh), which powers our microcontroller; a 5 V supply via a DC-DC boost converter from the LiPo; and the 100 V via a DC-DC flyback converter from the 5V. The 5 V is supplied to the channel switching demultiplexers and battery-charging circuit. The 100 V is used for the EMS.

Stimulation modes. Further, by toggling a switch on our PCB, our circuit can switch between *constant voltage* and *constant current* stimulation. In constant-voltage mode we utilize pulse-width modulation to vary the intensity of EMS—always at 100Vpp, but with varying duty cycles. Conversely, in constant-current mode, we control the output of a voltage-current converter from the digital-analog converter (DAC) connected to our microcontroller (0 V to 3.3 V) to regulate the current between 0-15 mA—the maximum current value was defined from the data of values used in Study#1. Since medically compliant EMS devices typically use constant-current stimulation due to their improved safety, we employ this method in all our interactions.

5.3 Control Unit & Communications

A microcontroller (*Seeeduino*, nRF52840) with Bluetooth low energy (BLE) controls functionality and communication. Our microcontroller implements a simple BLE protocol that target applications can adhere to request muscle stimulation. Target applications send the EMS parameters (channels, intensity, pulse width, frequency) to our device.

5.4 Channel-switching (Demultiplexer)

A channel-switching circuit was implemented to allow our signal generator to be routed to any of the 12 electrodes. Using our demultiplexer, each electrode can be in three states: *high* (connected to the generator), *ground* (0 V), and *HiZ* (high-impedance mode). The stimulation current flows from the electrodes set *high* to the body and returns to the device through the *ground* electrode. HiZ electrodes are not connected to any source, so no current flows through them.

Each channel-switching PCB comprises an 8-bit shift register (*Nexperia*, 74AHCT595) and eight photocouplers (*Toshiba*, TLP188). The shift registers' eight output pins are connected to the anodes of each photodiode. Each pair of photocouplers forms one half-bridge. Thus, each channel-switching PCB controls four channels, and with three of these, our device can switch a total of 12 output channels.

6 PRELIMINARY STUDY: WHERE DO USERS WEAR THEIR SMARTWATCHES?

Before investigating whether the EMS at the location where a smartwatch is worn could actually actuate fingers and wrist, it was necessary to determine the arm locations where people generally find it most suitable to wear a smartwatch.

6.1 Design and Procedure

Participants. We recruited 11 participants (three women, eight men; 24.8 ± 2.6 years old) from our institution.

Procedure. We asked participants to wear a smartwatch (*Samsung,* Galaxy Watch 5) on any arm and place it in the location where they usually wear this type of device—they were not instructed in any other way. After participants placed and adjusted the device to their preference, we measured the distance from the head of the ulnar bone to the edge of the watch on the distal side (i.e., away from the body). Then, the experimenter proceeded by manually moving the device up the participant's arm (in the proximal direction, i.e., towards the body) by 5 mm at a time. At every position, the participant reported whether this position was acceptable; this was repeated until they reported a position that was no longer acceptable. Finally, this process was repeated to determine the acceptable position in the distal direction (i.e., away from the body and towards the hand).

6.2 Results

As depicted in Figure 7, we found that the usual preferred position was 18.9 ± 6.7 mm (mean ± confidence interval using a t-distribution), with the highest position towards the body at 41.5 ± 6.5 mm, and the lowest away from the wrist at -1.5 ± 12.1 mm. The latter position's variation was larger since participants who wear wristwatches loosely described that they did not care if their device fell towards the hand.

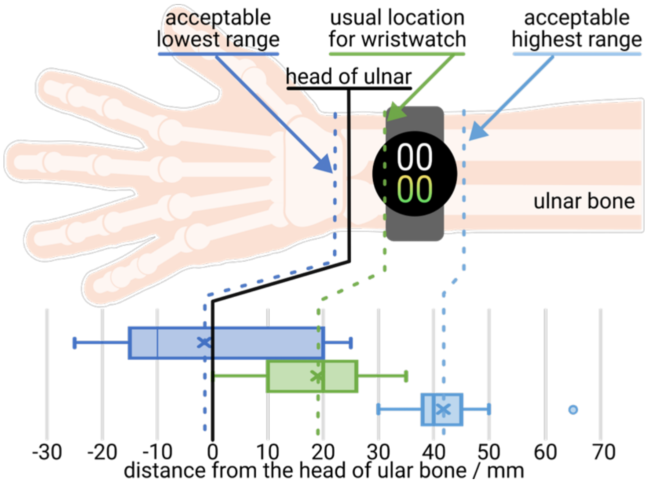

Figure 7: Average positions (mean ± confidence interval) where participants wore smartwatches (usual & max/min).

