

SplitBody: Reducing Mental Workload while Multitasking via Muscle Stimulation

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Figure 1: (a) This user finds themselves having to split their attention (dashed green arrow depicts their split attention) between two sub-tasks, continuously stirring the pot to make caramel (a repetitive muscle movement) and writing an essay (a cognitively-demanding task)—multitasking is hard and even a simple repetitive muscle task detracts an untrained user from devoting more cognitive resources to the competing task. To explore this space, we (b) propose using electrical muscle stimulation (EMS) to “split” the user’s body and allow the EMS (lightning icon depicts the electrical stimulation) to automate the simple & repetitive muscle movements while focusing on writing (depicted by the solid green arrow).

ABSTRACT

Techniques like electrical muscle stimulation (EMS) offer promise in assisting physical tasks by automating movements, e.g., shaking a spray-can or tapping a button. However, existing actuation systems improve the performance of a task that users are already focusing on (e.g., users are already focused on using the spray-can). Instead, we investigate whether these interactive-actuation systems (e.g., EMS) offer any benefits if they automate a task that happens in the background of the user’s focus. Thus, we explored whether automating a repetitive movement via EMS would reduce mental workload while users perform parallel tasks (e.g., focusing on writing an essay while EMS stirs a pot of soup). In our study, participants performed a cognitively-demanding multitask aided by EMS (*SplitBody* condition) or performed by themselves (baseline). We found that with *SplitBody* performance increased (35% on both tasks, 18% on the non-EMS-automated task), physical-demand decreased (31%), and mental-workload decreased (26%).

CCS CONCEPTS

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

KEYWORDS

Haptics, Electrical Muscle Stimulation, Agency, Mental Workload, Cognitive Load

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1 INTRODUCTION

Techniques such as electrical muscle stimulation (EMS) offer promise for assisting users with physical tasks. These interactive systems do this by automating entire movements, e.g., shaking a spray-can [47], tapping a button on a touchscreen [29] or playing a musical instrument [87]. However, it is key to note that the majority of these actuation systems improve the performance of a task that users are *already focusing on* (e.g., users are already focused on using the spray-can in [47] or already attempting to press the button in [29]). In other words, body-actuation driven by interactive systems (e.g., EMS) happens in the *foreground* of the user’s main



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focus of attention, in which the interactive system assists the user in completing the same task the user is *also* attending to.

Instead, we investigate whether these interactive actuation systems (e.g., EMS) offer any interactive benefits if they automate a task that the user is *not* attending to. In other words, we explore a novel space in which the body actuation happens in the *background*, out of the user's main focus of attention, enabling users to potentially attend to another task in parallel—this would enable new forms of physical multitasking.

However, much is unknown about body-actuating systems. When it comes to EMS, only recently have researchers found that actuating the user's muscles can also decrease the user's sense of agency [29, 30, 85] or even distract users (e.g., EMS causes a tingling that can distract [39, 44, 65, 74, 89]). Thus, while actuation systems can automate simple & repetitive gestures, it has not been studied whether their limitations (e.g., tingling or loss of agency) might prove detrimental to task performance by distracting users.

To shed light on this, we conducted a study where participants performed a cognitively-demanding multitask, in which both their hands performed parallel tasks: a repetitive movement task and a cognitive task. They performed these tasks twice, once with the movement task aided by EMS on one hand (a condition we call *SplitBody*) and another entirely by themselves (baseline).

We found that with *SplitBody*, participants reported less physical-demand (decrease of 31%) and less mental-demand (decrease of 26%) than when performing the task by themselves. Moreover, the performance increased by 35% (averaged over both tasks), including the task that was not automated by EMS, which increased by 18%. This suggested that, with *SplitBody*, participants were able to free-up cognitive resources that they then allocated to this task. Moreover, accounts of their experience suggested they felt less overwhelmed since they could just focus on one task—the non-automated cognitive task with *SplitBody* while not being distracted by the EMS moving their arm involuntarily.

2 RELATED WORK

Our work builds on interactive systems based on EMS that assist users by electrically actuating their limbs. While EMS is not the only class of haptic actuators capable of displacing limbs involuntarily, we focus on it due to its inherent wearability when compared to mechanical actuators [8–10, 18, 24, 57, 66]—EMS does not require heavy & cumbersome power supplies (e.g., batteries or air compressors).

2.1 EMS as a means to move the body

Electrical muscle stimulation (EMS) has been used to actuate muscles as a form of highly compact force-feedback. Many in HCI have explored its ability to actuate limbs, including: fingers [2, 31, 60, 86, 87, 91], wrists [11, 19, 46, 77, 79, 92], arm [13, 47, 48], legs & ankles [13, 22, 45, 73], and even neck [88]—all in wearable form factors. EMS has been used in a variety of tasks, from outdoor sports (e.g., golf [14] or running [22]), musical instruments (e.g., piano [61, 62, 86] or percussion [13]) to tool use (e.g., using a spray-can [47] or sketching [49]).

2.2 EMS is always in the foreground

EMS systems are typically used to aid users in tasks *they are already focused on*. For instance, in the seminal *PossessedHand* [87], EMS plays the next musical note for a user who is *already seated & playing* this musical instrument. Similarly, in *Affordance++* [47], EMS shakes a spray-can that the user is already focused on using. As such, designers & engineers tend to position EMS in the *foreground* of the user's attention by using the stimulation to tackle primary tasks. This approach proved successful in that it sparked new usages of EMS for interactive contexts. Thus, it inspired us to propose a new design position for EMS in the *background*, i.e., assisting the user by automating repetitive tasks, and leaving the user's attention to focus more on more challenging concurrent tasks.

To the best of our knowledge, this has not been systematically studied. The idea that comes closest and from which we draw inspiration is *Pedestrian Cruise Control* [73], an EMS system that turns the user's legs. While Pfeiffer et al. envisioned their system going as far as to help users by steering them automatically, they only tested it in a study where participants were not engaged in a multitasking scenario; in fact, participants who were being guided by the system to walk in a park were asked "to pay attention to any obstacles, (...) and to stop or circumvent these as necessary"; thus, the EMS of [73], much like prior work, was acting in the *foreground* of the user's attention.

2.3 Mixed agency while interacting with "integrated" devices

There is an emerging body of literature exploring the concept of *mixed agency* [55] between a user and their device [54, 55]. While EMS provides one of the most extreme case-studies for this concept [11, 15, 29, 30, 33, 46, 51, 55, 81, 82, 85], others have also started to discuss this for the case of force-feedback devices [12].

Central to the frameworks of thought in this area (e.g., human-computer *integration* [55] or [12]) are two dimensions: sense of *body-ownership* ("this is my body") and sense of *agency* ("this is my action") [12, 54]. In Mueller et al.'s taxonomy [54], most EMS interfaces score low on agency since users do not initiate the action that the EMS carried out. Conversely, EMS interfaces score high in ownership, since it is the user's body that carries out the actions [54]. The authors also emphasize that if the EMS system does not control the entire body, some agency remains [54]; this is also the case in *SplitBody*, as our users were always in control of other upper joints of the actuated extremity (e.g., they controlled their shoulder while their hand was EMS-automated). Taken together, this allows us to denote *SplitBody* as a type of EMS interface with high body-ownership but low agency.

Finally, it has been argued that these mixed agency devices introduce new design spaces that foster playful experiences [46, 54, 71], creativity [11, 13, 94], and even new forms of productivity [69, 83], to which we believe *SplitBody* contributes to with its *multitasking perspective* (i.e., design spaces with concurrent physical tasks).

