

Perceptual Characteristics of EMS-Induced Finger Flexion for Bodily Information Displays

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Abstract

Electrical muscle stimulation (EMS) can directly induce finger flexion, providing a promising supplementary modality for information presentation beyond vision and audition. However, the perceptual resolution of EMS remains poorly understood, particularly when applied to different fingers. We conducted a systematic experiment to examine how accurately humans can discriminate multiple levels of EMS intensity applied to different fingers. Results showed that participants were able to discriminate EMS intensities both with and without visual access to their fingers, indicating that reliable recognition was possible even in the absence of visual feedback. Across fingers and visibility conditions, mean accuracies reached 87.5%, 72.9%, and 60.6% for the 3-, 4-, and 5-step conditions. The little and middle fingers yielded higher performance than the index and ring fingers. These findings provide the first systematic characterization of finger-specific perceptual limits and error patterns in EMS-based interaction, and derive design guidelines for allocating signals across fingers and intensity steps.

CCS Concepts

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

Keywords

Electrical Muscle Stimulation (EMS), Finger Flexion, Perception

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1 Introduction

Electrical muscle stimulation (EMS) is a technique that applies electrical pulses through surface electrodes to induce muscle contractions. By activating the muscles, EMS can directly bend or move specific body parts, such as the fingers [30, 39, 40] or the wrist [32, 33]. In HCI, EMS has been applied in diverse domains such as motor learning [27–29], and functional feedback [11, 17, 19].

Recent years have seen a growing body of research that leverages EMS to use the human body itself as a medium for information presentation. Lopes et al. [18] demonstrated that EMS can be used to move the wrist to present information. Takahashi et al. [40] proposed an EMS-based navigation technique that guides finger movement in the direction of travel. Furthermore, bodily interaction has diversified into various directions, such as supporting social experiences across multiple users [32].

Among body parts, the fingers stand out due to their high sensory resolution and fine motor control [13, 35, 44]. Various approaches have leveraged the fingers for information output. While finger-worn vibrotactile devices stimulate only the skin surface, EMS directly stimulates the muscles to induce finger flexion. EMS enables fine-grained and expressive information presentation in a lightweight and compact form, making EMS a compelling way to deliver intuitive and private information to the fingers without overloading visual or auditory channels.

Nevertheless, the discriminability of EMS stimuli when applied to the fingers remains an open question. For EMS to function as a reliable interaction modality, it is essential to understand how accurately users can perceive and distinguish stimulation patterns, and how many steps can be consistently discriminated in this context. Clarifying these perceptual limits is crucial for designing finger-based EMS interfaces, as it determines the feasible granularity of signals and helps mitigate the risk of misperception.

To address this challenge, the present study investigates the discriminability of EMS applied to the fingers. We administered multiple step levels to the index, middle, ring, and little fingers, and measured how accurately participants could identify the presented levels. We also examined how discriminability was influenced by visibility (visible vs. invisible), since visual information may either support or interfere with proprioceptive and tactile perception. Our evaluation clarifies the perceptual resolution of EMS-based interaction and characterizes patterns of misclassification.

The contributions of this paper are as follows. We conducted a systematic user study on the discriminability of EMS steps applied to the fingers, revealing recognition accuracy and characteristic patterns of misclassification. We further identified fundamental constraints that must be considered in the design of EMS-based interfaces and derived concrete design guidelines for employing EMS as an informational channel. Together, these contributions provide a foundation for future applications.



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2 Related Work

In this section, we review prior research that has investigated the use of EMS as an interactive modality and the role of fingers as potential information displays, situating our work within the broader landscape of embodied interaction.

2.1 EMS for Information Presentation and Interaction

EMS enables direct control of muscle contractions by applying electrical pulses through surface electrodes, offering a unique way to modulate human posture and movement. Prior psychophysical research has compared electrotactile and vibrotactile stimulation, showing that intensity modulation provides finer discriminability than frequency modulation, and that electrotactile feedback achieves significantly higher resolution than vibrotactile feedback at equivalent carrier frequencies [6]. Such findings establish EMS as a high-resolution sensory channel and motivate investigations into its perceptual limits in interactive contexts.

In HCI, EMS has been applied across a variety of domains, including motor skill acquisition [5, 27–29, 31, 46], silent or private notifications [8, 38], navigational assistance [36, 42], and immersive virtual environments [12, 26]. These studies demonstrate the potential of EMS to support physical learning, deliver subtle feedback, and create embodied interaction experiences without relying on traditional visual or auditory channels.

