

# Preserving Agency During Electrical Muscle Stimulation Training Speeds up Reaction Time Directly After Removing EMS

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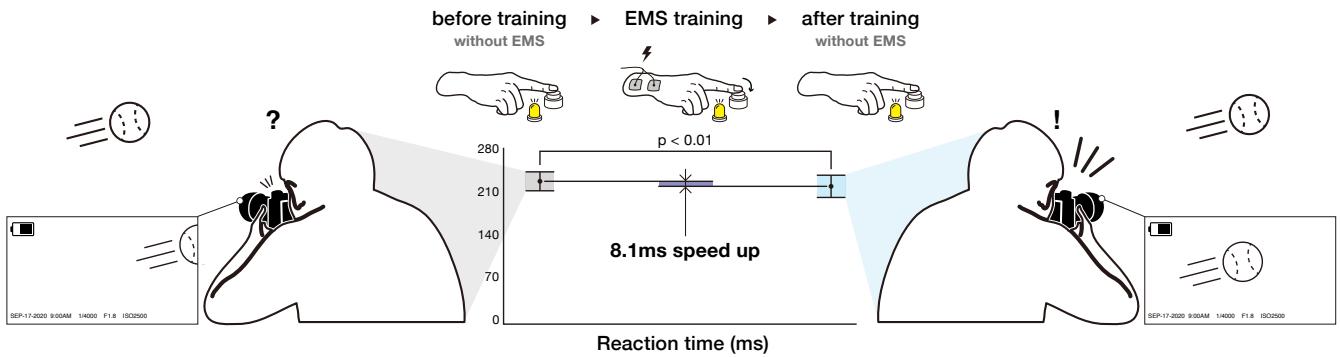
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**Figure 1:** We found that preserving the user’s agency while they are accelerated using a haptic device, such as electrical muscle stimulation (EMS), is key to retaining a faster reaction time *after removing* the haptic device. In our study, we used EMS to accelerate participants as they pressed a button when they saw an LED flash (inspired by taking a photo of a target).

## ABSTRACT

**Abstract:** Force feedback devices, such as motor-based exoskeletons or wearables based on electrical muscle stimulation (EMS), have the unique potential to accelerate users’ own reaction time (RT). However, this speedup has only been explored while the device is attached to the user. In fact, very little is known regarding whether this faster reaction time still occurs after the user removes the device from their bodies—this is precisely what we investigated by means of a simple reaction time (RT) experiment, in which participants were asked to tap as soon as they saw an LED flashing. Participants experienced this in three EMS conditions: (1) fast-EMS, the electrical impulses were synced with the LED; (2) agency-EMS, the electrical impulse was delivered 40ms faster than the participant’s own RT, which prior work has shown to preserve one’s sense of agency over this movement; and, (3) late-EMS: the impulse was delivered after the participant’s own RT. Our results revealed that the participants’ RT was significantly reduced by approximately

8ms (up to 20ms) only after training with the agency-EMS condition. This finding suggests that the prioritizing agency during EMS training is key to motor-adaptation, i.e., it enables a faster motor response even after the user has removed the EMS device from their body.

## CCS CONCEPTS

- Human-centered computing → Human computer interaction (HCI); Haptic devices.

## KEYWORDS

agency; electrical muscle stimulation; reaction time

### ACM Reference Format:

Shunichi Kasahara, Kazuma Takada, Jun Nishida, Kazuhisa Shibata, Shinsuke Shimojo, and Pedro Lopes. 2021. Preserving Agency During Electrical Muscle Stimulation Training Speeds up Reaction Time Directly After Removing EMS. In *CHI Conference on Human Factors in Computing Systems (CHI ’21), May 8–13, 2021, Yokohama, Japan*. ACM, New York, NY, USA, 9 pages. <https://doi.org/10.1145/3411764.3445147>

## 1 INTRODUCTION

Our nervous system possesses remarkable plasticity that enables us to improve our abilities by means of training, i.e., we get faster at tapping an icon on a screen or at sports by *practicing* these activities over and over. However, the optimization of our sensory and motor abilities by means of training is not a trivial task. It

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CHI ’21, May 8–13, 2021, Yokohama, Japan

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ACM ISBN 978-1-4503-8096-6/21/05...\$15.00

<https://doi.org/10.1145/3411764.3445147>

generally requires prolonged training on a task with a high number of repetitions in a trial-and-error fashion to get significant improvement [6]. To accelerate this cycle of learning (i.e., adapting one's motor patterns to acquire a new skill), researchers have been employing haptic devices, especially wearable ones. These are lightweight on-body haptic devices with sufficient force to actuate the user's body, and therefore, are able to physically enhance the user's motor abilities. As an example, exoskeletons [16] have been shown to augment users' grasping force [46] and to even improve their musical performance [41].