2.4 Evidence of lower performance in physical multitasking

It is well-known that multitasking comes at a performance cost compared to only focusing on a single task. Neuroscientists and

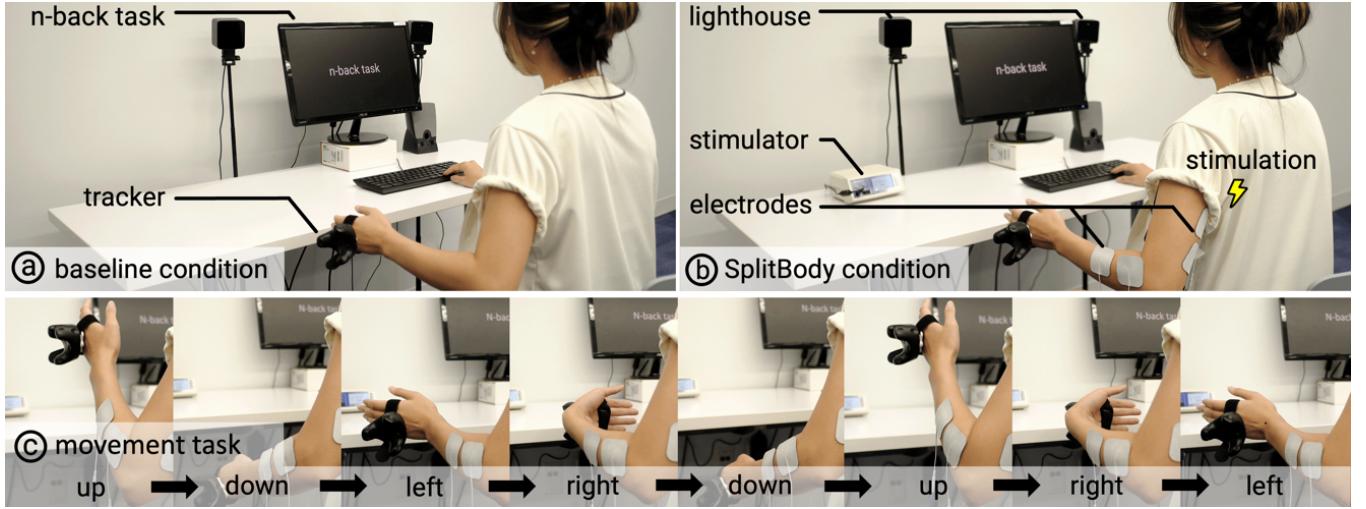


Figure 2: (a) In the baseline condition, the participants are performing a movement task and a n-back task by themselves. (b) In the *SplitBody* condition, the participants are performing the same tasks, but the movement task is being automated by EMS (lightning icon). In both conditions, the movement task (c) involves repeating the following arm gesture sequence: *up, down, left, right, down, up, right, and left*.

psychologists have correlated this cost to the limited cognitive resources available [4, 43] and the operations the brain undertakes when presented with a task: for each task, the brain has to ingest the information, process it, make a decision, and respond with movements. Therefore, when presented with concurrent tasks, the brain uses different strategies [27, 70], such as processing one task before moving to the next one (causing a bottleneck) [6] or reducing the capacity to process tasks in parallel [59, 90]—both strategies increase completion time [53, 76] and lower performance [67]. To improve physical multitasking, researchers have looked at different interfaces, such as adding haptics.

2.5 Exploring haptics for mental workload reduction

Adding haptics allows the conveying of additional information to the user [1, 3, 26, 72]. Researchers have found that haptic cues can improve the performance of single tasks [1, 58]. More recent studies have also shown that similar results can be seen while multitasking, lowering mental workload. For example, Zhou et al. [93] showed that surgeons using a haptic simulator performed better against a no-haptics simulator while concurrently answering arithmetic problems. Leung et al. [40] also found that adding haptic-feedback to a touchscreen improved the response time when undergoing a concurrent auditory-task, but no performance improvement was found. Moreover, Haghghi et al. [20] investigated the ability to recognize haptic cues with vibration while performing a cognitive task (1-back) and found that some parameters improved response time, but none improved performance. These haptic systems provide only haptic cues (e.g., vibrations or resistance) but *do not move the body*. Thus, users still need to focus on *executing the movements required to perform all concurrent tasks*.

3 USER STUDY: DOES EMS REDUCE MENTAL WORKLOAD DURING PHYSICAL MULTITASKING?

The goal of our study was to evaluate whether the use of an interactive-actuation system (in this case, EMS) would reduce mental workload while users perform parallel tasks. To this end, we designed a multitasking study in which participants were asked to perform a multitask: aided by EMS (our *SplitBody* condition) or performed by themselves (baseline). Our study was approved by our ethics review board (*IRB21-1158*).

3.1 Hypotheses

Our main hypothesis (**H1**) was that the *SplitBody*'s ability to automate one of the tasks would result in a decreased mental workload, when compared to the baseline; as such, we utilized the NASA-TLX questionnaire [21]. Our secondary hypothesis (**H2**) was that this reduced mental workload (i.e., if H1 was true), we would observe an increased task performance; as such, we measured task accuracy and response time. A corollary of the previous hypothesis was that both performances of each sub-task should increase, i.e., (**H2.1**) increased performance of the task automated by EMS (movement task); and (**H2.2**) increased performance of the voluntary task (cognitive task).

3.2 Study procedure

Study design. Our multitask was based on two standardized designs: (1) a **cognitive task**—the *n-back* task [32], a popular cognitive load test [23, 25, 28, 68]; and (2) a **movement task**—a repetitive sequence of movement often used to analyze cognitive load [41, 42, 64]; except participants were requested to perform these two tasks *simultaneously*—resulting in a challenging multitask, similar to the one depicted in our Figure 1.

Participants. We recruited 12 participants (six female and six male; average age=27.4 years old; SD=8.0). No participant reported any motor impairment. Participants were compensated with 20 USD for their time.

Conditions. Participants performed the multitask twice, once per condition (condition order counterbalanced across participants), as depicted in Figure 2. During **baseline**, participants performed the multitask by themselves. During **SplitBody**, participants performed the cognitive task, while EMS performed the movement task.

Cognitive task (dominant-hand). The objective of our cognitive task was to keep observing a sequence of letters on a screen, shown one at a time, and respond if the current letter was previously shown—n-back task [28]. We utilized an N=2, i.e., participants indicated if the current letter was shown two letters ago (2-back). If it was a 2-back, participants were asked to press the left arrow. Conversely, if it was not, press the right arrow. If the participants failed to press a key or if two keys were pressed, their response would be considered an error. A total of 32 letters were presented for 500 ms each at 2500 ms intervals. Two predefined sequences of letters were generated from the following eight visually distinct letters: B, F, K, H, M, Q, R, X where each letter appeared exactly four times in both sequences. Of the 30 responses (first two stimuli do not have n-backs), 10 were n-backs, and 20 were not. Furthermore, the difficulties of both sequences were equalized by featuring three types of n-backs at equal numbers (here illustrated with A, B, C for explanation purposes): "A, B, A" was shown four times, "A, B, A, B" was shown twice and "A, B, A, C, A" shown once per sequence.

Movement task (non-dominant hand). The goal during the movement task was to perform a sequence of hand-gestures for as long as the trial lasted, as depicted in Figure 2 (c): *up, down, left, right, down, up, right, and left* at a constant tempo of 50 BPM. In the baseline condition, an audible metronome was heard (no metronome was used in the *SplitBody* condition, as EMS already provides a temporal cue). A complete sequence was considered valid if the participant's hand performed all eight gestures in the correct order (i.e., each gesture was performed before the end of the current beat, and two gestures were not performed within the same beat).

Combined task design. Performing these two tasks simultaneously is challenging. Thus, we designed the combined task to start incrementally, i.e., participants first started the movement task (two complete rounds of the sequence), and only then did the cognitive task start. This was beneficial, especially for the baseline condition, allowing participants to get "a feel" for the movement before adding the cognitive task.

Apparatus. Movements were tracked using a VIVE Tracker 3.0 attached to the hand. An additional RGB camera was used to record trials and transcribe post-interviews. In the *SplitBody* condition, we utilized a medical-grade muscle stimulator (HASOMED RehaMove3 [75]). The stimulator interfaced with the n-back software, which we implemented in Python via the RehaMove3's library¹.

EMS parameters & calibration. We attached four pairs of electrodes to participants' muscles at the: *palmaris longus* for wrist

flexion (right gesture), *carpi radialis longus* for wrist extension (left), *biceps* (up), and *triceps* (down). Each participant was calibrated so that the EMS parameters could robustly actuate each gesture. First, we determined the stimulation intensity (i.e., current in mA) for each muscle by starting at 0mA and a pulse-width of 300 μ s and increasing by steps of 1 mA until a full & repeatable contraction was observed while also being comfortable to the participant (no pain, cramps, etc.). The pulse frequency was fixed at 100Hz. This process was repeated for all muscles following an anatomical guide.

3.3 Trial design & metrics

Warmup. Prior to the tasks, participants were introduced to EMS by having their hands actuated at a constant speed of 30 BPM for three minutes while, simultaneously, the experimenter explained the n-back. After this explanation was completed, participants performed the multitask (once per condition, order counterbalanced).

Trial. Participants were asked to score as high as possible on *both* tasks. A trial started with a visual countdown and ended when the n-back letters finished. At the end of a trial, participants complete an unweighted NASA-TLX questionnaire. Then, participants were invited to provide feedback on what they just experienced.

