Experiencing Electrical Muscle Stimulation

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Electrical Muscle Stimulation (EMS) offers rich opportunities for interaction. By varying stimulation parameters (amplitudes, pulse widths and frequencies), EMS can be used to either trigger muscle contractions, and so convey object affordances or guide user movements, or provide rich haptic feedback. However, the way users' experience changes with these parameters, and EMS in general, is poorly understood. Using a phenomenologically inspired interview technique, the explicitation interview, we study fifteen users' experience of EMS across 48 combinations of stimulation parameters. We synthesize the descriptions of EMS and relate stimulation parameters to categories of experience, such as 'temperature', 'motion', and 'sensitivity'. From the interviews, we explore more general topics in body-based interfaces, including the experience of control, metaphors for having your body actuated, and the relation between EMS parameters and perceived depth and location of sensations. These findings provide a vocabulary of EMS experience, and an insight into the relationship between specific parameters and associated sensations. In turn, this can help designers consider the user experience of EMS when developing interfaces.

CCS Concepts: •**Human-centered computing → Empirical studies in ubiquitous and mobile computing;** *Ubiquitous computing;* User studies;

Additional Key Words and Phrases: Electric Muscle Stimulation; EMS; User Experience

ACM Reference Format:
Jarrod Knibbe, Adrian Alsmith, and Kasper Hornbæk. 2018. Experiencing Electrical Muscle Stimulation. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 3, Article 118 (September 2018), 14 pages. DOI: 10.1145/3264928

1 INTRODUCTION

Electric muscle stimulation (EMS) has emerged as an output paradigm in body-based user interfaces. The key idea is to use electric pulses from a device attached to users' bodies to stimulate their muscles and thereby move their limbs (e.g., [9, 12, 17, 22]). Previous work has shown that EMS can be used for teaching complex movements [22], force feedback [9, 19], conveying object affordances [12], steering users' whilst they are walking [17], and assisting drawing [14].

This literature, however, contains no systematic exploration of the experience of EMS. Existing work has typically been evaluated by showing its benefits on users' performance (e.g., [7]), demonstrating user understanding of stimulated movements (e.g., [12]), showing that users can mimic movements generated by EMS (e.g., [11]), or showing that EMS can add to the enjoyment of an novel experience (e.g., [13]). A few of these evaluations have

This work is supported by the European Research Council under Grant No.: 648785, and the Volkswagen Foundation under Grant No.: 89429.
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2474-9567/2018/9-ART118 $15.00
DOI: 10.1145/3264928

briefly reported on subjective comments from users. For example, participants have voiced no concerns over handing bodily control to a computer [17], have attributed agency of their movement to inanimate objects [12], and have described EMS as 'scary, just scary' [22]. However, there is a gap in the literature providing a clear, systematic and parameter-mapped exploration of how EMS feels to the uninitiated.

When designing EMS-based interaction techniques, stimulation parameters must be chosen that both target the correct muscles and result in the desired outcome, whether a haptic sensation or a muscular actuation. These parameters are selected from a multi-dimensional parameter space of frequency (number of pulses per second, in Hz), pulse width (the duration of each individual pulse, in μs) and amplitude (the 'strength' of each pulse, reported variously) [20]. Not only can these parameters elicit different outcomes (no effect - haptic sensations - muscular actuation), but they can also result in different sensations within each outcome. For example, previous work has reported calibrating participants for 'visible, yet pain free movement' [9], suggesting that there is a space of parameters that result in a similar movement, yet provide a different user experience. Another example of this can be seen in the work of Pohl et al. [20], where participants highlighted a wide range of parameters that resulted in muscle actuation, yet only labelled a small subset of those as comfortable. Only through a more detailed, specific exploration of the user experience of different stimulation parameters can we begin to understand the nuance of parameter selection in EMS interaction techniques.

Given the brevity of discussions on user experience in EMS so far, we suggest the need for a systematic exploration. Through a better understanding of user perception, not only may we develop a shared vocabulary that allows us to better communicate how EMS feels, but we may come to better understand the trade-offs and nuance of parameter selection, allowing EMS practitioners to more carefully design haptic experience alongside the muscular control of EMS. To do so, we explore the experience of electrical muscle stimulation. We conducted explicitation interviews [16, 24] with 15 participants about the experience of 48 stimulation parameters (varying pulse widths, frequencies and amplitudes) across 3 muscle locations. Through thematic analysis, the transcripts were grouped into descriptors of: autonomic and peripheral sensation; location and dynamics; control and volition; emotional response and signal descriptions. We explore the key words, phrases and themes across all interviews. This provides (a) a reference point from which designers can consider the experiential factors of future EMS systems, (b) a common vocabulary with which to describe the experiential details of future EMS work, and (c) a launch pad for future EMS systems that may target complex user experiences rather than specific movements.

2 RELATED WORK

There have been a range of examples of EMS for interaction in ubiquitous computing and HCI; for example, to augment video conferencing [5], to teach musical instruments [22], to assist drawing [14], to improve running technique [25], and to convey emotions across distances [6]. However, the discussion of user experience has been brief. We have seen that parameters result in different sensations and outcomes across users (e.g., [20]) and, indeed, many different parameters are used in the HCI literature (e.g., 40Hz frequency - 200μs pulse width [22], 120Hz-100μs [17], 25Hz-290μs [9], 60Hz-260μs [19], 120Hz-150μs [11], or not reported at all [10, 12]). However, the literature does not yet provide a systematic, nor complete insight into the experiential-parameter space. While different parameters may result in different sensations, no empirical work has explored the existence of experiential trends across parameters and across users, for example. Here, we detail the existing HCI and ubicomp literature that provides insight into the experience of EMS.

The literature presents no clear mapping between experiential descriptors and stimulation parameters. In one of the earlier works on EMS in HCI, Tamaki et al. [22] report participant comments such as 'I felt like when I got cramp in my arm'. Pfeiffer et al. [19] and Hassib et al. [6] have reported descriptions including 'exciting', 'hectic', 'unnatural', 'aggressive', and 'magnetic force'. Lopes et al. have reported 'tingling'. And Gronvall et al., report sensations of fear [4]. It is clear from this work, then, that the descriptors of EMS are diverse, spanning both positive and negative sensations.