A more recent and emerging class of haptic devices for skill training are interactive systems based on electrical muscle stimulation (EMS). EMS induces involuntary muscle movements by applying electric pulses via electrodes attached to the user's skin. Besides actuating the user's muscles, EMS also provides also strong proprioceptive feedback to the user [25]. As such, EMS has been used to build interactive devices useful for: navigation [31], training a new skill (e.g., a musical instrument) [8, 42], and even learning how to operate tools that the user has never seen before [26]. These EMS-based force feedback devices have the potential to enhance our abilities and complement the traditional skill training. For example, it has been shown that EMS accelerates users' reaction time (RT) when EMS is applied before users' own action (preemptive-EMS) while even preserving their sense of agency [19]. However, it remains unclear whether this speedup *only occurs in the presence of EMS or also after the user removes off the haptic device*.

In this work, we tackle precisely this question to understand whether the accelerated reaction time caused by these devices happens even after the user has *removed* the device from their body. To answer this question, we conducted a simple user study in which participants were trained to press a button whenever they saw an LED flash (no-decision making involved), inspired by how one might attempt to take a picture of a fast moving object as soon as one spots it. Our results, depicted in Figure 1, suggest that timing the EMS impulses so as to preserve one's agency allowed participants to retain some of the speedup even after removing the muscle stimulation device from their bodies.

## 2 RELATED WORK

Our approach builds on the areas of haptics (such as EMS or exoskeletons), motor skill learning in neuroscience, and theories of the sense of agency from cognitive psychology.

### 2.1 Defining Learning and Motor adaptation

In psychology, learning has been defined as "changes in behavior as a result of experience" [22]. This definition applies to many situations involving users interacting with computer interfaces, as well as to our case (i.e., users pushing a button on a interface). On the other hand, we also acknowledge that this definition has been a point of controversy too [7]. As such, we denote the particular type of process that we are investigating in this paper as "adaptation", which has been used to indicate motor learning that lasts for short durations (in the order of minutes)—from the taxonomy of human sensorimotor learning by Krakauer et. [21]. In their breakdown, sensorimotor learning is comprised of several processes if which motor adaptation is a key process prior to long term skill learning [21].

### 2.2 Haptic devices capable of limb actuation (force feedback)

Force feedback systems are capable of moving a user's limbs, typically by applying a force that causes it to move even against the user's volition. There are, generally speaking, two main classes of actuators that provide enough output force to actuate human limbs: mechanical actuators (e.g., large robotic arms [35] or exoskeletons [14, 41, 46]) and EMS. Mechanically actuated exoskeletons provide force feedback for a wide range of haptic use cases, such as power assistance [46] or guiding the motion [41].

### 2.3 Electrical Muscle Stimulation

Electrical Muscle Stimulation (EMS) is an alternative means to achieve force feedback at a much smaller hardware footprint, i.e., typically interactive systems based on muscle stimulation are smaller, and therefore wearable, when compared to their mechanical counterparts. EMS originated in rehabilitation medicine as a means to restore lost motor functions, e.g., after spinal cord injuries [40]. Only recently, EMS was used in the domain of interactive devices, mostly as a technique to create force feedback in virtual environments [9, 23, 24, 27], as a method to miniaturize mobile information access systems [25, 30], and for training and tutorial purposes [8, 26, 29, 31, 42].

The latter systems that leverage EMS for training are of particular importance to our research question. For instance, in *Stimulated Percussions*, EMS enables the user's wrists to involuntarily drum on the correct tempo [8]. As another example, the *PossessedHand* device electrically actuated the user's muscles to reproduce the finger poses required to play stringed musical instruments [42]. These devices hint that EMS actuation is useful to learn a physical skill. However, all prior EMS research falls short in demonstrating that EMS provides a benefit to training *after* the user removed the electrodes and EMS stimulator. Essentially, a lot is known while users are wearing EMS devices but nothing is known after users have removed these.

A more recent emerging direction for EMS is using it to exceed the user's own physical abilities. For instance, in *Wired Muscle*, researchers demonstrated that when moved by means of EMS, a user can display an accelerated reaction time; therefore, in the presence of the EMS assistance the user's reaction time is faster than their own reaction time [29]. Furthermore, by delivering the EMS impulses in a particular time window (around 80ms faster than the user's own reaction time), researchers have optimized EMS systems to accelerate the user's reaction time *without entirely compromising the user's sense of agency* [19]. However, once again, the question whether the user can achieve this after taking off the EMS system is unsolved. Is this speedup permanent or only happens in while the user is connected to the EMS electrodes?

### 2.4 Reaction time

Reaction time (RT) is one of the fundamental factors in human computer interaction. The importance is evident in our everyday interactions with computer systems, be it clicking a target with a mouse, pressing a digital camera shutter, pressing a key to jump on a platform game, or swinging a bat in VR to hit a virtual baseball.

Generally speaking, speeding up one's reaction time offers a simple way to speed up interactions with computer systems. Moreover, when any system interface with human lives, it is critical even for survival, e.g., the shorter the reaction time of a pedestrian startled by a horn of an incoming vehicle is, the more time they have to avoid the danger. Psychophysical studies have long measured the reaction time of participants in response to visual stimuli, which has been found to be around 250 ms [18]; this metric became an important parameter in engineering interactive systems. Moreover, while one's reaction time appears relatively stable it is of course influenced by other physiological parameters, such as physical exhaustion [3, 28] or sleep deprivation [37]. Many other parameters are thought to potentially influence one's reaction time, for instance adrenaline excretion; however, some studies did not find evidence to support it [28].