Recent work has extended EMS usage beyond task guidance to more conceptual interaction paradigms involving asymmetric agency and altered body perception. Lopes et al. [18] showed that EMS-induced motion can blur the boundary of body ownership, enabling non-symmetric interactions in which the system controls part of the user's body. Building on this, Patibanda et al. [32, 33] demonstrated interaction techniques in which users relinquish control of certain muscle movements to a computational system or share their stimulation patterns with others, treating the body itself as an active medium for both system-driven and collaborative experiences.

While EMS Icons [7] highlighted the expressive potential of EMS for symbolic communication, it did not address the perceptual constraints that define how reliably such signals can be distinguished. Our work systematically investigates the discriminability of EMS intensities applied to the fingers, providing foundational knowledge for designing EMS as a fine-grained informational channel.

2.2 Fingers as Information Displays

Fingers offer a promising substrate for embodied information presentation due to their high tactile resolution, proprioceptive sensitivity, and fine motor control [13, 35, 44]. Prior research has explored a wide range of approaches to stimulate the fingers. Finger-worn vibrotactile interfaces convey short signals such as alerts or directional cues [2, 9, 10, 16, 22, 41], while friction and skin-slip modulation techniques enable the rendering of surface motion and texture qualities [14, 23]. More recent work leverages shape-changing or compliance-varying actuation, such as skin-stretch devices and EMS-induced movement, to directly manipulate finger posture [4, 30, 45]. Pneumatic and liquid-based devices have also been proposed, offering multi-dimensional force

feedback and richer haptic cues [3, 4, 10, 20, 21, 37, 41]. Furthermore, high-fidelity rendering has been achieved through multi-point actuation or relocation strategies, including devices such as NormalTouch/TextureTouch [1] and wearable systems that relocate fingertip sensations to the forearm for multi-finger interaction [25]. In addition to such implementations, complementary user studies have shown that users consistently prefer finger-level vibrotactile feedback over wrist or forearm feedback, both in virtual and physical environments [43], reinforcing the unique suitability of the fingers as embodied displays.

Collectively, these systems demonstrate the feasibility of finger-specific output, yet they primarily focus on momentary cues such as alerts, direction, or surface qualities. Sustained modulation of finger posture or symbolic information expression remains underexplored. Our work addresses this gap by positioning fingers not only as channels of action but also as embodied displays capable of dynamic and expressive information presentation.

3 Experiment

This experiment evaluated EMS-induced finger flexion as an information display. We examined how the number of steps, finger differences, and visibility affected recognition accuracy and subjective experience. Sixteen participants (9 male, 7 female; mean age = 23, range = 21–25, ID: P1–P16) all used their right hand. EMS experience was rated on a 5-point Likert scale (mean = 1.44), showing that most had little or no prior exposure.

3.1 Setup

Following Pfeifer et al. [34], we developed a custom EMS system to deliver controlled stimulation to the four fingers (Fig. 1A). The stimulation intensity was controlled by adjusting the output level of the EMS device through a custom control board. Figure 1B shows the surface electrode placement on the dominant hand. We utilized five electrodes: four smaller electrodes (1×3 cm), one for each finger, were placed alongside the respective finger's metacarpus as the positive ends, and a larger electrode (3×3 cm) was attached to the wrist as the common ground, following Takahashi et al. [39]. This configuration allowed localized stimulation while minimizing discomfort [24]. Each EMS channel delivered biphasic rectangular pulses at 100 Hz with a pulse width of 250 μ s. Each stimulus lasted 2 s. To prevent residual sensations, the inter-trial interval was set to 1 s plus the time allotted for participant responses. A browser-based interface controlled trial flow and recorded responses (Fig. 1C). Figure 1D illustrates the participant posture. Participants rested their elbow on the desk with the forearm vertical and the wrist relaxed. To manipulate visibility, we used a partition to occlude the hand.

3.2 Design and Procedure

We employed a within-subjects design with three independent variables: Finger (index, middle, ring, little), Step (3, 4, 5), and Visibility (visible, invisible). Each unique combination was presented twice, resulting in 48 trials per participant. Trials were organized into finger blocks to reduce cognitive load and ensure consistent stimulation within each finger. The order of finger blocks was counterbalanced across participants using a Latin square.