The only insight we have regarding a more generalised pattern of sensations comes from Pfeiffer et al. [18]. They suggest that EMS 'ticks' at lower frequencies, while the individual stimulations become less discernible as the frequency increases. Our work seeks to understand how the dimension of pulse width interacts with and builds on this sensation. Furthermore, through a systematic exploration, we seek to provide evidence to support this claim.

Alongside felt descriptors of the sensation itself, authors report anthropomorphised descriptors of control. For example, in Affordance++ [12], participants used phrases such as 'it doesn't want me not to drink from it' and 'it moves me back and forth', suggesting that 'it', the object, was guiding them. Similar descriptions are reported by Tamaki et al. [22]: 'It felt like my forearm was pushed by someone', also suggesting another agent of control. This highlights an interesting dimension of attributions of agency within EMS. However, the extant literature does not yet provide a clear insight into whether these attributions of agency are a constant across all EMS, or whether they are coupled to specific stimulation parameters.

In more recent work [13], where EMS is paired with virtual reality (VR), participants appear to suggest a lack of awareness of their movements' origins (i.e., less awareness of the other sensations typically involved in EMS use, such as on-skin, surface sensations). It is interesting that visual decoupling, or immersive distractor tasks, may have an impact on the usability of EMS. In this work, however, we seek to explore the experience of EMS itself and, as such, do not provide contextual or distractor tasks.

While there has been a large body of work on EMS, the work discussed above provides the only contribution to our understanding of the experience of EMS. It is telling from the brevity of this related work, therefore, that there exists a need for a more extensive exploration of the experiential factors of EMS.

3 EXPLORING THE EXPERIENCE OF ELECTRIC MUSCLE STIMULATION

To explore the experience of EMS, we recruited 15 participants, stimulated them with 48 combinations of EMS stimulation parameters and muscle locations, and interviewed them about their experience using the explicitation interview technique [16, 24]. (This has become a popular technique for unpacking subjective experiences, e.g., [8, 15]). We chose to explore the experience of EMS in a context-free setting (i.e., without a contextualising or distractor task). While any experience may be nuanced or altered by its context (such as using EMS in VR [13]), gaining a deeper understanding of the raw experience of EMS offers the most generalisable reference from which to begin designing novel EMS interfaces. We report on thematic trends across the participants' descriptions.

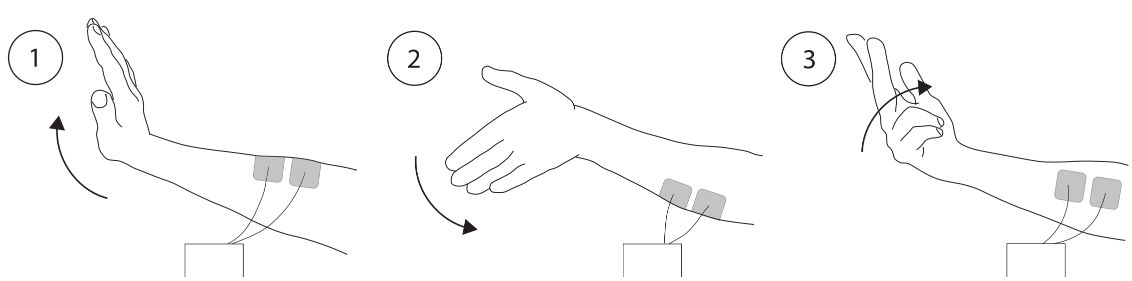
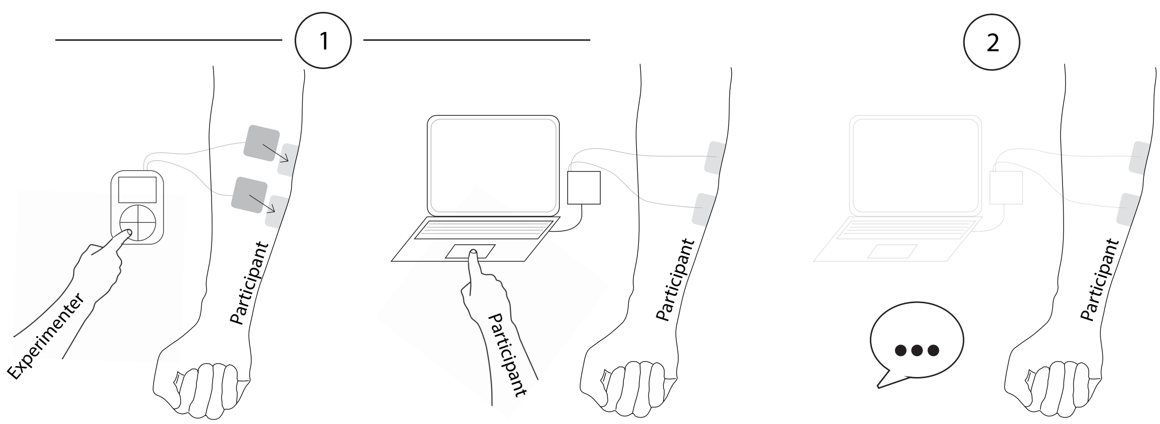


Fig. 1. Illustration of electrode position and targeted movement. (1) Electrodes on extensor carpi ulnaris, for wrist extension. (2) Electrodes on flexor carpi ulnaris and palmaris longus, for ulnar deviation. (3) Electrodes on flexor carpi radialis and brachioraadialis, for bending third and fourth fingers toward the hand.

3.1 Apparatus

We used an off-the-shelf EMS device (MedFit 1 by The Tens Company). The majority of HCI EMS work focuses on the upper limbs and, in particular, the forearm muscles [9, 11, 12, 19]. With this as motivation, in this study we targeted three muscle groupings: (1) the extensor carpi ulnaris, for wrist extension, (2) the flexor carpi ulnaris and palmaris longus, for flexing the hand inwards at the wrist (ulnar deviation), and (3) the flexor carpi radialis and brachioradialis, for bending the third and fourth fingers towards the hand (Figure 1). We report on patterns across pulse widths and frequencies, as opposed to muscle groups, to capture the general experience of EMS. Each muscle was targeted with a unique pair of electrodes (an anode and a cathode) and participants were calibrated (for electrode placement and stimulation amplitude, which differ based on muscle size and skin resistivity, amongst other factors) during the first part of the study.