Performance metrics. (1) **Movement task performance** was scored by the number of correctly performed sequences divided by the maximum number possible during a trial, which was ten full sequences. Moreover, we also recorded the response time of each movement according to the expected 50 BPM beats. (2) **Cognitive task performance** (n-back) was scored by the correct number of answers over the total number of letters (30). Moreover, we also recorded the response time. Finally, the NASA-TLX was scored by averaging equally the six metrics (unweighted TLX)—the higher a TLX score is, the higher the perceived workload was.

3.4 Results

Movement task performance. We analyze the *movement task performance*. As our data did not follow a normal distribution using the Shapiro-Wilk test, we conducted a Mann-Whitney U-test. We found a significant difference ($p<0.005$) between movement task performance of *SplitBody* ($M=79\%$, $SD=26\%$) and baseline ($M=28\%$, $SD=21\%$). Results suggest that **movement performance was**

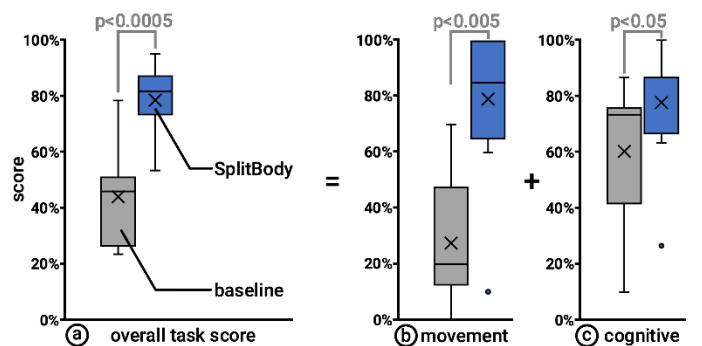


Figure 3: (a) Score with *SplitBody* and baseline, including a breakdown for the (b) movement (gesture) and (c) cognitive (n-back) tasks.

¹We provide all source-code needed to replicate our experiment in the supplementary material and at <https://lab.plop.es/#SplitBody>.

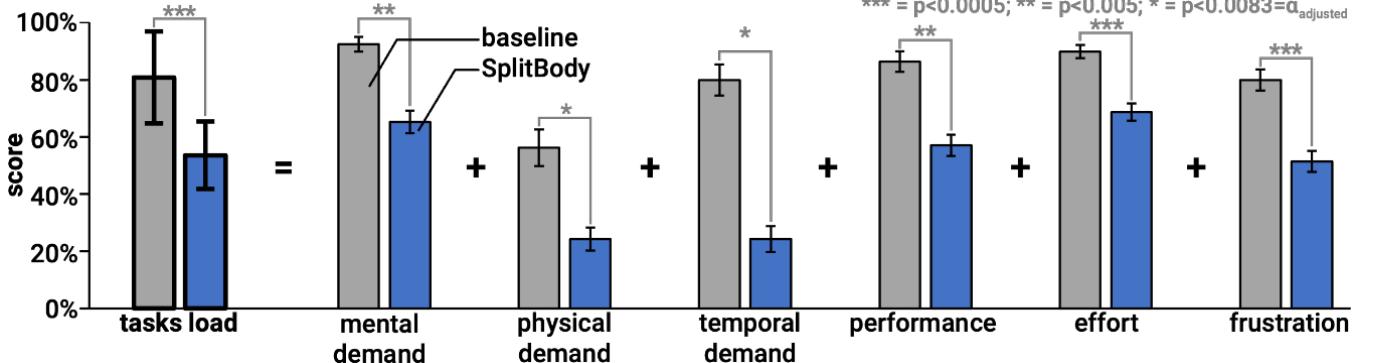


Figure 4: The NASA Task Load Index score for both conditions.

increased 2.5x with SplitBody, as depicted in Figure 3 (b). Note that this was expected since we calibrated the EMS to be robust and it was automating the task. This result supports our H2.1 (i.e., increased performance of the EMS-automated task).

Cognitive task performance. Most relevant to our H1, we analyze the *cognitive task performance*. As our data did not follow a normal distribution using the Shapiro-Wilk test, we conducted a Mann-Whitney U-test. We found significant difference ($p<0.05$) between cognitive task performance of *SplitBody* ($M=78\%$, $SD=19\%$) and baseline ($M=60\%$, $SD=23\%$). These results suggest that **cognitive task performance was increased by 1.3x with SplitBody**, as depicted in Figure 3 (c). Average wrong-answers decreased by 1.6x with *SplitBody* ($M=13\%$, $SD=6\%$) compared to baseline ($M=21\%$, $SD=9\%$). Similarly, average no-answers (failed to press either key as a response, potentially caused by mental overload) decreased by 2x with *SplitBody* ($M=9\%$, $SD=19\%$) compared to baseline ($M=19\%$, $SD=24\%$)—These results are highly supportive of our H1, this task was performed by participants unassisted (no EMS), suggesting that the gain was due to the *SplitBody*'s assistance of the background task. This also further supports our H2.2 (i.e., increased performance of non-automated). Critically, this increase in performance on the cognitive task shows that despite EMS' shortcomings (e.g., EMS can distract with its tingling sensation [39, 44, 65, 74, 89]), it provides a benefit when automating another demanding task.

Overall performance. We analyze the *overall multitasking performance*, i.e., the average of both tasks. As our data followed a normal distribution using the Shapiro-Wilk test, we conducted a two-tailed paired t-test. We found a significant difference ($t(11)=5.6$, $p<0.0005$) between the multitask performance of *SplitBody* ($M=78\%$, $SD=13\%$) and baseline ($M=44\%$, $SD=17\%$). Results suggest that **multitasking performance was almost doubled with the SplitBody**, as depicted in Figure 3 (a).

Workload (NASA TLX). Figure 4 depicts our results from the NASA-TLX unweighted questionnaire (higher values indicate higher perceived workload). All comparisons below are Bonferroni corrected ($\alpha_{adjusted} = 0.0083$).

First, we analyzed *workload* data, which followed a normal distribution (Shapiro-Wilk test), with a two-tailed paired t-test. We found a significant difference ($t(11)=5.7$, $p<0.0005$) between the workload with *SplitBody* ($M=52\%$, $SD=11\%$) and baseline ($M=78\%$,

$SD=14\%$)—suggesting that **workload was 1.5x lower with SplitBody**. Second, we analyzed *mental-demand* data, which did not follow a normal distribution (Shapiro-Wilk), with a Mann-Whitney U-test. We found significant difference ($p<0.005$) between mental-demand with *SplitBody* ($M=63\%$, $SD=4\%$) and baseline ($M=89\%$, $SD=2\%$)—suggesting that **mental-demand was 1.4x lower with SplitBody**. Third, we analyzed *physical-demand* data, which followed a normal distribution (Shapiro-Wilk), with a two-tailed paired t-test. We found a significant difference ($t(11)=3.2$, $p<0.008$) between the physical-demand with *SplitBody* ($M=23\%$, $SD=4\%$) and baseline ($M=54\%$, $SD=6\%$)—suggesting that **physical-demand was 2.3x lower with SplitBody**. Next, in a similar fashion, we conducted statistical analyses for the remaining NASA-TLX metrics, all found to be significantly different: (1) *temporal-demand* using a Mann-Whitney U-test ($p=0.0081$, not normal distribution via Shapiro-Wilk); (2) *perceived performance* via Mann-Whitney ($p<0.005$, not normal distribution via Shapiro-Wilk); (3) *perceived effort* via two-tail paired t-test ($t(11)=6.6$, $p<0.0005$, normal distribution via Shapiro-Wilk); (4) *perceived frustration* via two-tail paired t-test ($t(11)=6.1$, $p<0.0005$, normal distribution via Shapiro-Wilk). Overall, these results indicate a **decreased perceived workload using SplitBody**.

Response time. Figure 5 depicts participants' response time, which, as we will analyze, we found to be statistically faster with *SplitBody* than with the baseline condition.

