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Wanding Through Space: Interactive Calibration for Electric Muscle Stimulation

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ABSTRACT

Electric Muscle Stimulation (EMS) has emerged as an interaction paradigm for HCI. It has been used to confer object affordance, provide walking directions, and assist with sketching. However, the electrical signals used for EMS are multi-dimensional and require expert calibration before use. To date, this calibration has occurred as a collaboration between the experimenter, or interaction designer, and the user/participant. However, this is time-consuming, results in sampling only a limited space of possible signal configurations, and removes control from the participant. We present a calibration and signal exploration technique that both enables the user to control their own stimulation and thus comfort, and supports exploration of the continuous space of stimulation signals.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**; *Gestural input*; • **Hardware → Emerging interfaces**;

KEYWORDS

Electric muscle stimulation, EMS, functional electrical stimulation, calibration, haptic feedback

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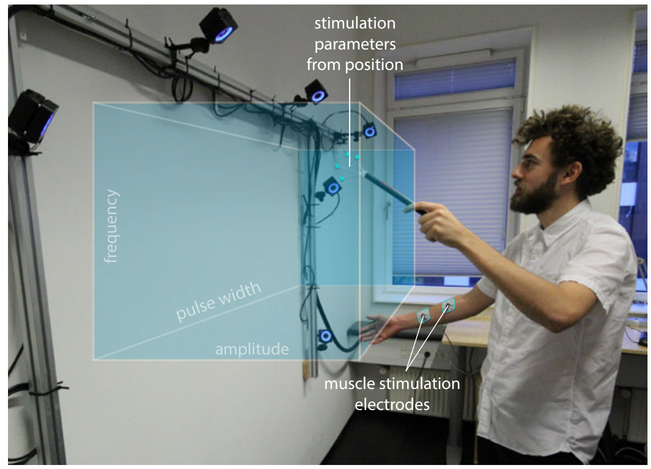

Figure 1: A user explores the 3D parameter space of Electric Muscle Stimulation. The location of the 'wand' in 3D space determines the stimulation parameters applied to their electrodes. With this technique, many parameter configurations can be explored quickly, while giving the user full control over the stimulation experience.

1 INTRODUCTION

Electric muscle stimulation (EMS) and Functional electric stimulation (FES) have seen increased use in HCI. Both use electrical signals to stimulate a user's nerves and muscles, either to provide haptic feedback or to cause movement. However, this stimulation requires careful calibration of many signal parameters, such as frequency, pulse width, or amplitude, as these influence *what* kind of sensation is evoked in the user. Furthermore, individual differences in skin thickness or subcutaneous fat necessitate per-user calibration.

Existing calibration techniques, especially in HCI, either use pre-selected pulse widths and frequencies, and thus only calibrate for amplitude, or explore only a small number of discrete pulse-widths and frequencies, alongside the amplitude. Whichever of these techniques is adopted, they both result in an exploration of only a limited part of the signal parameter space. Furthermore, these calibration techniques are time-consuming and rely on a complex collaboration between the experimenter and the participant. Typically, the experimenter selects parameters, controls the amplitude, and waits for a reaction from the user (either physical or verbal). This process removes control from the participant, even though FES can result in uncomfortable stimulations.

We present a new calibration and exploration technique, which addresses these problems. Selection of pulse width, frequency, and amplitude parameters here is mapped to a 3D space in front of the user. The user can then explore the stimulation parameters by moving through this space. This both puts the control back in the hands of the participant, and results in a calibration based on an exploration of a much wider space of parameters, without any incurred time penalty. Through a user study, we demonstrate the calibration of movement-causing EMS and FES for haptic feedback for smartwatches.

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2 RELATED WORK

FES/EMS has been used to a variety of ends—both to cause movement (e.g., [7, 12, 15, 16]) and provide haptic feedback (e.g., [5, 10]). At Augmented Human, for example, EMS has been used to change the flavor of soup by stimulating the tongue [1], add vibrato to speech [4], and to teach drumming rhythms [2].