7 USER STUDY 1: CAN A WATCH MOVE YOUR FINGERS?

Now, equipped with the range where the smartwatches are worn (between 0-40 mm, measured from the head of the ulnar bone), we measured if our cross-sectional electrical stimulation could actuate wrist/fingers and, if possible, what joints are flexed or extended. This study was approved by our Institutional Review Board (*IRB19-1949)*.

7.1 Design and Procedure

Participants. We recruited 12 participants (six male and six female; 24.3 ± 4.2 years old) from our institution. Nine wore their watches on their left arm and the rest on their right hand. Participants were compensated with 20 USD for their time.

Apparatus. We utilized our previously described prototype (including a 12-electrode ring-shaped band, demultiplexers, etc.), except our signal generator. Instead, since this was the first study to determine the design of our signal generator, we used a medically compliant EMS stimulator (*HASOMED,* Rehamove3), which is capable of stimulation up to 100 mA. The results of this study informed the design of our final stimulator, which we found only required 15 mA of current—thus leading to a smaller circuit (no need for large high-current transformers). The stimulation was a sequence of pulses at 100 Hz, and each pulse-width was 200 µs in duration. We adjusted only the first electrode to sit atop each participant's finger extension muscle (*extensor indicis*). The remainder electrodes landed in their nominal position as the band was wrapped around the participants' wrists.

Study conditions. We conducted our study in three wrist locations (20 mm, 30 mm, and 40 mm from the head of the ulnar bone—all acceptable ranges from the results of our previous study). For each location, we studied our device under four different hand poses (i.e., the palm facing up/down/left/right), which is common in observing limb movements under EMS, as also employed by prior work [3, 62]. The evaluation with the different hand poses was also paramount since this is, unfortunately, an understudied yet well-known issue of EMS [3, 62]—as the skin rotates independently from the muscles, electrodes land in incorrect locations, and the stimulation becomes inaccurate [62]. Given our focus on practicality, we selected actuations that our system could perform under as many hand poses as possible. Note that this study did not require a baseline EMS condition, as prior work demonstrated that these target movements are feasible with conventional EMS [3, 62].

Cross-sectional stimulation. Our stimulation works by stimulating electrodes on opposing sides of the participants' wrists. In this study, the procedure automatically explored all twelve electrodes, rotating between them one by one. For each selected stimulation electrode, the other seven electrodes on the opposite side acted as a common ground—the remainder four (two on each side) were turned off (HiZ mode) and thus non-stimulating nor ground. We found via extensive pilot experiments (e.g., as shown in Figure 3) that this offered the best results.

Task design. Per trial, the stimulation started at 0mA and increased by 1mA at a time until either a full contraction was achieved, or the participant reported discomfort. This was repeated for all channels at three locations & four hand poses.

Analysis. For each trial, the participant's hand was filmed via two video cameras (top and thumb's side). In the end, we analyzed the videos to extract the frames depicting the maximum pose reached per trial. Following the process of Nith et al. [46], all joint angles were annotated and extracted.

Trials. Each participant was stimulated for a total of 144 trials, which brings our total to 1728 trials across participants.

7.2 Results

Overview. From our 1728 trials, we obtained the angles for 22 degrees of freedom (5 fingers × 4 DoF per finger + 2 DoF for the wrist), resulting in 38,016 data points. We also provide this raw data as a supplemental file for other researchers to explore. Figure 8 depicts the overview of results, summarizing what movements are possible when the stimulation is applied at the wrist. Each entry denotes the percentage of participants for which this actuation reliably occurred with an angle larger than 5°. We denote a reliable actuation when it occurred over 75% of the trials (colored green). Furthermore, we later apply this same threshold for classifying an actuation as reliable across hand poses (e.g., if it can be performed in 3 out of 4 hand poses). To simplify this visualization, all joints (DIP: distal interphalangeal, PIP: proximal interphalangeal, and MP: metacarpal phalangeal) are combined—however, it is worth noting that typically only PIP and MP were observed. Further, the adduction and abduction of the four fingers, except for the thumb, are not shown because those were observed less reliably (< 25%).

Results for 2 cm (no reliable actuations). Only two movements were observed at the 2 cm location (e.g., index flexion and pinky flexion), but these did not match our reliability criteria (reliable over 75% of hand poses).