Both movement and n-back response time data followed a normal distribution via Shapiro-Wilk. Using a two-tail paired t-test, we

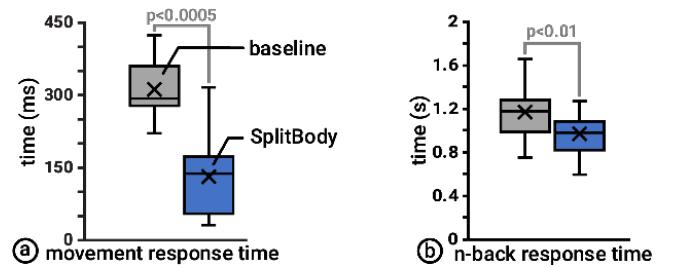


Figure 5: Response time results: (a) movement task and (b) cognitive (n-back) task.

found both tasks to be statistically different: (1) *movement response time* ($t(11)=5.2$, $p<0.0005$) with *SplitBody* ($M=131\text{ms}$, $SD=82.8$) compared to baseline ($M=312\text{ms}$, $SD=59.0$), and (2) *n-back response time* ($t(11)=3.3$, $p<0.01$) with *SplitBody* ($M=0.93\text{s}$, $SD=0.20$) compared to baseline ($M=1.17\text{s}$, $SD=0.24$). Results suggest that, as expected, participants were 2.3x faster at movements with *SplitBody* but, more importantly, **1.2x faster at answering the n-back task with *SplitBody***.

3.5 Participants' experiences

Perceived improvement. Ten (out of 12) participants expressed that they perceived performing better with *SplitBody* (P1, P2, P4, P5, P6, P7, P8, P9, P10, P12). For instance, P12 stated, "with [*SplitBody*] I did not have to think too much about the direction of moving the left hand, so I could focus on the [n-back] task". Of the two participants who did not mention a perceived improvement with *SplitBody*, P11 stated "[I did] a little better with no EMS (...) but pretty close [on both conditions] for the computer task", and P3 stated that they "performed better on the movement task without EMS but did better in the [n-back] with EMS." These are perceived scores, not their scores; in fact, P3 performed marginally better with *SplitBody* (2%) and P11 performed 40% better with *SplitBody*.

EMS distractions. Overall, seven participants specifically stated they did not find EMS distracting (P1, P2, P4, P5, P6, P7, P12), while five still found it distracting (P3, P8, P9, P10, P11). Of the participants who stated not to find EMS distracting, P2 noted "I wasn't even focused on it (...) since I was focused on the [n-back]", while P6 stated "the EMS intensity was just enough that I could put it in the background." On the other hand, three participants (P8, P9, P10) mentioned that the EMS was, at times, too strong and distracting. To this end, P10 stated "I felt like the pulse was strong, and I would forget the letter I was on, but for the most part, it was fine."

Trust in EMS' performance. All participants, except P6, stated they trusted the EMS automation to perform the correct pattern. They expressed either forgetting about it, such as P9 stating "I did not think about it at all. I did not even think about if it was doing the wrong pattern", or feeling that it was correct, as P10 stated, "I did not question it (...) they seemed correct". P6 stated being skeptical at times, saying, "I was trying to optimize the letter task. There were times I was doubting [the EMS movements]; it feels like at times, I think it wasn't going in the right direction of the sequence, but I was also not focused on it, so it was hard to keep track".

3.6 Discussion & study limitations

Summary of findings. Taken altogether, our results (i.e., reduced overall workload and mental-demand) support our main hypothesis (H1, i.e., our *SplitBody* condition's ability to automate one of the tasks would result in a decreased mental workload). We also observed increased performance & faster response time, supporting our second hypothesis (H2, i.e., reduced mental workload improves task performance).

Study limitations. Our study is not without its limitations. First, we focused on creating a challenging multitask and thus

resorted to one that combines muscle movements and cognitive operations (e.g., short-term memory). Yet, this is only one of many possible physical multitasking situations that users encounter, so we advise to be mindful in extrapolating our results to tasks that are fundamentally different. Secondly, the ability of the EMS actuation to assist users with complex movements is limited by the capability of EMS research (e.g., many explore how to make it more precise [2, 7, 16, 31, 34, 37, 46, 63, 86, 91]. In fact, our observations lead us to believe that there are per-participant differences in how well participants let the EMS move their hands (e.g., we noticed that three participants tensed up their non-dominant hand as they are not used to the feeling of having their limb move involuntarily, and hence decreasing the quality and precision of each EMS stimulate). This points to an open challenge in EMS research in optimizing how natural these actuated movements feel to the user.

4 ENVISIONED APPLICATIONS

We illustrate the use of *SplitBody* in four envisioned applications, in which our system assists by performing repetitive background tasks: (1) writing while cooking; (2) drawing while coloring; (3) soloing on the snare-drum while playing a backbeat; and, (4) playing an instrument while being accompanied by another.

We designed these applications to highlight scenarios that are not meant to be automated by a machine, but instead, where users seek to be physically engaged in the task, either for the sake of creativity (e.g., drawing), learning (e.g., playing music), or pleasure (e.g., cooking). These were chosen to convey how *SplitBody* can open up a new design space for interactive EMS systems.

Also, these examples were designed by taking into account the precision of existing EMS systems. In fact, the interactions depicted were designed conservatively with respect to the accuracy already possible with EMS.

4.1 Split-chef: making caramel while writing an essay

In our first envisioned application, a user multitasks by preparing caramel while writing an essay. Making caramel demands constant stirring and monitoring to prevent burning. Our user taps on their EMS device, activating a pre-programmed stirring motion with *SplitBody*. This allows them to divert their focus to writing, as shown in Figure 6 (a). Once they feel the sugar is consistently melted, as their sense of proprioception lets them feel the change in viscosity while stirring (even though this hand is EMS-controlled, proprioception is never off [46]), they suspend writing to switch their focus to add butter into the pot, finalizing the mixture, as depicted in Figure 6 (b). Subsequently, they switch back most of their focus to writing as the EMS continues stirring the added butter. Upon achieving the desired caramel consistency, they tap the stimulator to stop *SplitBody*. While this application is envisioned due to its simplicity (e.g., open-loop-EMS, no-tracking), the user in Figure 6 (c) was indeed successful at cooking/writing with *SplitBody* while avoiding burning the caramel (this caramel was taken home for their enjoyment).



Figure 6: (a) A user is multi-tasking by making caramel with *SplitBody* on their left arm (lightning icon) while they are writing an essay with the other arm (solid green arrow depicts their main attention). By feeling the consistency of the melted sugar in the pot, (b) they switch their attention back to the cooking caramel (solid green arrow depicts the switch of their main focus) and butter to the mix while their left arm is still automated by EMS (lightning marker). Finally, (c) they stop *SplitBody* by taping on the stimulator.

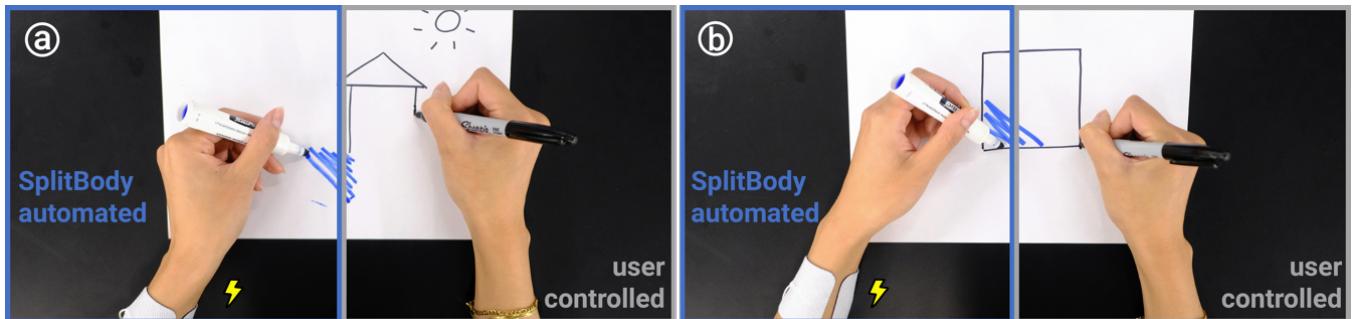


Figure 7: A user drawing (a) simple shadows and (b) coloring with *SplitBody* on their non-dominant hand (lightning icon) while continuing to draw with their dominant hand.

Technical feasibility. The EMS movement used in this application was inspired by Kaul et al.'s [31], which demonstrated that EMS can actuate a user's arm in a circular motion with an average error of 17.8mm—this system's implementation & accuracy would be sufficient to realize our proposed stirring gesture.