While it is a critical part of any EMS system, calibration has received relatively little attention in HCI so far. We know from Lopes et al. [12], that calibration can be time consuming (2–5 minutes per participant per pose), and Pfeiffer et al. [15] describe the need for high levels of accuracy (electrode placement within 5mm of the optimal location). However, no standardized or generalizable approach has yet been adopted.

EMS calibration can be split into two components parts [9]: (1) spatial calibration—selecting the location for the electrodes—, and (2) signal calibration—selecting signal parameters to use (frequency, pulse width, and amplitude).

In this paper, we focus on signal calibration. This is typically approached in one of two ways: either (1) the authors pre-select the frequency and pulse width (e.g., [2, 11, 18]), and explore the amplitude with the participants. Alternatively, (2) the authors and participants explore a limited sub-range of the available parameter space (e.g., [13], where they fix the frequency, and explore pulse width and amplitude). Whichever technique is selected, only a small part of the available parameter space ends up being explored. While research in HCI has reported that selected amplitudes differ between participants [15], the same is also true for pulse width and frequency [14].

Current calibration processes proceed as an iterative back-and-forth between the experimenter and the participant, with the experimenter trying different parameters and the participant reporting sensations and movements. As a result of this process, EMS calibration necessarily focuses on a reduced space of parameters. This process is not scalable to include an exploration of a wider, continuous, parameter space. Having experimenters in the loop also limits the process to what they can observe or what participants can vocalize.

More recently, research has presented techniques for prediction of stimulation effects [3, 6], and automatic spatial calibration for EMS (e.g., [17]). Knibbe et al. [9], present a multi-electrode, spatial calibration approach using electromyography (EMG). By reading muscle activity with EMG, they could select combinations of a 60-electrode sleeve for stimulation to re-create the same pose. While promising, this technique still relies upon manual signal calibration, a factor that they suggest limits their accuracy. At Augmented Human 2013, Katoh et al. [8] presented an automatic electrode selection technique based on muscle twitch measurements. They fixed the frequency, amplitude, and pulse width of stimulation, varied the pulse length, and measured muscle twitch responses using an accelerometer on a finger. This goes some way towards selecting both optimal electrodes and stimulation parameters to cause movement. However, this technique fails to explore the larger space of signal parameters that may have resulted in more comfortable, or smoother actuation. To date, no such automated techniques have been presented for signal calibration.

3 SELECTING SIGNAL PARAMETERS IN 3D

We propose mapping EMS stimulation parameters to 3D space, allowing users to explore the calibration parameters by moving within the space. In our current setup, we map pulse width (x-axis), frequency (y-axis), and amplitude (z-axis) to a $1.1\,\mathrm{m} \times 0.7\,\mathrm{m} \times 0.6\,\mathrm{m}$ cuboid in front of the user. Parameters are transmitted to a custom electrotactile stimulator that continuously alters the output signal correspondingly. The used signal is a biphasic square wave that is current-limited according to the chosen amplitude setting (maximum signal strength capped at 35 V over skin resistance).

Users wear a set of electrodes on their desired location (we focus on the forearm) and then move a tracked wand through the parameter cuboid with their non-instrumented hand. The wand is tracked in 3D space with an OptiTrack motion capture system (eight Prime13 cameras at 240 Hz). This could equally be performed using hand tracking with a Kinect, or Leap Motion, for a more ad hoc setup. The user is free to move the wand around in 3D space, varying all parameters simultaneously, or can constrain their movements to single axes at a time, thus only varying individual parameters. By moving the wand away from themselves, the user increases the stimulation amplitude. Thus, should the user simply relax and let their arm fall to their side, or quickly pull their arm back towards themselves (a common reaction to shock, for example), then the amplitude quickly decreases and the stimulation stops.

We decouple the space exploration and the stimulation, choosing to use different arms for each role. While the same arm could be used, the stimulation can result in hand and arm motion that would cause the parameters to change in unintended ways.