Results for 3 cm (up to two actuations). With the electrodes placed 3 cm away from the wrist, we observed two reliable actuations: (1) index extension and (2) wrist flexion for all hand poses.

Results for 4 cm (up to six actuations). Our findings revealed that 4 cm was the most expressive location concerning the number of unique actuations with up to six reliable actuations: (1) thumb extension, (2) index extension, (3) index flexion, (4) middle flexion, (5) pinky flexion, and (6) wrist flexion—this was observed for most poses, except the index & thumb extension which were not reliable when the palm was facing up, and the index flexion was not reliable when the palm was facing inwards.

Results for all locations (up to eight actuations). While we were able to create the six movements from a single location (4 cm), our approach can create two additional finger actuations if a device would make use of all three locations (2, 3, or 4 cm). We found this overall result adds the following reliable actuations: thumb flexion and ring flexion.

Possible form-factors. From our results, two form factors emerge: (1) one electrode band at the best location (4 cm), or (2) a wider electrode band that covers all three locations (from 2 cm to 4 cm). While the latter version can reliably actuate eight movements, it adds at least ∼ 2 cm in width to cover all three locations, which limits wearability. While future researchers might want to pursue this avenue to reach more gestures, we optimized for a practical form factor and opted for a single electrode band at 4 cm, which can already reliably actuate six finger/wrist movements.

Electrode positions. Next, we analyze the results by looking into the joints that successfully moved for >75% of the participants at the most expressive location (4 cm). Per joint, we analyzed which electrode positions (from our 12 possible channels) were most effective in actuating this joint. Figure 9 depicts a heatmap of which electrode channels achieved which movements, with blue shades for flexion and red shades for extension. We found that four actuations were consistent in specific electrode positions across most of our participants: (1) **index extension** was most reliably achieved at channel 12 (and directly adjacent channels) for all hand poses beside the upwards pose; (2) **wrist flexion** was most reliably achieved at channel 9 for all poses; (3) **middle flexion** was observed to be most reliably actuated at channel 5, but only when the palm was facing upward or inward; (4) **pinky flexion** was observed to be most reliably actuated at channel 8 for all hand poses besides downward pose.

Additional observations. The thumb extension was difficult to observe when the palm was facing up, likely because, in this pose, the thumb is already passively extended. Also, we found that the pinky and ring fingers were flexed at the MP joint (unlike the index and middle, which flexed at the PIP), which suggests that the current was also stimulating the motor nerves that innervate

down pose
palm facing
downwards

distance	thumb		index		middle		ring		pinky		wrist	
	fl & ad	ex & ab	fl	ex	fl	ex	fl	ex	fl	ex	fl & ad	ex & ab
2cm	>50%	>25%	>50%	>50%	50%	×	50%	×	**75%**	×	>50%	×
3cm	>50%	50%	**75%**	**83%**	>50%	×	50%	×	>50%	×	**83%**	×
4cm	>50%	**83%**	**75%**	**83%**	**75%**	×	50%	×	>50%	×	**75%**	25%
All	**83%**	**92%**	**92%**	**83%**	**100%**	×	**75%**	×	**100%**	×	**83%**	25%

in pose
palm facing
towards torso

distance	thumb		index		middle		ring		pinky		wrist	
	fl & ad	ex & ab	fl	ex	fl	ex	fl	ex	fl	ex	fl & ad	ex & ab
2cm	>25%	25%	**75%**	>50%	>50%	×	>50%	×	>50%	×	>50%	×
3cm	**75%**	>25%	>50%	**83%**	**75%**	×	50%	×	>50%	×	**83%**	×
4cm	>50%	**75%**	>50%	**75%**	**92%**	×	**75%**	×	**92%**	×	**83%**	×
All	**83%**	**83%**	**83%**	**83%**	**92%**	×	**83%**	×	**100%**	×	**92%**	×

up pose
palm facing
upwards

distance	thumb		index		middle		ring		pinky		wrist	
	fl & ad	ex & ab	fl	ex	fl	ex	fl	ex	fl	ex	fl & ad	ex & ab
2cm	>50%	25%	>50%	>50%	>50%	×	>50%	×	**83%**	×	50%	×
3cm	**92%**	25%	>50%	**75%**	**83%**	×	**83%**	×	**100%**	×	**75%**	×
4cm	**75%**	>25%	**75%**	>50%	**92%**	×	**75%**	×	**83%**	25%	**75%**	>25%
All	**92%**	50%	**83%**	**75%**	**92%**	×	**92%**	×	**100%**	25%	**83%**	<50%