4.2 Split-draw: enabling synchronous shadow drawing and coloring while sketching

In this envisioned application (inspired by the *Split Body* artwork of Stelarc [84], to which our system's name is an homage), we explored drawing with *SplitBody*: (a) shadow-drawing and (b) coloring. While these are envisioned explorations, it is possible to track & actuate a user's drawing with an EMS system similar to *Muscle-Plotter* [49]. First, Figure 7 (a) depicts a user drawing a house under a sun. Because the user drew a sun, *SplitBody* actuates the user's non-dominant arm to simultaneously draw the shadows cast by the house without needing to shift all of their attention. Second, Figure 7 (b) shows *SplitBody* coloring inside a shape that the user just finished drawing, allowing the user to move to the

next shape, while the coloring process continues as a background task.

Technical feasibility. The EMS used is similar to *Muscle-Plotter*'s [49], which achieves a drawing accuracy of $\pm 4.07\text{mm}$ —this system's implementation & accuracy would be sufficient to realize our proposed drawing gestures.

4.3 Split-drum: learning to drum one limb at a time

In this envisioned application, we depict a novice drummer playing a full drum set without, yet, being able to multitask on each drum kit's part (a hard skill when learning drums, referred to as *limb independence* [95]). Figure 8 depicts our user choosing to have *SplitBody* automate the backbone of a funk drumbeat (i.e., EMS plays the bass & hi-hat) while, voluntarily, the user focuses more of their attention on playing the snare at the correct timings.

Technical feasibility. The EMS used for drumming is inspired by Ebisu et al.'s [13], which demonstrated EMS' ability to play rhythms with both hands (using more complex beats than ours). Also, EMS lends itself well to timing-based applications, such as the



Figure 8: A novice drummer only focusing on playing the snare drum while *SplitBody* automates the hi-hat and bass (lightning icon).

envisioned drumming, due to its fast actuation speed (e.g., 40ms for [29]).

4.4 Split-musician: alternating foreground & background musical tasks

Finally, we explored the concept where users alternate between which task is automated with *SplitBody* and which task is performed voluntarily. Figure 9 (a) shows our user soloing on the synthesizer while letting *SplitBody* play the drum. Then, as depicted in Figure 9 (b), our user decides to swap these around by pressing a footswitch, which causes *SplitBody* to, in the background, play simple three-note arpeggios on the synthesizer, while the user redirects more

of their attention to playing a more advanced rudiment pattern on the drum.

Technical feasibility. The EMS used to move individual fingers in this application is based on Takahashi et al.'s [86], which demonstrated that EMS can actuate all four fingers with an index of independence of 0.62—their approach's accuracy is sufficient to play single keys on the synthesizer as we depict in this application.

5 DISCUSSION

Safety & Ethics. We believe that any interactive system with the capability of moving the body must be ethically designed by grounding it in the principles of user-agency & safety. This is precisely the case for *SplitBody*. First, while our explorations were entirely lab-based, in all these situations, our users were given full control of *when to activate* *SplitBody*'s EMS (e.g., pressing a button while cooking, pressing a footswitch while drawing, etc). In other words, *SplitBody* does not include automatic triggers that invoke EMS assistance, only user-defined triggers. This mechanism further implements a simple way for users to *turn off* the EMS assistance. Importantly, *SplitBody* only actuates a subset of muscles (e.g., forearm & wrist muscles while cooking, wrist & calf muscles when drumming, etc), always leaving most of the user's limbs non-actuated and completely under the user's voluntary control—this allows the user to turn off the assistance when desired. Secondly, as with other interactive systems based on EMS, we believe that fully realizing any of *SplitBody*'s applications outside of a research environment must include features that provide agency to the user, such as: automatically halting any EMS when the user moves against the stimulated movement (e.g., as used in [47]), providing user-defined gestures that immediately suspend the stimulation (e.g., as used in [46]), or only enabling the stimulation in user-defined areas (e.g., as used in [47] or [49]). Moreover, all our experiments followed the established EMS guidelines [36, 65, 80], were approved by our ethics review board, and conducted with the informed consent of all participants.

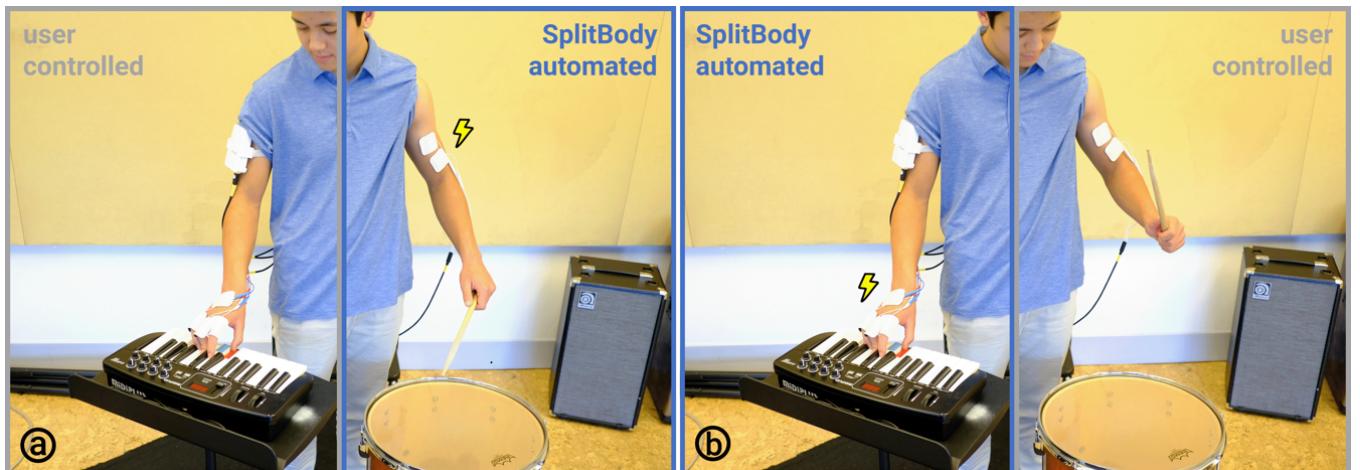


Figure 9: A user switching between which task is automated with *SplitBody* (lightning icon) and which task is performed voluntarily.

Conceptual differences to external automation. Unlike devices that automate background tasks using machinery (e.g., robots) that are *external* to the user, interactive actuation systems (e.g., EMS) act *on* the user's body. While EMS-actuated movements feel less agentic than one's own voluntary movements [29, 30, 85], users are still involved as they feel their body moving via their sense of proprioception/touch [46, 89]. This distinction is key to our concept, which focuses on interactive contexts where utility is not the user's sole objective (e.g., unlike tasks viewed as chores such as vacuuming by hand), and, instead, the user's goals involve not only utility but also *body-ownership* [12, 54]. As such, we focused on situations where users *want* to automate repetitive gestures but *also want* to be bodily-engaged with the tasks—for the sake of their creativity, learning, pleasure, or even for a sense of ownership over the outcome [12, 54, 55, 85]—rather than letting an external machine perform the background task for them, which offers no sense of involvement due to the "full automation" [5, 52]. Naturally, we acknowledge there are many scenarios where background automation is beneficial using external devices and where users might feel no desire to be bodily engaged (e.g., vacuuming robots), which were not the focus of our investigation.

6 CONCLUSIONS & FUTURE WORK

We proposed and evaluated a novel concept (*SplitBody*) that uses electrical muscle stimulation to assist users in movement tasks that happen in the *background* while the user is focusing on another task in the *foreground*. We found that participants assisted with *SplitBody* were able to perform better on a physically demanding multitask. Inspired by these findings, we envisioned a set of applications to illustrate the design space that *SplitBody* opens.

Future renditions. While EMS is a highly portable actuator capable of moving the body, other force-feedback actuators (e.g., exoskeletons [8, 18, 38, 50, 66], artificial-muscles [17]) may exhibit more precision at the expense of their larger form-factor. As our concept hopes to one day integrate with everyday interactions, it was important for us to choose a small & portable device. That being said, we expect that similar benefits can be found using mechanical devices, and we hope that our work inspires future work in that unexplored direction.

Future integration with supernumerary limbs or VR. We believe that some of the advantages of *SplitBody* might be integrated with supernumerary-limb interfaces [56, 78], such as the decreased mental workload or the ability to alternate between automated/voluntary tasks. Similarly, researchers started to explore how users simultaneously control two VR avatars [35] (also a type of *SplitBody*, but for input); we believe that our *SplitBody* might provide useful haptic feedback so that these VR users can synchronize their body pose with their virtual avatars prior to initiating control.