Naturally, reaction time decreases with training, i.e., one becomes faster at reacting [1, 43]. For instance, Taniguchi et al. and Ando, et al. showed a reduction in reaction time in a simple reaction task with three weeks training. As these previous works suggest, a user's reaction time can be improved (i.e., sped up/shortened) through training [1, 2, 43]. In light of this, we ask our research question again: if we accelerate a user's reaction time externally during training, e.g., by means of EMS, does this user still exhibit an accelerated reaction time after they remove the EMS device from their body?

The key difference between a movement that is accelerated by EMS and one that is not (e.g., during voluntary training) is *the lack of agency experienced during EMS*, i.e., with EMS, the user is *moved by the EMS system* rather than self-propelled. As such, one would not expect that much of the improvements that EMS can do on the user's reaction time would last after the user has removed the device. However, previous work has shown that even when stimulated by means of EMS one can conserve some agency if the EMS impulses arrive within a certain time window (as found in [19]). So, we put forward a new hypothesis: **could this type of EMS that preserves agency lead to more speedup after training when compared to naive EMS?**

### 3 OVERVIEW OF STUDIES AND OUR HYPOTHESIS

We hypothesize that agency is key to retain the accelerated reaction time that one experienced by means of EMS training. Simply put, we expect that without feeling that we have performed an action *by ourselves*, it is unlikely that we become better at it. With this insight in mind, we formulated our hypothesis: *effects of training should more pronounced when participants felt agency of their action during the EMS training*. This is precisely what we set out to study in our main experiment.

To measure participants' reaction times, we employed a standard visual reaction task with finger tapping. To understand if there was a improvement in participants' reaction time, we compared reaction times before (pre) and after (post) training with EMS-actuated finger movements. Note that both pre and post measurements are taken without the participants wearing an EMS device. Only in between these two phases they train using EMS.

In order to investigate whether agency is key to this motor-adaptation effect, we need to use an EMS approach that allows participants to preserve some sense of agency, even though their reaction time is actually accelerated; this is achieved by adjusting the timing of the EMS impulses so that it is closer to the user's own voluntary reaction time and becomes somewhat imperceptible to the user—this is the so called "Preemptive Action" [19]. To estimate the preemptive time window (how early the EMS is applied) for our main study, we first replicated the study by Kasahara et al. from [19]. Given that our apparatus was different from that of Kasahara et al.'s (i.e., we utilized a more precise touch detection system at a sampling rate of 1KHz), this also implied the needed replication. We therefore conducted two studies: (1) **determination of preemptive timing** (replication study) and (2) **is agency the key for user's adaptation to faster motor responses?**; the latter is our main study.

### 4 STUDY#1: DETERMINATION OF PREEMPTIVE TIMING

The objective of our first study was to investigate the relationship between EMS acceleration and perceived sense of agency in our experimental design, so as to **find the best EMS stimulus timing** that accelerates one's reaction time while also **preserving one's sense of agency**. Our study was approved by our local ethics committee.

#### 4.1 Task

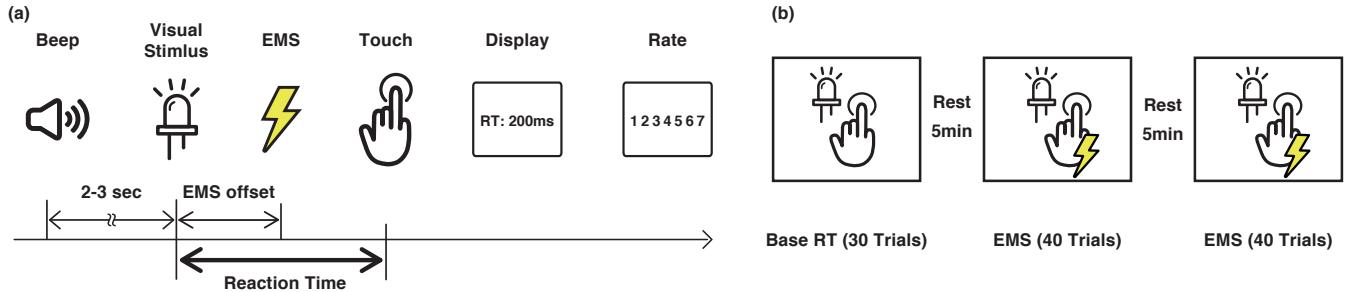
To measure participants' reaction times, we employed a standard visual reaction task with finger tapping, as in [19]: participants saw a light flash (using an LED) and tapped on a button as fast as they could, which is depicted in Figure 2 (a).

We used this standard and simple visual reaction time task to avoid potential confounds, such as other factors that can be modulated one's reaction time, such as stimulus complexity [17, 20, 32], stimulus-response compatibility [13, 38, 39], number of potential responses [5, 10, 15], intensity of the stimulus [4, 44], and an expected level of response accuracy [11, 12, 33].