Stimulation was directed to the targeted electrodes using a basic relay switching circuit (using solid-state relays - CPC1218Y). We controlled the device's amplitude, pulse width and frequency through two 2-channel digital potentiometers (DS1803, 50kOhm), in place of the devices' original four analog potentiometers. The relay circuit and potentiometers were controlled with a microcontroller, connected to the study computer.



Participant is manually calibrated for electrode position by the experimenter. Electrodes are moved until desired movement is produced.

Amplitude calibration is performed. Participant taps space-bar to indicate:
(1) perception of stimulus,
(2) movement caused, and
(3) maximum comfort.

Participants are taken through 48 different stimulation parameters and describe them, starting from *'What words would you use to describe how this feels?'*

Fig. 2. Walkthrough of the Experimental Procedure Steps. In part (1), participants are calibrated for both electrode placement and stimulation amplitude, to achieve the desired movement whilst maintaining comfort. In part (2) participants describe their experience of 48 different stimulation parameters.

3.2 Task and Experimental Design

3.2.1 Part 1. Calibration: Participants were initially calibrated for electrode location. This involved placing the three pairs of electrodes and checking for the desired resultant movement (Figure 1).

The initial electrode location was determined through palpation under tension (manually inspecting muscle locations while the participant performs the target movement). If, upon stimulation, the desired movement was not performed, the electrodes were moved slightly and the test was repeated. This initial step was performed manually (with a Sanitas Sem43 EMS device) and also served to acclimate the participants to EMS prior to computer-controlled stimulation (as no participants had any previous experience with EMS). While this step could have equally been achieved with our computer controlled device, during a pilot study we found that this manual, personal approach helped to reduce any apprehension in our participants. Though the device itself is different from that used for the rest of the study, both devices produce similar asymmetric biphasic waveforms (when examined with an oscilloscope).

The participants were then connected to the computer-controlled EMS device. Participants were stimulated across pairs of electrodes with increasing amplitude. Participants were asked to indicate, by pressing the space-bar on a computer placed in front of them, when (1) they could feel something, (2) when the stimulation caused movement, and (3) when the stimulation was considered to be at the limit of comfort. The amplitude, frequency and pulse-width values were recorded at each key press.

This process was completed for all combinations of four frequencies (20Hz, 55Hz, 90Hz, 120Hz) and four pulse widths (100μs, 150μs, 200μs, 250μs). The order of combinations was randomised. These frequencies and pulse widths cover a wide range of those previously used in HCI (e.g., [9, 17, 22]) and those made available by off-the-shelf devices, as frequently adopted in HCI (e.g., [11, 17]). Though a wider range of frequencies and pulse widths are used in medical domains, our work aims to start by characterizing the experience of EMS as had within HCI [1]. The conditions were performed in a random order. Overall, each participant completed 48 trials: 4 (pulse-widths) x 4 (frequencies) x 3 (electrode pairs).

3.2.2 Part 2. Explicitation Interview: The participants were stimulated again with the 4x4x3 signal parameters. The order of parameters was randomised per participant. The amplitude used was halfway between the movement and comfort limit thresholds determined in part 1. The participants could control the overall duration of the stimulation themselves. During this stimulation and immediately after, the participants were asked to answer the following on-screen question (adapted from [15]): *What words would you use to describe how this feels?* The experimenter would on occasion ask participants further prompting questions (such as 'does this relate to any previous experience?' and 'how would you describe this to someone new to EMS?') to encourage reflection. Participant responses were recorded with a microphone and transcribed post-interview. Participant transcriptions were 2895 words long on average (about 4.5 pages similar to this).

Upon completion of all participants, the authors conducted an initial thematic analysis (following [1]) on 5% of the corpus. The authors then individually coded a further 5% of the corpus using the initial themes to refine the coding manual. Finally, the first author coded the remaining transcriptions, highlighting key words and phrases per theme.

4 CALIBRATION RESULTS

The calibration process demonstrates some initial objective differences in experiences between participants. Across participants there was a significant effect of muscle location on: perception threshold (f(2,717)=4.756, p=0.009); movement causing amplitude (f(2,717)=59.83, p=<0.0001); and comfort limit amplitudes (f(2,717)=25.45, p=<0.0001). Additionally, there are significant effects of both stimulation frequency and pulse-width on calibrated amplitudes (perception threshold x freq.: f(3,716)=20.09, p=<0.0001, movement causing x freq.: f(3,716)=32.05, p=<0.0001, movement causing x pwm.: f(3,716)=5.715, p=0.0007, comfort threshold x freq.: f(3,716)=99.57, p=<0.0001, comfort threshold x pwm: f(3,716)=3.96, p=0.008). These differences demonstrate both that (a) the way users experience EMS differs, and (b) that the user experience of stimulating different muscle locations and targeting different muscle depths is non-uniform.

[1]We made this decision for two reasons. First, the EMS work in ubicomp and HCI continues to choose parameters within these ranges (perhaps as informed by the extent HCI literature). Secondly, by using these parameters, our work can also support reflection upon the experiences produced in the existing literature, as much as supporting the design of future work.

Having demonstrated differences in participant calibration data, we now explore the subjective descriptions of the user experience of EMS. First, we explore recurrent themes across the descriptions. Then, we explore the adjusted residuals of keywords from the participants' transcriptions (exploring keywords that differ most from the expected distribution). This provides an insight into how aspects of the user experience of EMS are bound to different stimulation parameters.

5 EXPLICITATION INTERVIEW: THEMATIC ANALYSIS

Based on an initial thematic analysis [1], the interviews were coded into six themes: autonomic sensation, peripheral sensation, location and dynamics, emotional reaction, control and volition, and signal.