out pose
palm facing
away from torso

distance	thumb		index		middle		ring		pinky		wrist	
	fl & ad	ex & ab	fl	ex	fl	ex	fl	ex	fl	ex	fl & ad	ex & ab
2cm	>25%	×	>50%	>50%	50%	×	50%	×	>50%	×	>50%	25%
3cm	>50%	50%	>50%	**83%**	>50%	×	**75%**	×	>50%	25%	**75%**	25%
4cm	**75%**	**75%**	**75%**	**83%**	**75%**	×	>50%	×	**75%**	×	**100%**	>25%
All	**83%**	**75%**	**100%**	**83%**	**83%**	×	**92%**	×	**100%**	25%	**100%**	>25%

Figure 8: Percentage of participants whose movements occurred reliably. Values $>75\%$ **are shown in green. Values** $74\%-25\%$ **are shown in gray. Values** $<25\%$ **are shown as ×. Fl. stands for flexion, ex. for extension, ad. for adduction, and ab. for abduction.**

the *lumbricals* or *interossei* muscles—as these typically flex the MP joints [62].

Required stimulation intensity. Across all trials, we found that the elicited movements required no more than 12 mA of current. This allowed us to design a more compact final circuit that can deliver up to 15mA of current instead of relying on large transformers (e.g., as used in Rehamove3), which allow for much larger currents (e.g., up to 100 mA).

Study conclusions. Despite moving all electrodes to the wrist (a location not known for its accuracy concerning actuation of fingers/wrist with EMS), we still observed reliable finger/wrist actuations up to six from a single location (i.e., a subset of what is possible with conventional forearm-EMS), which enables a wide range of applications with our wrist-worn device (see *Applications*). Importantly, the key benefit of moving all electrodes to the wrist is practicality, which we confirmed in our next study.

8 USER STUDY 2: THE PRACTICALITY OF WRIST-EMS

Now that we have confirmed the feasibility of our wrist-EMS for finger/wrist actuation, we turn our attention to evaluating its practicality. This study was approved by our Institutional Review Board *(IRB19-1949)*.

8.1 Study Design

Participants. We recruited eight participants (four women and four men; 23.3 ± 3.5 years old) from our institution; none had partaken in Study#1. Participants received 20 USD. All participants wore their watches on their left arm.

Interface conditions. This study featured two tasks: Task#1 and Task#2. In Task#1, participants experienced two EMS conditions: **forearm-EMS** (i.e., the traditional approach used in virtually all EMS papers) and our **wrist-EMS** device. Importantly, the only difference between the two conditions was that the forearm-EMS had two electrode bands instead of one to replicate electrode placement in traditional EMS. Note this was done to create an advantage to the forearm-EMS condition—most interactive systems using forearm-EMS rely on experimenters who place pairs of electrodes manually [21, 38]. Preliminary pilot experiments revealed that participants new to EMS were not able to confidently calibrate with individually placed electrodes. As such, we utilized two of our bands for forearm-EMS, replicating a setup similar to *PossessedHand* [64].

Apparatus. Besides the one-to-two band difference in the interface conditions, the remainder setup was the same, including the stimulation hardware, the design of the electrode bands, and the calibration interface. Participants interacted via our calibration app on a smartwatch's screen, which laid flat on the table for consistency across the two interface conditions. This calibration screen allowed participants to test all 12 channels while adjusting the stimulation intensity (Figure 10). When they ran through all 12 channels, the app automatically prompted participants to adjust the placement of the bands.

Task#1: calibrate the EMS by yourself. We asked participants to wear one of the EMS interfaces (forearm or wrist) at a time and calibrate it, to "create three reliable finger movements (i.e., thumb extension, index extension; and middle flexion)". Our goal was to observe how participants would calibrate *without assistance from the experimenter*, unlike most EMS research where experimenters calibrate each participant [21, 35, 62] —again, this highlights another key reason why EMS is still limited to lab settings. As such, participants had to perform every aspect of the calibration *by themselves*, including deciding where to place the electrode bands, putting bands on/off, and adjusting the stimulation.