During each trial, participant's reaction time was accelerated by means of EMS. The time window of preemptive stimulation (EMS offset time) ranged from -100ms (i.e., 100ms before the visual stimulus) to 300ms after the LED blink, in steps of 20ms. We randomized the EMS offset time for every trial. After each trial (i.e., observe light flash and tap on the button), participants were presented with their reaction time followed by a questionnaire regarding their perceived sense of agency. We follow the typical agency questionnaire, i.e., a Likert scale question with 1 = "I did not do it" and 7 = "I did it", as in [19].

#### 4.2 Procedure

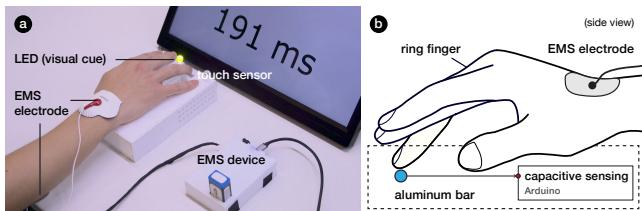
Before engaging in the study, participants were briefed on the study protocol. Then, as depicted in Figure 2 (b), participants were asked to perform 30 trials to record their average reaction time without EMS. Then, we asked participants to perform two sessions of the simple visual reaction time test (40 trials), totalling 80 trials per participant. Participants took 5 minute breaks between sessions.



**Figure 2:** (a) In our study participants are asked to touch the bar as soon as the LED goes on. Then, an EMS impulse stimulates their finger to contract (from -100ms before the LED to 300ms after). After each touch, participants rated perceived agency on a scale from 1 to 7. (b) Procedure of Study #1. After measuring the average reaction time, participants performed the task with 2 blocks.

### 4.3 Apparatus

Our experimental setup is depicted in Figure 3-(a). To assist readers in replicating our experiment, we provide the necessary technical details and the complete source code<sup>1</sup>. Participants were actuated using the *bioSync* EMS device used also in [19].



**Figure 3:** (a) Setup for our visual reaction task. (b) Side view of our capacitive touch sensor mechanism.

**Hand and finger posture:** In this study, the experimental setup was controlled to eliminate possible disturbances such as posture change, decline of concentration, EMS responsiveness change, and visual stimulus size change. The finger-holder and the touch detection bar were adjusted per participant, ensuring the hand is a natural rested pose (Figure 3-(b)). Furthermore, this prevents participants' muscles from quickly getting tired.

**Measuring reaction time:** We utilized an Arduino-based capacitive touch sensor system with LED light as visual stimulus. This system measured the reaction time from the duration between the LED on and user's touch on an aluminum bar embedded in the finger-holder with less than 1ms of latency (which was verified using a high speed camera).

**Electrode placement:** A pair of electrodes was placed on each participant's *flexor digitorum profundus muscle*. This muscle flexes the ring finger clearly. We actuated the ring finger since, as found by other previous EMS researcher, one can "robustly actuate it without any parasitical motion of neighboring muscles" [19].

**EMS calibration:** We interactively adjusted the stimulation parameters to actuate the ring finger robustly for our task (i.e., to touch the button). The parameters used in EMS calibration were: a pulse width from 100-300 microseconds and the number of pulses,

between 1-4 repetitions. We chose this since prior research suggests that shorter stimulation is less noticeable [24].

**Robust muscle stimulation:** We performed an EMS stability test per participant to ensure that the EMS can actuate the ring finger stably. Participants are asked to relax their muscles while in the apparatus. Then, EMS impulses induced involuntary finger movements. After 30 trials, we evaluated the variance of the duration ( $T_{EMStoTouch}$ ) between the moment of triggering EMS and the moment of touch detection. When the variance of  $T_{EMStoTouch}$  was below 4ms, we consider this stable, otherwise we re-calibrated the EMS.

### 4.4 Participants

We recruited 18 participants (4 self-identified as female, 14 as male, M=23 years old; SD=2.60) from our local institution. Participants performed the experiment for a total of four days and received 70 USD as compensation for their time. With their prior written consent, we transcribed their comments. The study design was approved by the local ethics committee and all participants provided written informed consent prior to their participation.

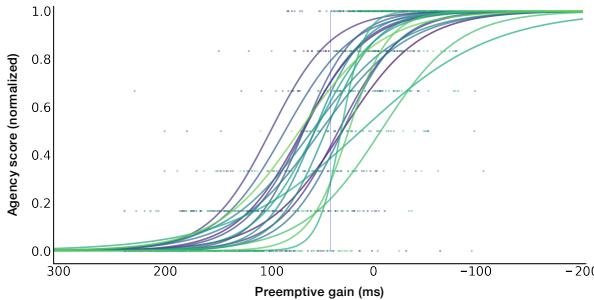
### 4.5 Results

We collected 80 trials per each participant, with two data points per trial: reaction time and assessment of agency. We found participants' average reaction time to be M=203.8ms (SD=15.0ms), which is close to findings in psychophysics research depicting a reaction time of 250 ms in response to visual stimuli [18].

Then, we normalized the data by subtracting each participant's baseline reaction time (their own voluntary reaction time, acquired prior to the study) to each trial's reaction time (with EMS actuation). This allows us to instead depict the time gained by means of pre-emption, which Kasahara et al. defined as **preemptive gain** [19]. Moreover, following [19], we also normalized the agency axis from 0 to 1.