Table 1. Table showing key themes, descriptions, keywords, and examples from the interview data.

Themes	**Description**	**Examples**
Autonomic Sensation	Relating to unconscious muscular reactions or functions	Keywords: pulsing, cramping, shaking, twitching, beating. Example phrases: 'When you are standing on your foot when it is asleep', 'hitting your funny-bone' and 'muscle fatigue after a workout.'
Peripheral Sensation	Non-autonomic surface-based descriptions of sensations, that would typically be attributed to an external cause	Keywords: vibrating, tapping, needles, pinching, knife, warm. Example phrases: 'Like a rubber band around the skin', 'the feeling after being slapped very hard with a flat hand,' and 'starting an engine.'
Location and Dynamics	Concerning the experienced location of stimulation and the way in which these sensations appear to move or travel	Keywords: wavey, internal, local. Example phrases: 'like balls moving around inside my arm', 'have been on a ship, then suddenly stood on fast ground', 'in my knuckles', 'a rock hard point in my forearm.'
Emotional Reaction	Relating to experiences of enjoyment or those resulting from novelty, and references to comfort, including the ability to endure the stimulation.	Keywords: annoying, weird, aggressive. Example phrases: 'Jesus Christ, can you really isolate only that [finger]', 'that was the best shock I have got so far', 'I think I'd be able to do whatever I had to do at home.'
Control and Volition	Descriptions including attributions of agency, co-presence or referring to changes in perceived sense of control.	Keywords: move, pull, bend. Example phrases: 'it wants to go in this position... and I have to fight to keep it up', 'I'm not sure if its me or if its something doing it to me.'
Signal	Literal descriptions of signal features or simply relating to the electrical nature of the experience.	Keywords: electric, fast, constant, strong, intense. Example phrase: 'it's definitely a feeling that you are being electrocuted.'

5.1 Autonomic Sensation

Throughout their descriptions, participants related the sensation of stimulation to unconscious muscular reactions or functions. For example, participants referred to sensations of pulsing (n=122), cramping (n=53), shaking (n=144) and twitching (n=66). Participants compared EMS to exercise: 'my tendons are cramping up, if you are lifting something heavy... then you let it go and its like you still have the feeling for another 5-10 seconds' (P0, 20Hz, 250μs) and 'like, for an example, getting off the bike or something... you can feel your muscles' (P6, 90Hz, 200μs). Participants also described the sensation of blood rushing within their arm: 'the same thing [as] when I have my head beneath my heart... all the blood in my head rushes down' (P11, 90Hz, 150μs). The most frequently used keyword related to 'sleeping' sensations (158 occurrences), for example 'all my fingers are asleep' (P11, 55Hz, 100μs) and 'I have slept on my arm for very long and its sort of dead' (P2, 90Hz, 200μs).

5.2 Peripheral Sensation

These descriptions included sensations that could typically be attributed to an external cause, such as vibrating (n=67), tapping (n=120), and pinching (n=40). Participants described experiences such as 'like when you have your hand on someone's chest and they're humming, [it's a] vibration' (P2, 55Hz, 150μs), 'somebody tapping you with their finger' (P3, 120Hz, 100μs), and 'squashing and pinching' (P11, 55Hz, 100μs). Participants described changes in perceived temperature, such as 'a warm feeling, the beginning of a little burn, but it doesn't get any worse' (P0, 90Hz, 200μs). Although these references were frequent (n=14), participants were often unable to determine the direction of the temperature change 'like you have just been outside bathing in ice water and are then going inside a sauna. It's both warm and cold' (P1, 120Hz, 100μs) and 'warm, it can also be like touching an ice cube actually' (P1, 20Hz, 250μs).

5.3 Location and Dynamics

A body of descriptions related to the perceived location and movement patterns of the stimulation. Participants described wavy (n=138) patterns of stimulation: 'wavy somehow, as if you would have been on a ship and then suddenly stood on [solid] ground' (P1, 120Hz, 250μs) and 'wavy feeling... all the time constantly changes' (P6, 55Hz, 250μs). Frequent descriptions also referred to the source of the sensation: 'feels like its coming from the inside' (P9, 55Hz, 150μs), 'underneath my thumb' (P14, 120Hz, 150μs) and 'outside of my skin' (P14, 20Hz, 100μs). Descriptions were also given based on the participants' movements, 'when my hand is palm down, its feeling soft' (P1, 90Hz, 250μs), and 'if I take my wrist the other way, I can feel more on the left' (P6, 120Hz, 250μs).

In addition, participants also described the experience of certain stimulations changing, especially as they move their arms: 'when I move [my hand] to the left, it feels a lot worse' (P8, 55Hz, 200μs) and 'if I place my hand in some places, it is more uncomfortable than if I have it at other places' (P12, 120Hz, 250μs). As participants move their arms, especially with rotation, the electrodes come to cover other muscles than those originally targeted, and this can change the user experience. More interestingly, participants also reported changes in sensation over time while not moving - 'it feels like it kinda changes as I get used to it' (P3, 90Hz, 200μs). This included participants simply adapting to the sensation: 'It's not as uncomfortable now as it was ten seconds ago' (P3, 120Hz, 250μs) and 'now it's almost gone' (P8, 20Hz, 250μs).

5.4 Emotional Reaction

Participants described moments of surprise: 'Jesus Christ... can you really isolate only that [finger]?' (P8, 90Hz, 200μs), and of uncertainty: 'Am I supposed to like this? I don't think so, but...' (P2, 20Hz, 100μs). Participants additionally made reference to the comfort of different stimulation parameters, from 'its almost painless' (P13, 55Hz, 100μs), 'that was the best shock I've gotten so far' (P10, 90Hz, 250μs), to 'this kind of hurts, I think' (P14, 120Hz, 200μs). From here, participants discussed the experience of EMS over longer periods: 'I think I'd be able to do whatever I had to do at home' (P7, 20Hz, 100μs) and 'I could live with this for a day or two... or maybe not' (P7, 20Hz, 200μs).