4 STUDY

We recruited 17 participants (age 19–43, M=29.8, SD=6.8, 6 female) to use our system. Participants provided informed consent and were then introduced to the system by the experimenter. The experimenter explained that the participants could move anywhere within the 3D cuboid (as outlined by red tape on the floor and walls). The participants were told that as they move through the x- and y-axes the stimulation and associated sensation would change (i.e., they were not specifically told about pulse width and frequency mappings). Moving in the z-axis would increase the intensity. Throughout the entire study, participants explored the space holding a tracked wand in their left hand. Electrodes were placed in different locations (per task) on the right forearm.

The participants completed three tasks. First, participants were instructed to *explore* the 3D parameter space and develop an understanding of the changing stimulation sensations. For this task, participants wore a pair of electrodes on the top of their right forearm, targeting the flexor digitorum superficialis and the flexor digitorum profundus. The stimulation cuboid was configured with the parameters: 1–5 ms pulse width, 5–80 Hz frequency, 0–100 % intensity. At the end of this task, participants completed 7-point Likert scale questions on their understanding of the space, their sense of apprehension, and ease of use of the system.

Second, the participants' electrodes were moved to the top and bottom of the wrist, akin to the position of a watch face and band. The stimulation cuboid was configured with the parameters: 2–4 ms pulse width, 5–75 Hz frequency, 0–78 % intensity. Participants were

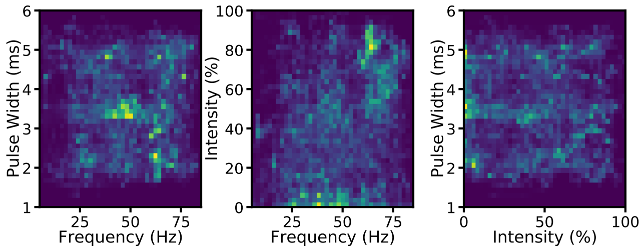

Figure 2: This heatmap shows where participants spent most of their time while exploring the parameter space.

asked to explore the space and find 5 distinct sensations that they may use for smartwatch *notifications*. Participants detailed what they would use the notification for, and provided Likert responses about comfort and disruption. At the end of the second task, participants were asked (1) how easy it was to distinguish sensations, (2) how long it took to find their chosen sensations, and (3) their movement and selection strategies for the task.

Finally, the electrodes were moved to cover the flexor carpi radialis and palmaris longus muscles, on the inside of the forearm. The stimulation cuboid was configured with the parameters: 1–4 ms pulse width, 35–80 Hz frequency, 0–100 % intensity. The participants were asked to find movement causing (muscle *activation*) parameters within the space, and rate them as comfortable or not-comfortable. In this way, the users specified their preferred movement causing parameters across a continuous parameter space. The experimenter recorded the participants' ratings. At the end of this task, participants completed a questionnaire about anxiety, intuitiveness and simplicity, and were asked about strategies of movement for this task.

The study took 25 minutes on average. Participants were compensated the equivalent of $15 for participating.

5 RESULTS

For the analysis, we removed data from three participants (P1, P7, and P16), because they only completed parts of the study. P1 and P7 were due to experimenter error with the study interface, while P16 opted to not complete the study. We describe the results, based on the data from the remaining 14 participants, below.

5.1 Exploration

As shown in Figure 2, participants explored a large portion of the available space. Participants explored on average 31 % of the space over 3.7 minutes. They tended to stay towards the inside of the space, as shown by the drop-off towards the edges of the graph.

Participants described exploring the stimulation space as intuitive and easy (Figure 3). The exploration did not make them anxious or nervous, and they were able to develop a good understanding of the stimulation space.

5.2 Notification

Figure 4 shows the participants explored 27 % of the available space while picking notification parameters (on average). They placed 3–5 (M=4.4) notifications, making use of the available space (see Figure 4). Participants spent on average 6.6 minutes finding notifications. Interestingly, participants explored the space for 45 seconds on average before selecting their first notification.