Figure 4 depicts results for the relationship between **preemptive gain** and perceived sense of agency. Following the protocol of [19], we computed a logistic regression. This resulted in a mean fit of R<sup>2</sup>=0.74 (with SD=0.073, MIN=0.60, MAX=0.85) for our logistic model. This demonstrates that the participant's curves are in most cases similar and relatively consistent, as suggested by the

<sup>1</sup><https://lab.plop.es/#EMSSpeedup>



**Figure 4: Results for the preemptive gain timing.** We depict the relationship between sense of agency [0-1] vs. preemptive gain (timing of EMS in respect to the participant's own baseline). The solid lines represent regression curves derived from a logistic regression for each participant.

low standard deviation. From this curve, we found that 40ms of preemptive gain would provide a preserved sense of agency larger than 0.5 for 15 in our 18 participants. This mid-point in the sense of agency (0.5) was chosen accordingly to [19]. Therefore, we defined our agency-preserving EMS timing as **40ms**, which we will use in our next study. Last, this result appears consistent with [19] since: (1) the curve distribution is similar; and, (2) while the value is lower, this is likely due to our use of a more precise hardware apparatus (i.e., our touch sensor was implemented at the microcontroller level, instead of a via a laptop touchscreen).

## 5 STUDY#2: IS AGENCY THE KEY FOR ADAPTATION TO FASTER MOTOR RESPONSES?

The purpose of our main study is to shine light of whether preemptive EMS is the key for a motor adaptation effect, i.e., it allows users to become faster than they were, even after removing the EMS device. As such, we employed a standard *pre/post* learning study. We measure participants' reaction time prior to the study (we call this *pre-RT*). Then, we trained participants to perform a reaction test under a series of conditions (the same simple reaction tap-test from our previous study). Lastly, we measure their reaction time after this training (we call this *post-RT*).

This study uses precisely the same apparatus and calibration procedures as our previous experiment.

### 5.1 Conditions

We designed three experimental conditions, which are depicted in Figure 5. These were:

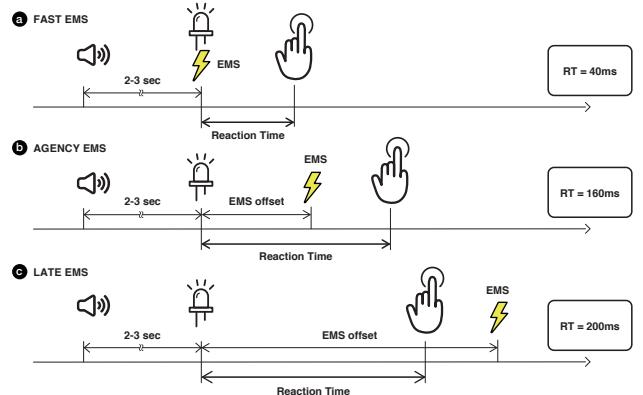
**1.fast-EMS:** EMS actuated participants' ring finger at the same time as the LED flashed ( depicts an EMS offset time of 0ms). Therefore, the measured reaction time is expected to be very fast; in fact, "super-humanly fast". Conversely, because the resulting reaction time is super-humanly fast, this condition results in no/very-low sense of agency (from [19]).

**2.agency-EMS:** EMS actuated participants' ring finger at 40ms of preemptive gain, where we expected to preserve some degree

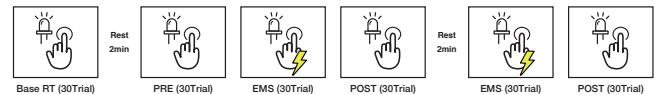
of agency according to previous experiment. The EMS offset time was calculated by subtracting  $T_{EMStoTouch}$  (EMS trigger to the touch detection) and preemptive gain (40ms) from  $T_{BaseRT}$  each participant's baseline reaction time (obtained pre-study). To sum it up, this condition enables a slightly faster reaction time, while preserving some degree of agency (from [19]).

**3. late-EMS:** EMS actuated participants' ring finger but only after the participant's baseline reaction time. The EMS offset time is defined as  $1.2 * T_{BaseRT}$  of each participant's baseline reaction time (i.e., participants are expected to be tap faster than the EMS assistance). In this EMS condition, participants will have complete sense of agency (or close to it, from [19]) but the reaction time will not be faster.

We added these conditions to allow us to make the proper comparisons. Only having *agency* as a variable would not allow us to exclude whether an EMS condition that makes subjects *act faster (speed)* could alone explain the gain in post-EMS reaction time. Thus, to have both *speed* and *agency* as variables it required us to the aforementioned design with these three conditions.