5.5 Control and Volition

Descriptions included attributions of agency and co-presence, and referred to changes in perceived states of control. Participants suggested that '[my hand] wants to go in this position... So I have to fight to keep it up' (P8, 120Hz, 250μs), 'my fingers are moving again' (P5, 120Hz, 200μs), and 'either my hand is twitching, or it wants to twitch' (P2, 90Hz, 250μs). These descriptions all attribute agency to the body parts themselves and hint at a lost sense of control. This was experienced both negatively: 'some of the other [stimulations] can be really unpleasant. Not in the sense that they hurt, but the loss of autonomy' (P4, 20Hz, 200μs), and positively: 'its just sort of doing things for me. So if I could control this myself, like if I could say, "Hey, please close"...' (P4, 90Hz, 200μs). Participants also described the sensation of 'someone' doing something to them 'someone's holding my ring finger and I can't really push it up' (P0, 20Hz, 150μs) and 'someone is holding my arm and shaking my hand' (P9, 55Hz, 100μs).

5.6 Signal

Participants described properties of the signal, using keywords such as electric (n=73), fast (n=96), constant (n=32), and strong (n=69). As these can be inferred from the stimulation parameters, and provide limited richness for the description of experience, we do not analyse this theme further.

5.7 Cross-Theme Analysis

Our analysis also revealed themes and connections that go beyond those presented above and may inform research in body-based interfaces.

Scariness has been reported at least once previously by a subject under EMS [19] and on six occasions our participants reported feeling frightened or scared. We found that scariness was associated variously with (1) a loss of control 'The feeling of not being able to control it is scary, but it's also, frightening' (P8), (2) mild emotional reaction 'It's a weird feeling but, I thought it would be worse, it's kinda scary, but it's kinda annoying' (P8, 120Hz, 250μs), (3) discomfort 'And this ... is ... a horrible feeling, this is definitely the worst [...] It's a little scary' (P7, 120Hz, 200μs) and (4) concerns about well-being 'It's doable to work against it, it's not like some of them you are kinda scared that you'll pop if you work against them' (P0, 55Hz, 150μs). This concern about well-being extended not only to concerns about resisting actuation, but also the effects of the stimulation more generally 'It just doesn't feel healthy. The other [stimulations] are sort of innocent; this one feels like it's not a good feeling. If I had this, I would worry' (P7, 55Hz, 250μs) and 'This one hurt, and feels like something would [wreck] ... the cells in my arm' (P11, 20Hz, 150μs). These findings demonstrate the challenge of addressing fear in EMS-based interfaces. The breadth of associations with scariness would suggest that there is no single way to control for participant apprehension.

Although part 1 required participants to provide thresholds for discomfort, they continued to report sensations of discomfort in part 2. On some occasions their discomfort was clearly more intellectual than others, being disconcerted with very idea of the seeming loss of control 'Well, if I had this every day all the time I am not sure I would enjoy it. And I am not laughing either, but it's not, I mean, some of the other [stimulations] can be really unpleasant. Not in the sense that they hurt, but the loss of autonomy' (P4, 20Hz, 200μs), 'And that might be more uncomfortable, because it [gives] even less control, I guess' (P7, 90Hz, 250μs). The findings demonstrate that not all fear and discomfort associated with EMS stems from physical discomfort. While we may calibrate for physical discomfort prior to using EMS (by finding maximal comfortable stimulation parameters, for example), it is important to note that not all discomfort is alleviated this way.

Describing sensations is a notoriously difficult task and participants often made use of comparative descriptions to evoke an image of what they were experiencing. Although most of these descriptions targeted tactile imagery and sensations, one subject appealed to a salient visual image to give a sense of what they experienced 'You know, when you have the cartoons, and they're having a shock, then things, yeah, you can almost feel why you're drawing the lines out here, because it sort of ... you can see this electric field around you' (P7, 55Hz, 200μs). In many cases, these descriptions would target relatively simple tactile imagery of one's boundaries being impinged from outside or within. Objects of comparison in these cases ranged greatly in scale, however, from relatively small objects such as needles (n=58), knives (n=13), drills (n=11) and even dwarves (n=1), to objects of greater scale '... it could just like be a giant finger tapping my arm' (P2, 55Hz, 100μs). In some cases, participants reported that the experience was complex (e.g., 'Many feelings!' (P1, 55Hz, 200μs)) or chose comparisons that evoked complex tactile imagery 'Like sometimes if you are driving on a motorway and you go a bit too far to the side and you get on those bumpy ... it feels a bit like that' (P12, 90Hz, 100μs) and 'Like when you're in a rollercoaster and you're going up, like there are these small ticks' (P2, 90Hz, 150μs).

On occasion, comparisons were also employed that combined complex tactile imagery with a sense of losing control or being subject to an external force 'A bit like when you stick your hand out from a window on a highway, and you can feel the wind and you can kind of control them but you cannot really' (P4, 20Hz, 250μs), 'I think that is what I think of when I say the water current thing, that is, it is always as if I try to move my arm in the different, against the current' (P12, 55Hz, 150μs), with one subject even speculating that the experience described might be similar to patients suffering from a motor disorder such as Parkinson's disease 'Jesus Christ. That's a weird feeling. Is that the way, when they can't control their muscles, is that the way they feel?' (P8, 20Hz, 100μs).

While perceptions of control seem fundamental across the participant data, the diversity of the comparative imagery that the participants draw upon demonstrates the complexity of the experience of EMS.