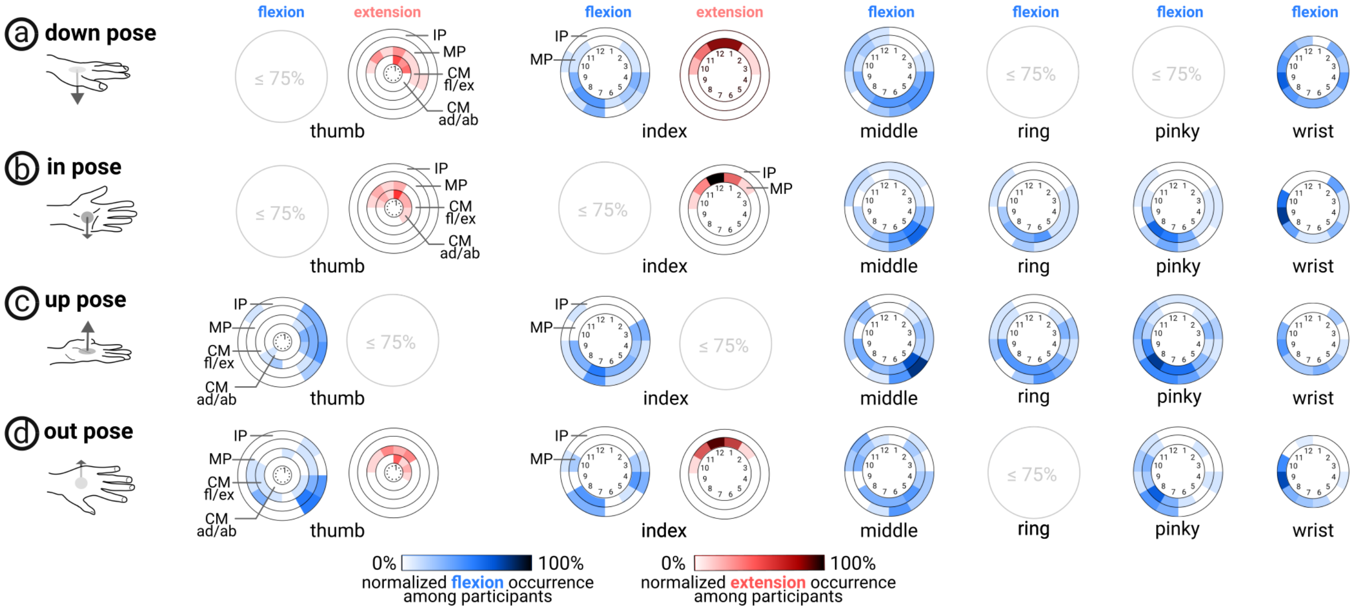

Figure 9: The results show which electrode contributes to each joint flexion/extension when the palm faces (a) down, (b) up, (c) inward, and (d) outward (IP: (proximal) interphalangeal, MP: metacarpal phalangeal, CM: carpometacarpal). The darker blue and red mean that the joints were flexed and extended for more participants, respectively. The ratio was normalized by the number of participants with the joint flex/extension. Conditions that did not achieve movements for >75% of the participants are grayed out.

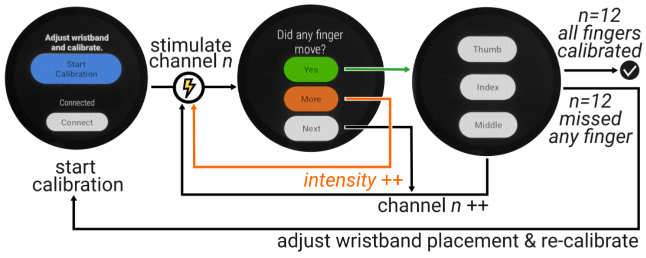

Figure 10: Our calibration app used in Task#1.

We ensured that the two conditions were balanced. Despite the difference in the number of electrode bands, both conditions had the same 12 stimulation channels. Finally, condition order was counter-balanced across participants.

Additionally, after the wrist-EMS condition, we validated the participants' calibration by having them use our navigation application (see *Applications* section), which was adjusted to work indoors for this study. Instead of walking outdoors, participants sat in a chair while our app autonomously updated their position to move along a predefined route. The wrist-EMS actuated their fingers corresponding to the turns (index finger extension for the left turn and middle finger flexion for the right), and upon arrival at the destination (thumb extension to represent a 'thumbs up'). We also placed the watch screen showing the route for context.