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REFERENCES

- [1] Abdi, E., Kulić, D. and Croft, E. 2020. Haptics in Teleoperated Medical Interventions: Force Measurement, Haptic Interfaces and Their Influence on User's Performance. *IEEE Transactions on Biomedical Engineering*. 67, 12 (Dec. 2020), 3438–3451. DOI:<https://doi.org/10.1109/TBME.2020.2987603>.
- [2] Bao, X., Zhou, Y., Wang, Y., Zhang, J., Lü, X. and Wang, Z. 2018. Electrode placement on the forearm for selective stimulation of finger extension/flexion. *PLOS ONE*. 13, 1 (Jan. 2018), e0190936. DOI:<https://doi.org/10.1371/journal.pone.0190936>.
- [3] Bara, F., Gentaz, E., Colé, P. and Sprenger-Charolles, L. 2004. The visuo-haptic and haptic exploration of letters increases the kindergarten-children's understanding of the alphabetic principle. *Cognitive Development*. 19, 3 (Jul. 2004), 433–449. DOI:<https://doi.org/10.1016/j.cogdev.2004.05.003>.
- [4] Basil, M.D. 2012. Multiple Resource Theory. *Encyclopedia of the Sciences of Learning*. N.M. Seel, ed. Springer US. 2384–2385.
- [5] Berberian, B., Sarrazin, J.-C., Blayne, P.L. and Haggard, P. 2012. Automation Technology and Sense of Control: A Window on Human Agency. *PLOS ONE*. 7, 3 (Mar. 2012), e34075. DOI:<https://doi.org/10.1371/journal.pone.0034075>.
- [6] Borst, J.P., Taatgen, N.A. and van Rijn, H. 2010. The problem state: A cognitive bottleneck in multitasking. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 36, 2 (2010), 363–382. DOI:<https://doi.org/10.1037/a0018106>.
- [7] Boudville, R., Hussain, Z., Yahaya, S.Z., Rahman, M.F.A., Ahmad, K.A. and Husin, N.I. 2018. Development and Optimization of PID Control for FES Knee Exercise in Hemiplegic Rehabilitation. *2018 12th International Conference on Sensing Technology (ICST)* (Dec. 2018), 143–148.
- [8] Carignan, C., Tang, J. and Roderick, S. 2009. Development of an exoskeleton haptic interface for virtual task training. *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems* (Oct. 2009), 3697–3702.
- [9] Choi, I., Corson, N., Peiros, L., Hawkes, E.W., Keller, S. and Follmer, S. 2018. A Soft, Controllable, High Force Density Linear Brake Utilizing Layer Jamming. *IEEE Robotics and Automation Letters*. 3, 1 (Jan. 2018), 450–457. DOI:<https://doi.org/10.1109/LRA.2017.2761938>.
- [10] Choi, I. and Follmer, S. 2016. Wolverine: A Wearable Haptic Interface for Grasping in VR. *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (New York, NY, USA, 2016), 117–119.
- [11] Colley, A., Leinonen, A., Forsman, M.-T. and Häkkilä, J. 2018. EMS Painter: Co-creating Visual Art using Electrical Muscle Stimulation. *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (New York, NY, USA, Mar. 2018), 266–270.
- [12] Danry, V., Pataranutaporn, P., Mueller, F., Maes, P. and Leigh, S. 2022. On Eliciting a Sense of Self when Integrating with Computers. *Proceedings of the Augmented Humans International Conference 2022* (New York, NY, USA, Apr. 2022), 68–81.
- [13] Ebisu, A., Hashizume, S., Suzuki, K., Ishii, A., Sakashita, M. and Ochiai, Y. 2016. Stimulated percussions: techniques for controlling human as percussive musical instrument by using electrical muscle stimulation. *SIGGRAPH ASIA 2016 Posters* (New York, NY, USA, Nov. 2016), 1–2.
- [14] Faltaous, S., Abdulkamsoud, A., Kempe, M., Alt, F. and Schneegass, S. 2021. GeniePutt: Augmenting human motor skills through electrical muscle stimulation. *it - Information Technology*. 63, 3 (Jul. 2021), 157–166. DOI:<https://doi.org/10.1515/it-2020-0035>.
- [15] Faltaous, S., Koelle, M. and Schneegass, S. 2022. From Perception to Action: A Review and Taxonomy on Electrical Muscle Stimulation in HCI. *Proceedings of*