6 KEYWORDS BY STIMULATION PARAMETERS

To analyze keywords from the participants' descriptions further, we followed an exploratory analysis approach. This analysis departs from the observation that word frequencies for the top 48 words differ across stimulation frequencies (x^2= 701.22, df = 94, p <.001) and pulse-widths (x^2 = 291.12, df = 94, p <.001). We then proceeded to look at the adjusted residuals, following Bakeman and Quera [2] and Sharpe [21]: adjusted residuals indicate the words that differ the most from the expected distribution. We use residuals in two ways. First, we look for words that increase or decrease monotonically over the EMS parameters we manipulated. Second, we look at residuals with an absolute sum greater than 8, indicating significant variation from the expected distribution. These keywords provide an insight into the relationship between stimulation parameters and the experience of EMS. We show sparklines [23] with each keyword to illustrate how their usage changes across the parameters. [2]

6.1 Frequency

Participants were stimulated across four frequencies (20Hz, 55Hz, 90Hz, 120Hz.) Figure 3 illustrates significant keyword usage across frequency parameters. As the frequency of stimulation increased, keyword usage with inherent temporal rhythms decreased. These keywords include 'tapping' (from the *Peripheral Sensation* analysis theme), 'shaking' (autonomic), 'pulsing' (autonomic), 'beating' (autonomic), pounding (autonomic), and 'stabbing' (peripheral). These keywords were replaced with those detailing continuous temporal properties; from vibrate (peripheral) and impulse (signal), to buzz (peripheral).

[2]Note: the sparklines show the keyword's adjusted residual and are normalised per keyword. Normalising per keyword maximises the information in the small figures, highlighting increases and decreases in distribution. As a result of this, the sparklines do not support direct comparisons between keyword distributions, but rather support comparisons of changes in distribution across parameters.

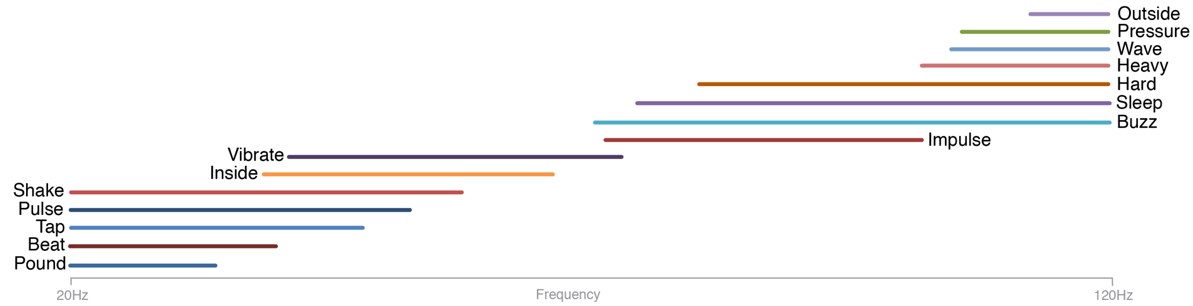


Fig. 3. Illustration of significant keyword usage by frequency. This illustration allows EMS designers and readers of EMS papers to look up specific frequency parameters and gain an understanding of the associated user experience. Process: Words were selected for the plot if their adjusted residuals monotonically increased or decreased across the frequency range, or if they vary significantly from their expected distribution. Adjusted residuals were plotted, and the above graph shows where words appeared significantly more than expected within the frequency range.

At the same time, keywords related to the application of force increased with frequency, including 'pressure' (peripheral), 'heavy' (peripheral), 'push' (peripheral) and 'hard' (emotional). So as the signal moves beyond the point at which individual signal peaks can be felt (for example, as a tapping), our participants related the experience to an increased sense of force. Interestingly, usage of 'stabbing' (peripheral) decreased as stimulation frequency increased, although usage of 'knife' (peripheral) ('like getting cut with a very sharp knife') increased with frequency. This suggests that usage of knife related more to the force and sharpness of a knife, than to the action of use. Although not significant, the use of 'needle' (peripheral) peaked in the mid-range frequencies, perhaps providing some insight into the amplitude of sensations (from small and lighter, to large and intense) experienced by the participants across the frequencies.

As stimulation frequency increased, participants increasingly discussed internal sensations, such as muscle (autonomic), and sleeping (autonomic). Interestingly, this is in contrast to the use of 'inside' (location), which was used significantly at lower frequencies. While not significant, 'outside' (location) was used more at higher frequencies. This suggests that lower frequencies lead to an experience of deeper penetration of the signal, where higher frequencies still create internal sensations, that may, however, be attributed to external sources.

6.2 Pulse Width

Similarly to frequency, the participants were stimulated across 4 pulse widths (100μs, 165μs, 230μs, 295μs). As stimulation pulse widths increased, usage of 'tapping' (peripheral) decreased and usage of 'pinching' (peripheral) increased. Similarly to the difference between knife and needle seen across frequencies, this provides some suggestion that an increase in pulse width leads to a sharper sensation. Conversely perhaps, usage of 'pounding' (autonomic) also increased with pulse width, such as 'my heart is pounding, but it's in my hand.' This does not mirror the sharpness seen between tap and pinch, instead alludes to an increase in intensity. This increase in intensity is not necessarily coupled to an increase in discomfort, however, as usage of 'hurt' (emotional) decreased as pulse width increased.

During the interviews, participants described some sensations as a 'pull' (control and volition) ('Someone is taking over control, and pulling your arm') and some as a 'push' (control and volition) ('my hand is being pushed down'). The adjusted residuals show that the usage of 'pull' increased with pulse width, and 'push' decreased.

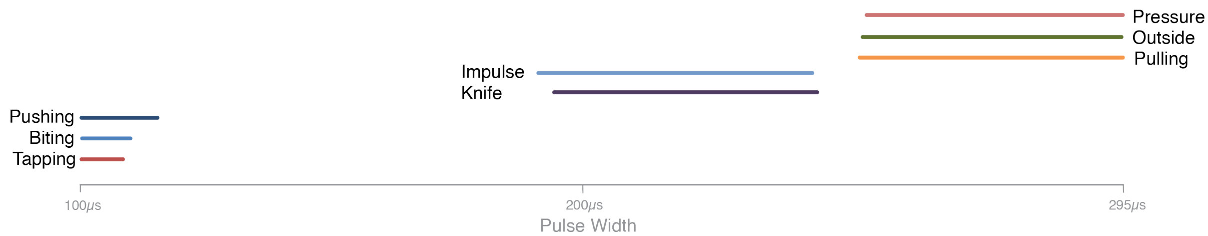


Fig. 4. Illustration of significant keyword usage by pulse width. Similarly to Figure 3, this graph provides an insight into the experience of specific pulse width parameters for EMS practitioners and readers of EMS papers. (See Figure 3 for an explanation of the process of producing this illustration.)