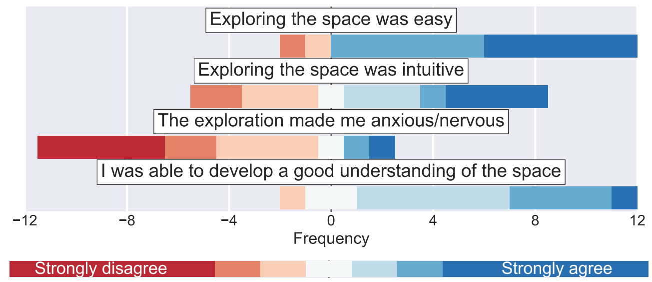

Figure 3: Participants found exploring the parameter both easy and intuitive. They reported little anxiety.

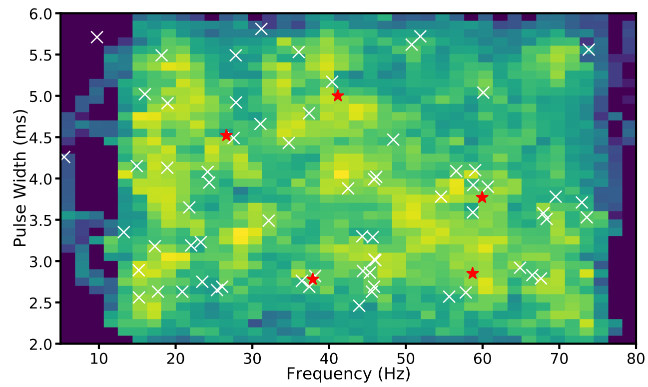

Figure 4: Participants made use of a large part of the available parameter space. The heatmap shows a projection of which parts of the space were visited with crosses marking chosen notification settings. Highlighted in red are the chosen notifications from one participant.

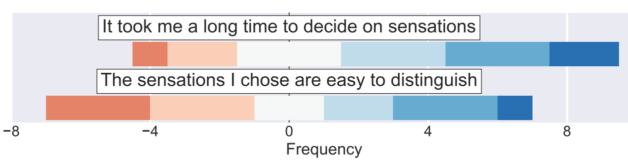

Figure 5: Participants felt it took a long time to decide on sensations and that there was no consensus on whether the sensations were easy to distinguish.

Participants also rated the comfort and disruption of their selections. Higher comfort ratings were seen as less disruptive: Spearman's rank correlation coefficient $r_s = -0.74, p < 0.0001$.

Participants defined notifications to cover a range of scenarios, including email alerts (n=5), phone calls (n=11), navigation updates (n=2), and medical warnings (such as diabetes alarms, n=3). Across these notifications, participants felt that, in general, it took them a long time to decide on sensations (Figure 5). There was no consensus about whether sensations were easy to distinguish.

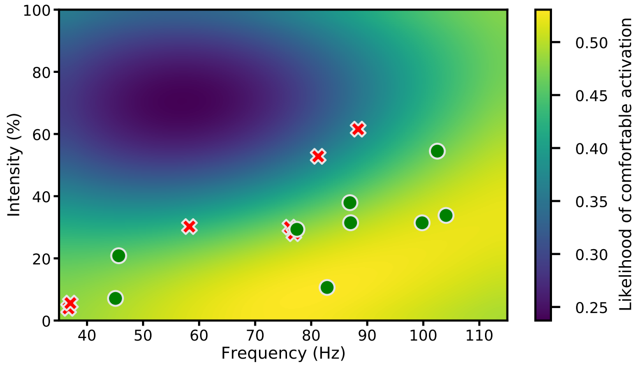

Figure 6: The likelihood of comfortable activation changes over the parameter space. Shown here is an averaged view of the space projected on the intensity-frequency plane. Highlighted are parameter ratings by P3.