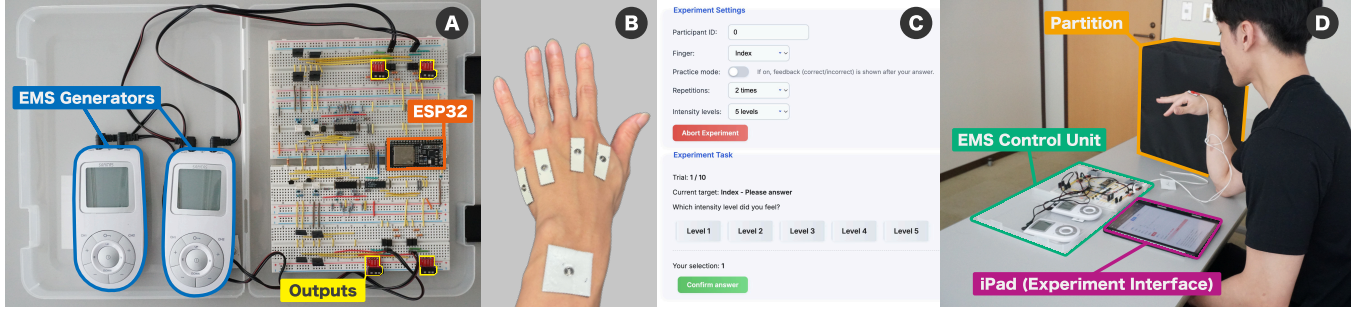


Figure 1: This figure illustrates the experimental setup. A represents the EMS circuit. B shows the electrode pad placement. C is the response interface, through which participants input their perceived stimulation levels. D shows the participant setup; in the non-visual condition, the hand with attached electrodes is hidden behind a partition.

Before each block, a calibration phase was conducted to determine the maximum non-painful intensity that produced full flexion. Based on this value, 3-, 4-, and 5-step intensity levels were subjectively adjusted so that perceived increments were approximately equal. To ensure consistency, each participant completed a brief pre-test to confirm that the calibrated increments were perceptually distinguishable, with minor adjustments made as needed.

Within each block, participants completed the 3-step condition first, followed by the 4-step and 5-step conditions. A 2.5-minute rest was provided between blocks. Each step condition included both visible and invisible trials, and the order of visibility conditions was counterbalanced across participants. At the beginning of each step condition, one practice trial was provided to familiarize participants with the stimulation and response interface; practice trials were not included in the dataset. During each trial, EMS was applied to the target finger at one of the calibrated step levels. Participants reported the perceived step using the interface, and the system automatically recorded both responses and correctness. Recognition accuracy and confusion matrices were used as quantitative measures.

After all blocks were completed, a semi-structured interview was conducted to collect qualitative insights, focusing on (1) subjective impressions of each step (discomfort, strangeness, pain), (2) difficulties across fingers and conditions, (3) impressions of EMS-induced finger flexion as an information channel, and (4) free comments or suggestions.

3.3 Results

Recognition accuracy was evaluated across finger (index, middle, ring, little), number of steps (3, 4, 5), and visibility condition (visible, invisible). Table 1 presents the mean accuracy for each condition. The 3-step condition yielded the highest accuracy (mean 87.5%), while accuracy declined in the 4-step (72.9%) and 5-step (60.6%) conditions as the number of steps increased. Finger-specific differences were also observed: the little finger (76.5%) and middle finger (75.1%) maintained relatively high recognition accuracy, whereas the ring finger (66.0%) and index finger (68.1%) showed lower performance, with accuracy dropping to around 50% in the 5-step condition. In addition to the overall tendencies, substantial inter-individual variability was observed. For example, P12 achieved 100% accuracy

Table 1: Accuracy (%) by finger, step, and visibility.

Finger	Step	Visible (%)	Invisible (%)	Mean (%)
Index	3	84.38	76.04	80.21
	4	71.09	75.00	73.05
	5	53.13	60.63	56.88
Middle	3	85.42	90.63	88.02
	4	77.34	76.56	76.95
	5	62.50	69.38	65.94
Ring	3	89.58	85.42	87.50
	4	64.06	68.75	66.41
	5	56.25	49.38	52.81
Little	3	92.71	95.83	94.27
	4	71.09	79.69	75.39
	5	70.63	63.13	66.88

for the ring finger in both the 3- and 4-step conditions, whereas P9 reached only 18.8% accuracy for the same finger in the 4-step condition. This illustrates that even under identical finger-step combinations, performance varied considerably across individuals. Such variability became more pronounced as the number of steps increased, indicating that higher task difficulty amplified individual differences.