Task#2: wear wrist-EMS in public. In this task, we instructed participants to wear our complete device (shown in *Implementation*), go to a café at the lower level of the building by themselves, buy a drink with a voucher, and then return to the study room. En route, a study confederate appeared (an experimenter that was not known to the participant), introduced themselves, offered to shake hands with the participant's left hand (where they wore the device), and engaged in a conversation with the participant—this is a standard method common in behavioral psychology [20] to create a naturalistic interaction with a stranger. We did not control the content of the conversation but timed it to last four minutes, after which the confederate departed. In total, participants experienced three social situations: (1) a conversation with a stranger; (2) walking by people; and, (3) ordering an item at the café.

Interview. Our semi-structured interview included three phases. **(1) Calibration**: after participants finished calibrating the EMS, we asked them about their experience. Then, after both conditions, we inquired which condition they preferred and the reasons behind their choice. **(2) Application use**: following the navigation application with wrist-EMS, we gathered feedback on their experience. **(3) Social situations:** after Task #2, we asked how wearing the device influenced their behavior in social situations, namely, conversations, handshaking, and visiting a café. Additionally, we explored their feelings about wearing the device in the presence of bystanders and strangers, and whether these feelings would change if they were using forearm-EMS instead. In total, this portion comprised of eight questions. Finally, interviews were recorded in audio (with participants' consent) for transcription.

8.2 Task 1 Results: Calibration & Preference

Figure 11 shows the quantitative results. We first found a significant difference in calibration time (paired t-test, $p<0.05$): wrist-EMS (M=7.7 min, SD=4.6); forearm-EMS (M=14.9 min, SD=10.1)—wrist-EMS was ~ 50% faster. Secondly, we found a significant difference in the number of adjustments that participants performed on device placement (paired t-test, $p<0.05$): wrist-EMS (M=0.75 adjustments, SD=0.9); forearm-EMS (M=2.1 adjustments, SD=1.9). Finally, we found **all participants preferred wrist-EMS** during calibration. Note that both setups were new to the participants and just differed in their number of electrode bands. Next, we turn our attention to participants' comments.

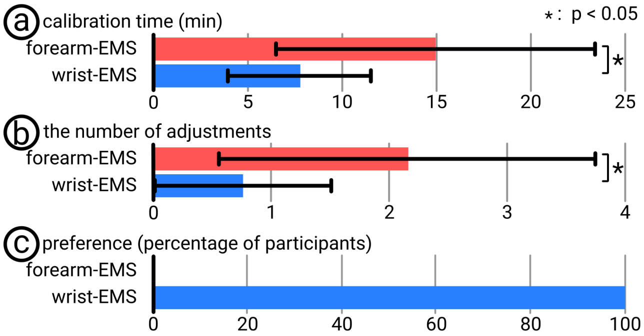

Figure 11: Results for (a) calibration time, (b) number of electrode band adjustments, and (c) participants' preferences. (Error bars depict 95% confidence intervals).

Wearability during setup. Seven (out of eight) participants directly remarked that a singular electrode band at the wrist facilitated their experience, their comments included: "less bands to move, so [it was] easier to set up" (P2); or "but this one, I only have to change one thing, and there (. . .) easier in that way" (P5). Moreover, four participants mentioned that an EMS device on their wrist felt easier to calibrate. For instance, P4 elaborated that the wrist was "a narrower target." Notably, three participants explicitly compared wearing our device on the wrist to wearing a watch. For instance, P1 described that "I would compare it definitely to putting my watch on the morning". Moreover, P6 added "I think definitely [wrist-EMS] is more comfortable because I wear my watch every day and also some bracelets so I'm more familiar with that." In contrast, this participant expressed forearm-EMS as "felt more like a medical device".

Using wrist-EMS in an application. Upon experiencing the finger actuation from the wrist-EMS in our navigation application, all participants had no issue with associating the force-feedback with directions. Namely, three participants described it as intuitive, their comments included: "those felt pretty intuitive to know where you're going" (P3); or "it's very easy for me to find association between them" (P6). P4 and P8 also detailed how wrist-EMS' force-feedback could add to their experience: "it gave me like, a sense of like, anticipation of when the turn was coming" (P4); and "(. . .) I don't have access to a screen, so I either use voice navigation or I can imagine using this device to like, force my hand to turn" (P8).