7 DISCUSSION

The user experience of EMS is complex, multi-dimensional and personal. Our work here demonstrates the breadth of experience that can be provided through EMS. Where previous work has focused on the muscle-actuation capability of EMS and paid limited attention to the associated user experience, we contribute a deeper insight into the nuance of this experience.

The descriptions reported here, and the significant keyword-parameter usage illustrated in Figures 3 and 4, provide a reference for better understanding the experience of EMS - offering new insights into the existing EMS literature and supporting the design of new interactions.

7.1 Understanding the Experience of Existing EMS Interfaces in the Literature

Our results here provide new insights into the existing EMS literature in HCI. By examining the reported frequencies and pulse widths against Figures 3 and 4, we can better consider the concept of learning a new musical instrument whilst your hand/forearm feels as though it is shaking and vibrating [22], or playing a game on your smartphone whilst your arm feels as though it is being pressed, and under pulsing, beating and tapping sensations [9], for example.

The results reported here also provide a deeper insight into the space of experiences that the participants in Wanding Through Space [20] were exploring as they self-calibrated their EMS setups by exploring a large, multi-dimensional space of parameters. For example, superimposed with our findings, Pohl et al.'s results show that users dislike the more temporal rhythms of EMS as the signal amplitude increases, instead preferring the 'pressure'-based sensations of a higher frequency of stimulation.

When describing the use of EMS in wearables, Pfeiffer et al. [18] suggest that EMS leads to sensations of 'ticking' at lower frequencies (30-60Hz). Our work supports this, with an increased frequency of rhythmic keywords (i.e., 'tapping', 'beating') at lower frequencies. At frequencies between 70 and 100Hz, Pfeiffer et al. suggest that the individual pulses can still be determined. While we report a significant use of 'impulse' within those frequencies, the other keywords relating to those parameters do not emphasise the individuality of stimulation pulses, instead emphasise more continuous sensations like 'sleeping', 'hard' and 'buzzing'.

7.2 Designing Novel EMS Interactions

Prior work on EMS has typically chosen stimulation parameters based on actuation effect, without consideration for the wider nuance of experience bound to their parameter selection. Our findings can guide EMS systems towards certain types of user experience. Furthermore, our paper can go some way towards clarifying the trade-offs between experience and stimulation accuracy in EMS. The vocabulary derived here can then be employed as an evaluation tool (similarly to [15] for touch), providing both authors and participants with a vocabulary through which to talk about their experience.

Our results provide an opportunity to not only consider EMS for actuation, but also for creating particular experiences. Participants descriptions of textures, forces and temperatures could provide novel interaction opportunities. For example, EMS could enable a sense of relief when putting down an object ('if you are lifting something heavy, then you let go', low pulse width and high frequency); or the sensation of someone tapping on your arm ('like someone is tapping', low pulse width and low frequency). These experiences could add additional richness to the use of EMS in VR [13]. The subtlety of stimulation could also present opportunities for haptic notifications and feedback, for example through a watch strap. A rich spectrum of sensations (such as tingling, buzzing, tapping, waving, and pressure), can all be applied through one modality, without any secondary effects (such as found with the sound of vibration motors). This could extend the concept presented in Revel [3], for example, with a wider range of user experiences.

7.3 Limitations

The study presented here has some limitations. First, the exploration here is of an EMS-only experience (i.e., the EMS is not bound to a specific task). Thus, the observations are about the sensation of the EMS itself. Future research may find that these sensations are reduced, or mitigated, through contextualized EMS relating to a specific task (for example EMS and VR, as in [13]). The exploration of EMS experience against task immersion remains an interesting avenue for future work, and for better clarifying the overall suitability of EMS as an output paradigm in HCI. Is EMS too awful to ever be an acceptable paradigm for HCI? Our results suggest that the answer to that question is complicated, but that there exists a space in which stimulation effect (i.e., actuation) and stimulation experience can be bound together into a coherent and acceptable output technique. If the intensity of these experiences is further reduced by the immersiveness of the accompanying task, then the opportunities for EMS become greater still.

Second, we targeted only a limited set of muscles in the forearm (those most prevalent in the HCI literature), using a limited subset of pulse width and frequency parameters. The user experience of further muscle locations, muscle sizes, and signal parameters, may differ. Our work lays the foundation for an experiential understanding of EMS, but as HCI research continues to use EMS, further experiential studies of new muscle locations, or new stimulation parameters will further develop our understanding.

Further, the participants were carefully calibrated to cause specific muscle actuations. However, as skin moves independently of the underlying muscles, their movement during the study could cause small changes in the actuation effect (for example, rotating the forearm may result in an electrode covering the flexor carpi radialis, rather than the palmaris longus as intended, causing a different movement). This kind of movement-caused misalignment is an inherent feature of on-skin electrodes and, as such, we chose not to constrain participants' movement in our study.

Finally, users may become accustomed to EMS and thus need increasing amplitudes of stimulation over time. By varying the stimulation parameters and keeping periods of stimulation short, we mitigated the effect of this within our study. Gaining a better understanding of the properties of this acclimatisation, and its impact on the experience of EMS, remains an avenue for further work.

8 CONCLUSION

HCI has so far used electrical muscle stimulation primarily for actuation. We have systematically explored a wide range of stimulation parameters, to gain a better understanding of the user experience of EMS. Our findings can help in the selection of stimulation parameters when designing future interfaces, present a range of novel opportunities for the wider use of EMS in HCI, and support reflection on the experience associated with existing work on EMS.

ACKNOWLEDGMENTS

The work is supported by the European Research Council (ERC) under grant number: 648785, and the Volkswagen Foundation under grant number: 89429. We would like to thank Pedro Lopes for his feedback on the manuscript and AxelGaard Manufacturing Co. Ltd. for their electrodes.

REFERENCES

[1] Jodi Aronson. 1995. A pragmatic view of thematic analysis. *The qualitative report* 2, 1 (1995), 1–3.