²<https://www.chiinhawaii.info/>

- the 21st International Conference on Mobile and Ubiquitous Multimedia* (New York, NY, USA, Dec. 2022), 159–171.
- [16] Ferrarin, M., D'Acquisto, E., Mingrino, A. and Pedotti, A. 1996. An experimental PID controller for knee movement restoration with closed loop FES system. *Proceedings of 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Oct. 1996), 453–454 vol.1.
- [17] Goto, T., Das, S., Wolf, K., Lopes, P., Kurita, Y. and Kunze, K. 2020. Accelerating Skill Acquisition of Two-Handed Drumming using Pneumatic Artificial Muscles. *Proceedings of the Augmented Humans International Conference* (New York, NY, USA, Jun. 2020), 1–9.
- [18] Gu, X., Zhang, Y., Sun, W., Bian, Y., Zhou, D. and Kristensson, P.O. 2016. Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2016), 1991–1995.
- [19] Gui, K., Yokoi, H. and Zhang, D. 2016. Human-FES Cooperative Control for Wrist Movement: A Preliminary Study. *European Journal of Translational Myology*. 26, 3 (Jul. 2016). DOI:<https://doi.org/10.4081/ejtm.2016.6162>.
- [20] Haghghi, N., Vladis, N., Liu, Y. and Satyanarayan, A. 2020. The Effectiveness of Haptic Properties Under Cognitive Load: An Exploratory Study. arXiv.
- [21] Hart, S.G. and Staveland, L.E. 1988. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*. P.A. Hancock and N. Meshkati, eds. North-Holland. 139–183.
- [22] Hassan, M., Daiber, F., Wiehr, F., Kossmalla, F. and Krüger, A. 2017. FootStriker: An EMS-based Foot Strike Assistant for Running. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*. 1, 1 (Mar. 2017), 2:1–2:18. DOI:<https://doi.org/10.1145/3053332>.
- [23] Hermant, E., Tapie, B., Dupuy, O., Fraser, S., Compagnat, M., Salle, J.Y., Daviet, J.C. and Perrochon, A. 2019. Prefrontal Cortex Activation During Dual Task With Increasing Cognitive Load in Subacute Stroke Patients: A Pilot Study. *Frontiers in Aging Neuroscience*. 11, (2019).
- [24] Hincher, R., Vechev, V., Shea, H. and Hilliges, O. 2018. DextriES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake. *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, 2018), 901–912.
- [25] Jaeggi, S.M., Buschkuhl, M., Perrig, W.J. and Meier, B. 2010. The concurrent validity of the N-back task as a working memory measure. *Memory*. 18, 4 (May 2010), 394–412. DOI:<https://doi.org/10.1080/09658211003702171>.
- [26] Jafari, N., Adams, K.D. and Tavakoli, M. 2016. Haptics to improve task performance in people with disabilities: A review of previous studies and a guide to future research with children with disabilities. *Journal of Rehabilitation and Assistive Technologies Engineering*. 3, (Oct. 2016), 2055668316668147. DOI:<https://doi.org/10.1177/2055668316668147>.
- [27] Janczyk, M. and Kunde, W. 2020. Dual tasking from a goal perspective. *Psychological Review*. 127, 6 (Nov. 2020), 1079–1096. DOI:<https://doi.org/10.1037/rev0000222>.
- [28] Kane, M.J., Conway, A.R.A., Miura, T.K. and Colflesh, G.J.H. 2007. Working memory, attention control, and the N-back task: a question of construct validity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 33, 3 (May 2007), 615–622. DOI:<https://doi.org/10.1037/0278-7393.33.3.615>.
- [29] Kasahara, S., Nishida, J. and Lopes, P. 2019. Preemptive Action: Accelerating Human Reaction using Electrical Muscle Stimulation Without Compromising Agency. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2019), 1–15.
- [30] Kasahara, S., Takada, K., Nishida, J., Shibata, K., Shimojo, S. and Lopes, P. 2021. Preserving Agency During Electrical Muscle Stimulation Training Speeds up Reaction Time Directly After Removing EMS. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, May 2021), 1–9.
- [31] Kaul, O.B., Pfeiffer, M. and Rohs, M. 2016. Follow the Force: Steering the Index Finger towards Targets using EMS. *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (New York, NY, USA, May 2016), 2526–2532.
- [32] Kirchner, W.K. 1958. Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology*. 55, 4 (1958), 352–358. DOI:<https://doi.org/10.1037/h0043688>.
- [33] Knibbe, J., Alsmith, A. and Hornbæk, K. 2018. Experiencing Electrical Muscle Stimulation. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*. 2, 3 (Sep. 2018), 118:1–118:14. DOI:<https://doi.org/10.1145/3264928>.
- [34] Knibbe, J., Strohmeier, P., Boring, S. and Hornbæk, K. 2017. Automatic Calibration of High Density Electric Muscle Stimulation. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*. 1, 3 (Sep. 2017), 68:1–68:17. DOI:<https://doi.org/10.1145/3130933>.
- [35] Kondo, R. and Sugimoto, M. 2022. Split body: Extending self-location by splitting a body left and right. *Frontiers in Virtual Reality*. 3, (2022).
- [36] Kono, M., Ishiguro, Y., Miyaki, T. and Rekimoto, J. 2018. Design and Study of a Multi-Channel Electrical Muscle Stimulation Toolkit for Human Augmentation. *Proceedings of the 9th Augmented Human International Conference on - AH '18* (Seoul, Republic of Korea, 2018), 1–8.
- [37] Koohestani, A. and Moghadam, E.A. 2013. Controlling Muscle-joint System by Functional Electrical Stimulation Using Combination of PID and Fuzzy Controller. *APCBEE Procedia*. 7, (Jan. 2013), 156–162. DOI:<https://doi.org/10.1016/j.apbce.2013.08.027>.
- [38] Koyama, T., Yamano, I., Takemura, K. and Maeno, T. 2002. Multi-fingered exoskeleton haptic device using passive force feedback for dexterous teleoperation. *IEEE/RSJ International Conference on Intelligent Robots and Systems* (Sep. 2002), 2905–2910 vol.3.
- [39] Kruijff, E., Schmalstieg, D. and Beckhaus, S. 2006. Using neuromuscular electrical stimulation for pseudo-haptic feedback. *Proceedings of the ACM symposium on Virtual reality software and technology* (New York, NY, USA, Nov. 2006), 316–319.
- [40] Leung, R., MacLean, K., Bertelsen, M.B. and Saubhasik, M. 2007. Evaluation of haptically augmented touchscreen gui elements under cognitive load. *Proceedings of the 9th international conference on Multimodal interfaces* (New York, NY, USA, Nov. 2007), 374–381.
- [41] Levy-Tzedek, S. 2017. Changes in Predictive Task Switching with Age and with Cognitive Load. *Frontiers in Aging Neuroscience*. 9, (Nov. 2017), 375. DOI:<https://doi.org/10.3389/fnagi.2017.00375>.
- [42] Longo, A., Federolf, P., Haid, T. and Meulenbroek, R. 2018. Effects of a cognitive dual task on variability and local dynamic stability in sustained repetitive arm movements using principal component analysis: a pilot study. *Experimental Brain Research*. 236, 6 (Jun. 2018), 1611–1619. DOI:<https://doi.org/10.1007/s00221-018-5241-3>.
- [43] Longo, L., Wickens, C.D., Hancock, G. and Hancock, P.A. 2022. Human Mental Workload: A Survey and a Novel Inclusive Definition. *Frontiers in Psychology*. 13, (2022).
- [44] Lopes, P. and Baudisch, P. 2017. Immense Power in a Tiny Package: Wearables Based on Electrical Muscle Stimulation. *IEEE Pervasive Computing*. 16, 3 (2017), 12–16. DOI:<https://doi.org/10.1109/MPRV.2017.2940953>.
- [45] Lopes, P., Ion, A. and Baudisch, P. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (New York, NY, USA, 2015), 11–19.
- [46] Lopes, P., Ion, A., Mueller, W., Hoffmann, D., Jonell, P. and Baudisch, P. 2015. Proprioceptive Interaction. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (New York, NY, USA, 2015), 939–948.
- [47] Lopes, P., Jonell, P. and Baudisch, P. 2015. Affordance++: Allowing Objects to Communicate Dynamic Use. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (New York, NY, USA, 2015), 2515–2524.
- [48] Lopes, P., You, S., Cheng, L.-P., Marwecki, S. and Baudisch, P. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2017), 1471–1482.
- [49] Lopes, P., Yüksel, D., Guimbretière, F. and Baudisch, P. 2016. Muscle-plotter: An Interactive System based on Electrical Muscle Stimulation that Produces Spatial Output. (2016), 207–217.
- [50] MA, Z. and Ben-Tzvi, P. 2015. RML Glove—An Exoskeleton Glove Mechanism With Haptics Feedback. *IEEE/ASME Transactions on Mechatronics*. 20, 2 (Apr. 2015), 641–652. DOI:<https://doi.org/10.1109/TMECH.2014.2305842>.
- [51] Matsubara, S., Wakisaka, S., Aoyama, K., Seaborn, K., Hiyama, A. and Inami, M. 2020. Perceptual simultaneity and its modulation during EMG-triggered motion induction with electrical muscle stimulation. *PLOS ONE*. 15, 8 (Aug. 2020), e0236497. DOI:<https://doi.org/10.1371/journal.pone.0236497>.
- [52] Miller, C.A. and Parasuraman, R. 2007. Designing for Flexible Interaction Between Humans and Automation: Delegation Interfaces for Supervisory Control. *Human Factors*. 49, 1 (Feb. 2007), 57–75. DOI:<https://doi.org/10.1518/001872007779598037>.
- [53] Monsell, S. 2003. Task switching. *Trends in Cognitive Sciences*. 7, 3 (Mar. 2003), 134–140. DOI:[https://doi.org/10.1016/s1364-6613\(03\)00028-7](https://doi.org/10.1016/s1364-6613(03)00028-7).
- [54] Mueller, F. “Floyd,” Kari, T., Li, Z., Wang, Y., Mehta, Y.D., Andres, J., Marquez, J. and Patibanda, R. 2020. Towards Designing Bodily Integrated Play. *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (New York, NY, USA, Feb. 2020), 207–218.
- [55] Mueller, F.F. et al. 2020. Next Steps for Human-Computer Integration. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2020), 1–15.
- [56] Nabeshima, J., Saraiji, M.Y. and Minamizawa, K. 2019. Arque: artificial biomimicry-inspired tail for extending innate body functions. *ACM SIGGRAPH 2019 Posters* (Los Angeles California, Jul. 2019), 1–2.
- [57] Nagai, K., Tanoue, S., Akahane, K. and Sato, M. 2015. Wearable 6-Dof wrist haptic device “SPIDAR-W.” *SIGGRAPH Asia 2015 Haptic Media And Contents Design* (New York, NY, USA, Nov. 2015), 1–2.
- [58] Najmaei, N., Kermani, M.R. and Patel, R.V. 2015. Suitability of Small-Scale Magnetorheological Fluid-Based Clutches in Haptic Interfaces for Improved Performance. *IEEE/ASME Transactions on Mechatronics*. 20, 4 (Aug. 2015), 1863–1874. DOI:<https://doi.org/10.1109/TMECH.2014.2357447>.
- [59] Navon, D. and Miller, J. 2002. Queuing or Sharing? A Critical Evaluation of the Single-Bottleneck Notion. *Cognitive Psychology*. 44, 3 (May 2002), 193–251. DOI:<https://doi.org/10.1006/cogp.2001.0767>.