8.3 Task 2 Results: Public Interactions & Social Acceptance

During these social interactions (shown in Figure 12), all eight participants reported no change in their behavior while wearing the device. They described this across various contexts, for example: "It was a perfectly normal conversation (...) having the watch on felt very normal. I barely even noticed having it on" (P8); "I felt it was comfortable. I didn't really think too much about it" (P3); and "It was a normal interaction in the usual way I would order a drink at the café" (P7). Although the device did not affect their behavior, five participants observed that our device was thicker than their own watches, their comments include: "fits like any other industrial watch, obviously a little bigger than a normal watch, but wasn't intrusive" (P2); and "I mean, it's bulkier than something I would normally wear, but I didn't feel like anyone really noticed" (P7).

Figure 12: Participants wearing our device in social interaction scenarios (reproduced with participants' consent): (a) conversating with a "stranger"; (b) ordering a drink at a café.

How do you feel wearing this around strangers? None of our participants felt uncomfortable wearing the device around strangers, their comments included "the random people that I walked past they didn't even look twice, so it felt normal" (P1), "I think this is not awkward at all" (P6), or "like [a] fashion choice" (P8), underscoring a positive view of the device as an accessory. On the contrary, regarding the forearm-EMS, five participants expressed concerns about the visibility of the device, their comments included: "if I was wearing short sleeves, it would look really weird. I definitely wouldn't walk around" (P2); "I think definitely people would have like noticed me much more (. . .) I would have felt definitely more self-conscious" (P4); or "it would have felt more unnatural being there because I'm not used to having something stuck to my forearm like that" (P8).

Study conclusions. Taken together, the participants' feedback indicates that our wrist-EMS provided more practicality than forearm-EMS for the range of studied finger actuations, including faster calibration and social acceptance.

9 APPLICATIONS

Relocating EMS electrodes to the wrist and housing the hardware in a smartwatch enabled new EMS interactions, as well as expanded existing EMS-based interactions outside of the lab. To illustrate this, we developed two novel interactive applications and extended three existing EMS applications beyond tethered laboratory settings. All our applications were implemented via *Android Studio* and run on a *Galaxy Watch 5*; all applications communicate to our EMS device via BLE. Their source code is also in our repository[1].

9.1 Wrist-EMS Enables New Interactive Applications

The unprecedented wearability of wrist-EMS enables force-feedback in situations where existing EMS devices were impractical due to their interference with user's movements, unsuitability for public use, or need for lengthy calibrations.

Application#1: Haptic notifications for exercise. While vibrations are the most common haptic modality used for wearable notifications, our device allows users to benefit from more expressive haptics on their smartwatches. As depicted in Figure 13, we leverage force-feedback notifications during a HIIT (high intensity *interval* training) workout: (a) the wrist-EMS lifts up the thumb for each squat to indicate the cadence; (b) at the end of each HIIT interval, the wrist-EMS flexes the user's finger to indicate an interval is now done, and the rest will start; finally (c) when the rest period ends, the wrist-EMS flexes either the user's index, middle, or pinky fingers to indicate which exercise is next ("1", "2" or "3", from a list of different exercises the user loaded for this session).

Figure 13: Not just for tracking fitness, a smartwatch can now physically support workouts with our wrist-EMS.

Application#2: Eyes-free GPS navigation. As depicted in Figure 14, a user starts a wayfinding application to navigate to their destination using their smartwatch but continues eyes-free. In this example, instead of looking at the screen to check turns, the EMS integrated in their smartwatch directly actuates their (a) index finger, or (b) middle finger to indicate upcoming turns. Then, (c) actuates their thumb in a "thumbs-up" gesture to indicate the arrival at the destination. This functionality was implemented via *Mapbox API*.

Figure 14: Seamlessly integrating a wayfinding solution directly onto a user's hand with our wrist-EMS & Mapbox API.

9.2 Wrist-EMS Enables Prior EMS Apps Outside of the Lab

With the newly gained practicality of wrist-EMS, previous EMS applications can now be deployed outside of the lab settings.

Application#3: Haptic assistance in drumming. The compact form factor of our device allows it to be useful in a number of everyday situations, where pulling out an EMS device and calibrating it on the forearm would seem overly laborious. For instance, in Figure 15, a user benefits from force-feedback while using a drum assistant application: (a) after configuring the desired beat pattern (here a 4/4 beat), they (b) start the EMS, which in turn actuates the wrist to render the pattern, enabling the user to follow along.

Figure 15: Our drumming assisting app which allows users to update beat patterns on the spot, directly via the smartwatch.