[2] Roger Bakeman and Vicenc Quera. 2011. *Sequential Analysis and Observational Methods for the Behavioral Sciences.* Cambridge University Press, Cambridge. http://ebooks.cambridge.org/ref/id/CBO9781139017343

[3] Olivier Bau and Ivan Poupyrev. 2012. REVEL: Tactile Feedback Technology for Augmented Reality. *ACM Trans. Graph.* 31, 4 (July 2012), 89:1–89:11. DOI:http://dx.doi.org/10.1145/2185520.2185585

[4] Erik Grnvall, Jonas Fritsch, and Anna Vallgarda. 2016. FeltRadio: Sensing and Making Sense of Wireless Traffic. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems (DIS '16).* ACM, New York, NY, USA, 829–840. DOI:http://dx.doi.org/10.1145/2901790.2901818

[5] Shin Hanagata and Yasuaki Kakehi. 2018. Paralogue: A Remote Conversation System Using a Hand Avatar Which Postures Are Controlled with Electrical Muscle Stimulation. In *Proceedings of the 9th Augmented Human International Conference (AH '18).* ACM, New York, NY, USA, 35:1–35:3. DOI:http://dx.doi.org/10.1145/3174910.3174951

[6] Mariam Hassib, Max Pfeiffer, Stefan Schneegass, Michael Rohs, and Florian Alt. 2017. Emotion Actuator: Embodied Emotional Feedback Through Electroencephalography and Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17).* ACM, New York, NY, USA, 6133–6146. DOI:http://dx.doi.org/10.1145/3025453.3025953

[7] Oliver Beren Kaul, Max Pfeiffer, and Michael Rohs. 2016. Follow the Force: Steering the Index Finger Towards Targets Using EMS. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16).* ACM, New York, NY, USA, 2526–2532. DOI:http://dx.doi.org/10.1145/2851581.2892352

[8] Jarrod Knibbe, Jonas Schjerlund, Mathias Petræus, and Kasper Hornbæk. 2018. The Dream is Collapsing: The Experience of Exiting VR. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems.* ACM, 483.

[9] Pedro Lopes and Patrick Baudisch. 2013. Muscle-propelled Force Feedback: Bringing Force Feedback to Mobile Devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13).* ACM, New York, NY, USA, 2577–2580. DOI:http://dx.doi.org/10.1145/2470654.2481355

[10] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15).* ACM, New York, NY, USA, 11–19. DOI:http://dx.doi.org/10.1145/2807442.2807443

[11] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. 2015. Proprioceptive Interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15).* ACM, New York, NY, USA, 939–948. DOI:http://dx.doi.org/10.1145/2702123.2702461

[12] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++: Allowing Objects to Communicate Dynamic Use. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15).* ACM, New York, NY, USA, 2515–2524. DOI:http://dx.doi.org/10.1145/2702123.2702128

[13] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17).* ACM, New York, NY, USA, 1471–1482. DOI:http://dx.doi.org/10.1145/3025453.3025600

[14] Pedro Lopes, Dofla Yksel, Franois Guimbretire, and Patrick Baudisch. 2016. Muscle-plotter: An Interactive System Based on Electrical Muscle Stimulation That Produces Spatial Output. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16).* ACM, New York, NY, USA, 207–217. DOI:http://dx.doi.org/10.1145/2984511.2984530

[15] Marianna Obrist, Sue Ann Seah, and Sriram Subramanian. 2013. Talking About Tactile Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13).* ACM, New York, NY, USA, 1659–1668. DOI:http://dx.doi.org/10.1145/2470654.2466220

[16] Claire Petitmengin. 2006. Describing onefis subjective experience in the second person: An interview method for the science of consciousness. *Phenomenology and the Cognitive sciences* 5, 3-4 (2006), 229–269.

[17] Max Pfeiffer, Tim Dnte, Stefan Schneegass, Florian Alt, and Michael Rohs. 2015. Cruise Control for Pedestrians: Controlling Walking Direction Using Electrical Muscle Stimulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15).* ACM, New York, NY, USA, 2505–2514. DOI:http://dx.doi.org/10.1145/2702123.2702190

[18] Max Pfeiffer and Michael Rohs. 2017. *Haptic Feedback for Wearables and Textiles Based on Electrical Muscle Stimulation.* Springer International Publishing, Cham, 103–137. DOI:http://dx.doi.org/10.1007/978-3-319-50124-6_6

[19] Max Pfeiffer, Stefan Schneegass, Florian Alt, and Michael Rohs. 2014. Let Me Grab This: A Comparison of EMS and Vibration for Haptic Feedback in Free-hand Interaction. In *Proceedings of the 5th Augmented Human International Conference (AH '14)*. ACM, New York, NY, USA, 48:1–48:8. DOI: http://dx.doi.org/10.1145/2582051.2582099

[20] Henning Pohl, Kasper Hornbæk, and Jarrod Knibbe. 2018. Wanding Through Space: Interactive Calibration for Electric Muscle Stimulation. In *Proceedings of the 9th Augmented Human International Conference (AH '18)*. ACM, New York, NY, USA, 19:1–19:5. DOI: http://dx.doi.org/10.1145/3174910.3174948

[21] Donald Sharpe. 2015. Your Chi-Square Test Is Statistically Significant: Now What? *Practical Assessment, Research & Evaluation* 20, 8 (April 2015).

[22] Emi Tamaki, Takashi Miyaki, and Jun Rekimoto. 2011. PossessedHand: Techniques for Controlling Human Hands Using Electrical Muscles Stimuli. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 543–552. DOI: http://dx.doi.org/10.1145/1978942.1979018

[23] E Tufte. 2014. Sparkline theory and practice Edward Tufte. (2014).

[24] Pierre Vermersch. 1994. *L'entretien d'explicitation.* Vol. 2003. Esf Paris.

[25] Frederik Wiehr, Felix Kosmalla, Florian Daiber, and Antonio Krüger. 2017. FootStriker: An EMS-based Foot Strike Assistant for Running. In *Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers (UbiComp '17)*. ACM, New York, NY, USA, 317–320. DOI: http://dx.doi.org/10.1145/3123024.3123191

Received May 2018; revised July 2018; accepted September 2018