- [60] Niijima, A. and Kubo, Y. 2023. Assisting with Fingertip Force Control by Active Bio-Acoustic Sensing and Electrical Muscle Stimulation. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2023), 1–13.
- [61] Niijima, A., Takeda, T., Aoki, R. and Koike, Y. 2021. Reducing Muscle Activity when Playing Tremolo by Using Electrical Muscle Stimulation. *Proceedings of the Augmented Humans International Conference 2021* (New York, NY, USA, Jul. 2021), 289–291.
- [62] Niijima, A., Takeda, T., Aoki, R. and Miyahara, S. 2022. Muscle Synergies Learning with Electrical Muscle Stimulation for Playing the Piano. *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2022), 1–10.
- [63] Nith, R., Teng, S.-Y., Li, P., Tao, Y. and Lopes, P. 2021. DextrEMS: Achieving Dexterity in Electrical Muscle Stimulation by Combining it with Brakes. *Proceedings of the 34th Annual Symposium on User Interface Software and Technology* (Virtual Event USA, Oct. 2021).
- [64] Off-line learning of motor skill memory: A double dissociation of goal and movement: <https://www.pnas.org/doi/10.1073/pnas.0506072102>. Accessed: 2023-09-12.
- [65] Omura, Y. 1985. ELECTRICAL PARAMETERS FOR SAFE AND EFFECTIVE ELECTRO-ACUPUNCTURE AND TRANSCUTANEOUS ELECTRICAL STIMULATION: THRESHOLD POTENTIALS FOR TINGLING, MUSCLE CONTRACTION AND PAIN; AND HOW TO PREVENT ADVERSE EFFECTS OF ELECTROTHERAPY PART I. *Acupuncture & Electro-Therapeutics Research*. 10, 4 (Jan. 1985), 335–337. DOI:<https://doi.org/10.3727/036012985816714405>.
- [66] Önen, Ü., Botsali, F.M., Kalyoncu, M., Tinkir, M., Yilmaz, N. and Şahin, Y. 2014. Design and Actuator Selection of a Lower Extremity Exoskeleton. *IEEE/ASME Transactions on Mechatronics*. 19, 2 (Apr. 2014), 623–632. DOI:<https://doi.org/10.1109/TMECH.2013.2250295>.
- [67] Ophir, E., Nass, C. and Wagner, A.D. 2009. Cognitive control in media multitaskers. *Proceedings of the National Academy of Sciences*. 106, 37 (Sep. 2009), 15583–15587. DOI:<https://doi.org/10.1073/pnas.0903620106>.
- [68] Owen, A.M., McMillan, K.M., Laird, A.R. and Bullmore, E. 2005. N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping*. 25, 1 (2005), 46–59. DOI:<https://doi.org/10.1002/hbm.20131>.
- [69] Parietti, F. and Asada, H.H. 2017. Independent, voluntary control of extra robotic limbs. *2017 IEEE International Conference on Robotics and Automation (ICRA)* (Singapore, Singapore, May 2017), 5954–5961.
- [70] Pashler, H. 1994. Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*. 116, 2 (Sep. 1994), 220–244. DOI:<https://doi.org/10.1037/0033-2909.116.2.220>.
- [71] Patibanda, R., Li, X., Chen, Y., Saini, A., Hill, C.N., van den Hoven, E. and Mueller, F.F. 2021. Actuating Myself: Designing Hand-Games Incorporating Electrical Muscle Stimulation. *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play* (New York, NY, USA, Oct. 2021), 228–235.
- [72] Petermeijer, S.M., Abbink, D.A., Mulder, M. and de Winter, J.C.F. 2015. The Effect of Haptic Support Systems on Driver Performance: A Literature Survey. *IEEE Transactions on Haptics*. 8, 4 (Oct. 2015), 467–479. DOI:<https://doi.org/10.1109/TOH.2015.2437871>.
- [73] Pfeiffer, M., Dünte, T., Schneegass, S., Alt, F. and Rohs, M. 2015. Cruise Control for Pedestrians: Controlling Walking Direction using Electrical Muscle Stimulation. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2015), 2505–2514.
- [74] Pfeiffer, M. and Rohs, M. 2017. Haptic Feedback for Wearables and Textiles Based on Electrical Muscle Stimulation. *Smart Textiles: Fundamentals, Design, and Interaction*. S. Schneegass and O. Amft, eds. Springer International Publishing, 103–137.
- [75] RehaMove_Katalog_englisch_2017-02_Web: https://hasomed.de/wp-content/uploads/hasomed-fileadmin/RehaMove/Mediathek/Broschueren_Flyer/RehaMove_Katalog_englisch_2017-02_Web.pdf. Accessed: 2021-12-23.
- [76] Rubinstein, J.S., Meyer, D.E. and Evans, J.E. 2001. Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception and Performance*. 27, 4 (Aug. 2001), 763–797. DOI:<https://doi.org/10.1037/0096-1523.27.4.763>.
- [77] Sakashita, M., Sato, Y., Ebisu, A., Kawahara, K., Hashizume, S., Muramatsu, N. and Ochiai, Y. 2017. Haptic Marionette: Wrist Control Technology Combined with Electrical Muscle Stimulation and Hanger Reflex. *SIGGRAPH Asia 2017 Posters* (New York, NY, USA, 2017), 33:1–33:2.
- [78] Sasaki, T., Saraiji, M.Y., Minamizawa, K. and Inami, M. 2018. MetaArms: Body Remapping Using Feet-Controlled Artificial Arms. *Adjunct Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2018), 140–142.
- [79] Schiaffino, L. and Tabernig, C.B. 2013. Position control with PID regulation for a FES system: preliminary results. *Journal of Physics: Conference Series*. 477, (Dec. 2013), 012039. DOI:<https://doi.org/10.1088/1742-6596/477/1/012039>.
- [80] Schneegass, S., Schmidt, A. and Pfeiffer, M. 2016. Creating user interfaces with electrical muscle stimulation. *Interactions*. 24, 1 (Dec. 2016), 74–77. DOI:<https://doi.org/10.1145/3019606>.
- [81] Shahu, A., Wintersberger, P. and Michahelles, F. 2022. Scenario-based Investigation of Acceptance of Electric Muscle Stimulation. *Proceedings of the Augmented Humans International Conference 2022* (New York, NY, USA, Apr. 2022), 184–194.
- [82] Shahu, A., Wintersberger, P. and Michahelles, F. 2022. Would Users Accept Electric Muscle Stimulation Controlling their Body? Insights from a Scenario-based Investigation. *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, Apr. 2022), 1–7.
- [83] Shimobayashi, H., Sasaki, T., Horie, A., Arakawa, R., Kashino, Z. and Inami, M. 2021. Independent Control of Supernumerary Appendages Exploiting Upper Limb Redundancy. *Proceedings of the Augmented Humans International Conference 2021* (New York, NY, USA, Jul. 2021), 19–30.
- [84] STELARC | RE-WIRED / RE-MIXED: http://stelarc.org/_activity-20353.php. Accessed: 2023-11-14.
- [85] Tajima, D., Nishida, J., Lopes, P. and Kasahara, S. 2022. Whose Touch is This?: Understanding the Agency Trade-Off Between User-Driven Touch vs. Computer-Driven Touch. *ACM Transactions on Computer-Human Interaction*. 29, 3 (Jan. 2022), 24:1–24:27. DOI:<https://doi.org/10.1145/3489608>.
- [86] Takahashi, A., Brooks, J., Kajimoto, H. and Lopes, P. 2021. Increasing Electrical Muscle Stimulation's Dexterity by means of Back of the Hand Actuation. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama Japan, May 2021), 1–12.
- [87] Tamaki, E., Miyaki, T. and Rekimoto, J. 2011. PossessedHand: techniques for controlling human hands using electrical muscles stimuli. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2011), 543–552.
- [88] Tanaka, Y., Nishida, J. and Lopes, P. 2022. Electrical Head Actuation: Enabling Interactive Systems to Directly Manipulate Head Orientation. *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA), 1–15.
- [89] Tanaka, Y., Takahashi, A. and Lopes, P. 2023. Interactive Benefits from Switching Electrical to Magnetic Muscle Stimulation. *Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, Oct. 2023), 1–12.
- [90] Tombu, M. and Jolicœur, P. 2003. A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*. 29, 1 (2003), 3–18. DOI:<https://doi.org/10.1037/0096-1523.29.1.3>.
- [91] Watanabe, K., Oka, M. and Mori, H. 2019. Feedback Control to Target Joints Angle in Middle Finger PIP and MP Joint Using Functional Electrical Stimulation. *Human Interface and the Management of Information. Information in Intelligent Systems* (Cham, 2019), 440–454.
- [92] Widjaja, F., Shee, C.Y., Au, W.L., Poignet, P. and Ang, W.T. 2011. Using electromechanical delay for real-time anti-phase tremor attenuation system using Functional Electrical Stimulation. *2011 IEEE International Conference on Robotics and Automation* (May 2011), 3694–3699.
- [93] Zhou, M., Jones, D.B., Schwartzberg, S.D. and Cao, C.G.L. 2007. Role of Haptic Feedback and Cognitive Load in Surgical Skill Acquisition. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. 51, 11 (Oct. 2007), 631–635. DOI:<https://doi.org/10.1177/154193120705101106>.
- [94] Zoran, A. and Paradiso, J.A. 2013. FreeD: a freehand digital sculpting tool. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 27 2013), 2613–2616.
- [95] 2023. Limb independence. *Wikipedia*.