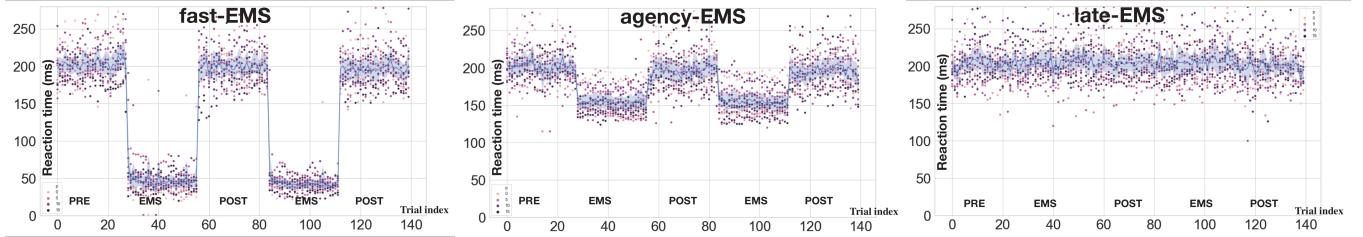
**Figure 5: We utilized three study conditions:** (a) *fast-EMS* (fastest but no sense of agency), (b) *agency-EMS* (faster and preserves some sense of agency), and (c) *late-EMS* (no speedup but with full sense of agency).



**Figure 6: The EMS training blocks were preceded and succeeded by a block that measured, respectively, the participant's pre and post reaction times.**

### 5.2 Hypothesis

Our hypothesis is: if agency is the key for motor adaptation, we should measure the largest adaptation effects (i.e., largest speedup in reaction time post-training) in the **agency-EMS** condition, when compared to any other condition.



**Figure 7: Reaction time (in ms) for all conditions: (top) fast-ems; (center) agency-EMS; and, (bottom) late-EMS.**

### 5.3 Procedure

Figure 6 depicts our study design. First, we measured the participant's baseline reaction time ( $T_{BaseRT}$ ). As described above, each participant's baseline is used to compute the precise timing of the stimulation in the **agency-EMS** condition (*preemptive gain - baseline*).

After this, participants engaged in two additional sessions, as depicted in Figure 6. The first session was comprised of three blocks: 30 trials without EMS (pre-RT), 30 trials with EMS (training), and 30 trials without EMS (post-RT). The second session was shorter, with one block of 30 trials with EMS (training) and one without (post-RT).

In order to isolate the influence of each condition, the three conditions were performed on different days. Our main study was conducted for a total of nine days, with breaks of three days in between. The order of these conditions was counter balanced. Lastly, participants were interviewed about their experience.

### 5.4 Participants

We invited 17 participants from the previous study (4 self-identified as female, 13 as male), only one participant (from the previous 18) was excluded due to low agency score on the previous study. This study occurred weeks after the previous one.

### 5.5 Results

We collected a total of 510 trials for pre-RT and 1020 for post-RT, for each conditions, totalling 1530 data points. Figure 7 depicts the raw reaction times for each condition. As expected, we observed that the measured reaction time was shorter during EMS session for both fast-EMS and agency-EMS condition, in contrast, the measured reaction time was longer in the late-EMS condition. The main question is whether there is a significant increase in post-RT that is dependent on agency, which will analyze next.

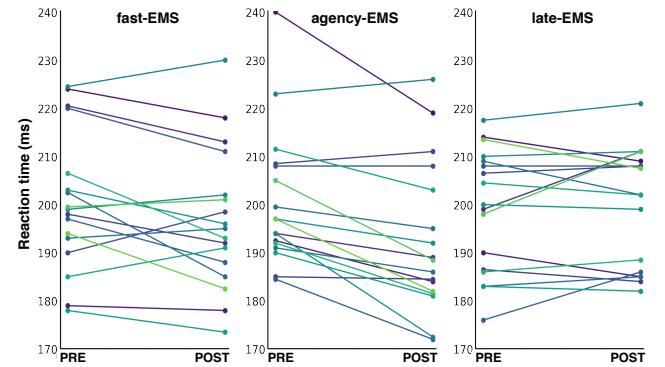
Note that before analyzing data, we excluded outliers. We removed data points with reaction time less than 100 ms (accidental activation of the touch sensor) or over 300ms (distracted participant). In total, we filtered 7% data from all data. Since the change of session may cause distraction, we also excluded first two sample data points from each session.

Furthermore, we confirmed that there was no session order effect throughout the study. We did not observe a decrease the reaction time over our study, since no correlation between the study order and the baseline reaction time on each day ( $R^2 < 0.0001$ ). We also confirmed that there was no after effect over the each sessions, since we found no correlation between the gain in the reaction time

within study session and the change in base reaction time between sessions ( $R^2 = 0.146$ ).

### 5.6 Analysis of the accelerated reaction time

Since the reaction time varies with participants and their condition in each day, we focus on the **gain** in reaction time after EMS session in each participant and each study session, i.e., a participant's post-RT - pre-RT. We depict this in Figure 8 denoting how each participant's reaction time (median) changed after EMS session for all conditions.

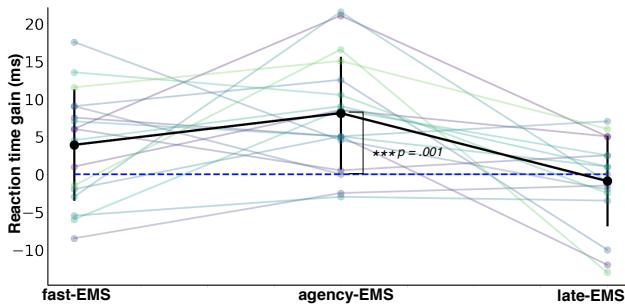


**Figure 8: Changes in pre-RT (reaction time before training, without EMS) and post-RT (after training, also without EMS), for all three conditions. Colored data points represent the different participants.**

To test whether the three EMS conditions led to differential gains in reaction times, we analyzed the gain in reaction time for these conditions by taking in the data from the two post-EMS blocks (Figure 9). Since no significant violation of normality was found in any data in median reaction times across participants (Shapiro-Wilk Test), we used parametric methods to evaluate a significance of statistical comparisons.