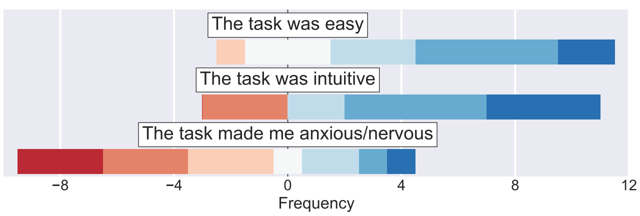

Figure 7: Participants found the muscle activation parameter search easy and intuitive and did not report anxiety.

5.3 Muscle Activation

The participants explored 27 % of the total stimulation space (on average). Participants spent on average 4.37 minutes exploring the space (SD=1.22). Participants marked on average 14.7 locations as movement causing (with 5.4 comfortable, SD=2.7, and 9.3 uncomfortable, SD=5.2). Figure 6 shows the Gaussian distribution of comfortable vs. uncomfortable actuation across all participants. The variation of positions marked by participants shows the importance of exploring a large space of parameters.

Asked about their strategies for exploration of the muscle activating parameters, participants often noted that they applied a structured/scanning approach. Our analysis confirms that participants mostly moved along the cardinal directions within the plane in front of them—moving up, down, left and right, with less forward and backward variation.

Similarly, to the initial exploration task, participants described exploring the muscle actuation space as easy and intuitive. The participants rated the task as not making them anxious or nervous.

6 DISCUSSION

Across the three study tasks, participants explored a combined 53 % of the stimulation space on average. As this is a continuous space across a wide range of pulse widths, frequencies, and intensities, this corresponds to a much wider range of parameter exploration than achievable using traditional signal calibration methods in HCI. In combination with the diversity of chosen stimulation parameters (either for notifications or activation), this shows the benefits of enabling exploration across a wide space. Exploring the parameters in 3D also enables faster signal calibration. Participants specified 14.7 muscle stimulation locations in 4.37 minutes, and 4.4 notification locations in 6.6 minutes. This represents a large improvement over the 2–5 minutes per pose (where pose is equivalent to selecting one preferred location) typical with traditional techniques [12].

Exploring 53 % of the stimulation space represents a large portion of the space where stimulation can be perceived, and is not uncomfortable. Anecdotally, participants were quick to identify 'unpleasant' locations in the 3D space, which they would then not explore further.

In this study, we have explored a 6 degree of freedom (DOF) exploration of a parameter volume. This enables participants to move the wand to a specific area to experience given stimulation parameters. However, additional degrees of freedom can be added. For example, once a parameter location has been selected, users could also specify the dynamics of the desired stimulation (i.e., the 'ramp' with which the stimulation is applied, from 0 % amplitude up to the desired x % amplitude, over time), by rotating the wand. Rotating left and right could specify the rate at which the intensity increases. This could be similarly achieved by allowing users to specify paths through the volume, rather than specific locations. Further, the wand could be replaced by a device that combines other input modalities (such as a VR controller), this could also enable dynamic rating or clutching interactions for varying the parameters within the space.

Importantly, our calibration technique gives control to the user. This is (ethically) important when they are exploring a space of interaction that could potentially be uncomfortable. The participants did not report being anxious or nervous during the study, however, anecdotally, some participants were uneasy when being introduced to the concept of the study. We believe that being in control is a valuable mechanism to help to reduce this apprehension surrounding EMS applications.

7 CONCLUSION

Calibration is a fundamental part of any FES/EMS-based system. To date, practitioners explore only a small range or subset of parameters when performing signal calibration. Typically this involves pre-selecting a small number of parameters and applying them to a participant to gauge their feedback. This results in control being removed from the participant, all while they can be exposed to uncomfortable, or sub-optimal, stimulation. We present a 3D exploration-based calibration technique that maps a large space of stimulation parameters to a 3D volume. By moving through the 3D volume, the participants control the parameters of their stimulation and can select those comfortable for them. In a study, we demonstrate participants exploring a wider range of stimulation parameters than previously attempted in HCI, all the while maintaining full control of the resultant sensations.

8 ACKNOWLEDGEMENTS

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