Application#4: Smartwatch as VR force-feedback. The most popular usage of EMS in HCI has been adding force feedback for VR; however, most existing form factors to achieve this (e.g., [22, 33, 36]) all require electrodes to be worn or placed in the forearm, reducing the practicality for users that want to quickly start their VR applications. Figure 16(a) depicts our smartwatch with integrated EMS doubling as a force-feedback device for a user engaged in a VR driving simulation, holding the virtual steering wheel of their F1 car. (b) When they press the ignition button, they feel a resistance rendered by our device's index extension. Similarly, as they (c) shift gears, they feel the resistance of pushing the paddle up or down, which our device renders by flexing the middle finger or extending the index finger.

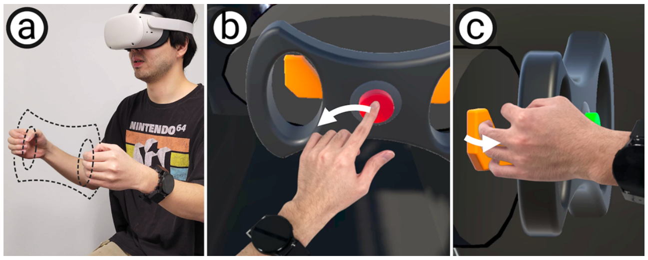

Figure 16: Our device doubles for enabling VR force-feedback.

Application#5: Actuating everyday objects with EMS. Finally, we depict a more public usage of EMS, made possible by the minimal form factor of our device. Purposefully, Figure 17 provides a reprise of *Affordance++*'s smart door [35], but this time, using our device instead of the traditional forearm-EMS. As in the original, this smart door provides the user who approaches it with haptic information, regarding if the occupant is busy or unavailable. As the user approaches the smart door, our application (running in the user's smartwatch) communicates with the door's microcontroller via BLE. When both devices are in range, the door informs the smartwatch of the occupant's status. (b) If the occupant has set the room to "unavailable", our smartwatch application responds by actuating the user's wrist with a "repel" gesture (achieved using our EMS extensions). Conversely, if the room was set to "busy", our device responds with a "knock-knock" gesture (rendered by alternating EMS flexions and extensions).

Figure 17: A more practical version of the door of *Affordance++* [35], leveraging the smartwatch's BLE integrated with EMS.

10 CONCLUSIONS AND FUTURE WORK

Smartwatches have gained popularity in the mainstream. Unfortunately, despite all the advancements in sensors that now fit well inside smartwatches, the large size of most actuators needed to render large forces makes force feedback impractical in smartwatches. Simultaneously, electrical muscle stimulation (EMS) promises a compact force-feedback that would be compatible with this form factor. However, to actuate the wrist or fingers, most EMS systems require users to wear many electrodes on their forearms—limiting the *practicality* of this force-feedback interface.

To address this, we proposed *moving all electrodes to the wrist*—conveniently integrating them into the backside of a smartwatch. Our compact EMS device resembles a wristband but features a custom EMS stimulator, 12 electrodes, demultiplexers, and wireless communication.

In our studies, we found that participants were able to calibrate our device by themselves ~ 50% faster than with conventional EMS in the forearm. Furthermore, all participants preferred the experience of this device, especially for its social acceptability & practicality.

We believe that our approach enabled new applications for smartwatch-based interactions, especially everyday interactions, which had been envisioned with EMS (e.g., haptic guidance and pose-based information output) but never realized via practical hardware.

For future work, we envision the integration of our approach with automatic EMS calibration techniques [25, 67] to enhance real-world deployment readiness. Additionally, we aim to enable our wrist-EMS to actuate fingers even as users' postures change dynamically. For this, we look forward to combining our technique with pose-detection techniques that can be integrated into a smartwatch [7, 28, 71]. To illustrate the ease of integrating wrist-EMS with other sensing approaches, we tested its integration with electromyography (EMG) sensing. Figure 18 shows the wrist-EMS electrode band momentarily converted into an EMG sensing band, enabling the detection of finger movements. In this example, the EMG signal on the oscilloscope indicates the extension of the index finger. Switching between EMS and EMG on the same electrode wristband can be achieved using time-multiplexing (e.g., as in [45]).

Figure 18: EMG sensing of the index extension via the same electrode wristband as wrist-EMS.

Finally, beyond the integration of sensing, it is important to also probe the experiential aspects of using our device, e.g., evaluating our eyes-free navigation app via navigation time & mental load, or exploring EMS force-feedback triggered amidst social situations. Moreover, future work should also examine if wrist-EMS retains the advantages of EMS over vibrotactile feedback, such as haptic realism [22] and notification efficacy in urgent situations [26].

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