First, we performed one-sample t-test between the gain of median reaction times in each EMS condition and 0 ms to check the valid gain of reaction time.  $p$ -value was adjusted by the Bonferroni method. A significant gain was found in the agency-EMS condition ( $t_{16} = 4.47, p = 0.0011$ ). However, no gain was found for either the fast-EMS condition ( $t_{16} = 2.16, p = 0.139$ ) or the late-EMS condition ( $t_{16} = -0.63, p = 1.0$ ). Second, a one-way repeated ANOVA on the

gains indicated that the gains were significantly different among the conditions ( $F_{2,32} = 7.06, p = 0.002$ ). Post-hoc analysis using Tukey method showed a significant difference in mean gain of reaction time between agency-EMS and late-EMS condition ( $p < 0.1$ ). In contrast, other combinations of condition were not significant(fast-EMS: M = 3.88, SD. = 7.41, agency-EMS:M = 8.09, SD. = 7.46, late-EMS:M = -0.91, SD. = 5.99). Collectively, participants' reaction times were kept accelerated after EMS-actuated training that involves the sense of agency. **These results are in accord with our main hypothesis: retaining agency during training led to a more effective motor adaptation after EMS training.** In other words, only the agency-EMS condition revealed a significant difference from the baseline, indicating that only agency-EMS had an effect of the motor adaptation after the participants removed the EMS device.



**Figure 9: Gain in reaction time (in ms) for all EMS conditions. Colored plots depict a participant's median gain of reaction time from pre-session (before training, without EMS) to post-session (after training, also without EMS). The black solid plot depicts average gain across all participants.**

## 5.7 Qualitative results

We here describe the qualitative aspect of our study from post-interviews with participants. We structured each interview around three key questions, which were asked regarding each study condition: (1) "How did you feel in the trials?"; (2) "Did you feel any change in your behavior between start and end of this study?"; and, (3) "Did you feel in control of your actions in the trials?". These questions were used to initiate the conversation, often participants added more observations, which we present below.

First, in **late-EMS** condition, we observed two types of reactions from participants, both expected. In some situations, participants did not recognize the EMS sensation during the tapping action, as they mentioned "I was not confident to have stimulation in this [EMS] session"(P5) and "I did not feel the [EMS] feeling at all" (P7). Yet, in other trials participants, were certain about their sense of agency of the tapping action: "I felt EMS stimulation but I moved my finger completely by my self" (P5), "I clearly felt that EMS stimulation came after my movement " (P7). Either way, they were confident that they touched the sensor by themselves. Moreover, most stated that, similarly to P13, "I didn't fell any change in my reaction time".

In **fast-EMS** condition, almost all participants reported that they felt some sort of EMS impulse much earlier than their own movement. They unlikely felt any agency, as we observed many comments such as "[EMS] it was really fast, I didn't feel that I touched it by myself (P14)", "At the moment when I found the light is on, my finger finished the touch motion (P10)", and "I felt that my finger was completely actuated by EMS" (P8). Interestingly, three participants explicitly mentioned negative emotional valence connected to a loss of motivation, such as "I found catching up the speed of EMS [fast condition] is impossible, therefore I wanted to give up for the touch task" (P13), and even "I lose my motivation to move by myself because I know EMS will exceed my speed (P4)". These comments indicate that too much assistance is not beneficial. This is corroborated by research in motor learning [34, 36].

Conversely, in the **agency-EMS** condition, participants described a more integrated feeling of movement such as "I felt good timing" (P11), more specifically "EMS actuate me during [my] own touch" (P9). A reminder that while they reported a synchronized timing with EMS and self motion, the moment of actual EMS impulse was earlier then they do. In this view, this comment represents the internal feeling of EMS ; "It feeling like EMS helps me in right time between my intention and my movement"(P1). Other comments also aligned with the perceived sense of agency as "with this one [agency-EMS], I felt that I could touch faster even with my own touch, it was positive for me" (P11, and similarly P5). We observed analogous comments from other participants such as "I know EMS was triggered when the LED is on, but still I felt my control"(P4). Those observations are also consistent with previous research [19]. This further indicated that our agency-EMS with 40 ms of preemptive gain successfully preserved a partial sense of agency even with EMS acceleration. We also noted a more positive emotional valence relating to motivation, such as "I could more focus on the task (...) gives me motivation for better performance" (P11).

## 6 DISCUSSION OF OUR STUDY'S LIMITATIONS

Our study revealed that one's reaction time shortened after the EMS training session in which participants' sense of agency on their action was preserved (so called preemptive-EMS). However, for the sake of completeness and for assisting future researchers to build on our work, we discuss our study's limitations.

### 6.1 EMS-specific

First, we focused on using EMS as the force feedback device that provided the "accelerated" reaction-time experience. We chose EMS since it allowed us to actuate the user rapidly and safely at speeds faster than the user's own reaction time. Furthermore, the electrodes of EMS do not interfere by covering the user's fingers (as most mechanically actuated devices do), and EMS is a emergent area in HCI, which appears to many researchers as a promising approach in miniaturization of haptic actuation [23, 24, 26, 27]. However, other force-feedback devices such as exoskeletons are also promising for movement-assistance and rehabilitation. Therefore, an open question is whether one should extend our findings to exoskeleton and other haptic devices; we believe that warrants future work.

## 6.2 Why 8ms of speedup is actually a lot

In our study, the average acceleration gain of reaction time in 17 participants was about 8 ms on a grand average. Here, we would like emphasize two aspects: (1) the duration of the study session that induced the acceleration was very short yet it still was enough to trigger the speedup effect. Previous research reported that three weeks of long-term training accelerate the reaction time approx. 20 ms, and its acceleration would last three weeks [1, 2]. On contrast in our case, we were able to observe accelerations with only 30 or 60 EMS trials in agency-EMS condition; therefore, it is unsurprising that we observed less than the 20 ms seen by [1, 2]. (2) 8 ms is not small speedup, in professional sports (baseball, tennis, etc) or other activities that require very fast movements, 8 ms is considerable, i.e., in a fast tennis serve the ball moves 0.5 meters in a mere 8 ms, which means if the player cannot react 8 ms faster they would have completely missed returning a serve<sup>2</sup>.

## 6.3 Training period

There are studies that demonstrate how repeated sessions (longer training) consolidates the learning effect [2]. In this view, we also expect to enhance and consolidate the effect of acceleration by repeatedly performing our EMS learning process for a longer period of time.

## 7 APPLICATIONS OF OUR FINDINGS

We envision that researchers and practitioners might apply our findings to interfaces where short-term accelerations are useful and the interface does not require predicting complex user intentions. As such, we now illustrate the applicability of our findings by means of two examples, both of which provide the user with short-term benefits without requiring decision-making. These are useful for researchers working on haptic interfaces or other interactive use cases that leverage EMS to provide a speedup of the users' reaction time.

**1. Speedups for sports requiring fast-reactions.** One of the most exciting applications of our work is to take our findings out of the lab and into user's body as they play/perform/train for sports that require fast-reactions. In Figure 10 (b) we depict this at the example of a user who trains for sprint runs by using a wearable EMS device on their legs (inspired by [45]), which assists them in retaining the speed-up of the starting trigger reaction time.

**2. Power-ups that speed up the user, not their video-game character.** Furthermore, the most intriguing and exciting of our findings is that our approach provides the experience of **boosting one's own reaction time** even if the context of application not just 'training'. Figure 10 depicts the example using our findings to transform the experience of playing a first person shooter game (games where players shoot targets as fast as possible). Here, a user can collect a "speedup power-up" that, rather than just making their avatars or rifle shoot faster, it makes the user shoot faster by means of preemptive EMS; literally accelerating the user. As a benefit, after collecting multiple of these power-ups, which act as a training EMS session, the user's own reaction time must get faster—as shown in our study.

<sup>2</sup>[https://en.wikipedia.org/wiki/Fastest\\_recorded\\_tennis\\_serves](https://en.wikipedia.org/wiki/Fastest_recorded_tennis_serves)



**Figure 10: Two applications.** (a) In this video-game, the user collects a "power-up" that instead of making their avatar shoot faster, it makes the user's own body shoot faster using EMS speed-ups. The power-up has a lasting effect because after the EMS training, the user still benefits from an accelerated reaction time. (b) This user trains for sprint runs with a wearable EMS device on their legs, which assists them in retaining the speedup for the starting trigger reaction time.

## 8 CONCLUSION

We demonstrated that it is possible to accelerate one's reaction time, by means of muscle stimulation, even *after the removing the EMS device and its electrodes*. In our study, we measured a user's reaction time before and after experiencing EMS in a reaction time experiment, in which participants were asked to tap as soon as they saw an LED lighting up in three EMS training conditions: (1) fast-EMS, the electrical impulses were synced with the LED; (2) agency-EMS, which made 40ms faster than the participant's own reaction time, thus preserving their partial sense of agency; and, (3) late-EMS: the impulse was delivered after the participant's own reaction time.

Our study revealed that participants' reaction time was significantly reduced by approximately 8ms (up to 20ms) in agency-EMS condition, even after removing the device. Our results suggest that the sense of agency plays a crucial role in the adaptation process for acceleration of reaction time.

As for future work, we expect that researchers might expand our findings to investigate how agency plays a role in more complex situations where users find themselves accelerated by means of EMS, yet, are still able to make decisions—a crucial element that we did not investigate in this paper.

## ACKNOWLEDGMENTS

We would like to thank Daisuke Tajima for his advice on the statistical analysis. This work was supported by JST Moonshot R&D Program (JPMJMS2013), JSPS KAKENHI (19H01041 and 20H05715) and Grant-in-Aid for JSPS Research Fellow (JP16J03777). This work is supported in part by NSF grant 2047189. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of any funding agencies.

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