To assess visibility effects, accuracies violated normality (Shapiro-Wilk, $p < .001$) but met homoscedasticity (Levene, $p = .17$). A paired Wilcoxon signed-rank test showed no difference between visible and invisible ($W = 72,610$, $p = .467$); Holm-Bonferroni across fingers confirmed non-significance ($p_{adj} > .05$). A GLMM (Step=3/4/5; random intercepts for Participant and Participant-by-Finger) replicated this pattern: Visibility was non-significant ($\beta = -0.46$, $z = -0.99$, $p = .323$), Step was significant ($4,5 < 3$, $p < .01$), and no visibility-related interactions survived Holm correction ($p_{adj} > .05$).

Figure 2 provides a detailed breakdown of misclassifications through row-normalized confusion matrices. Errors were not randomly distributed but occurred primarily between adjacent step levels, particularly between levels 2–3, 3–4, and 4–5 in the 5-step condition. This trend was most pronounced for the index and ring fingers, where participants frequently judged steps either higher or lower than the actual level. In contrast, the little and middle fingers

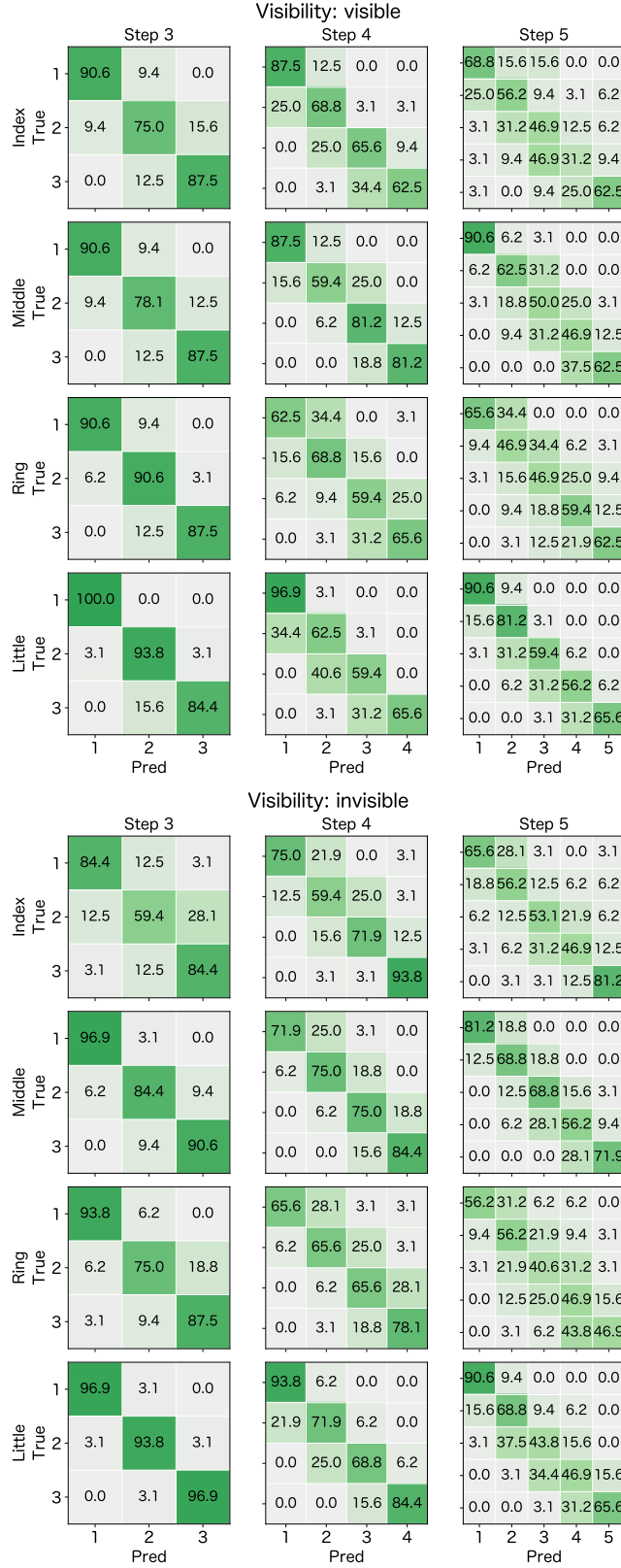


Figure 2: Row-normalized confusion matrices (in percentages) of predicted vs. true level for each finger across step conditions (3, 4, 5). Left: visible; right: invisible. Cell values indicate per-row percentages (0–100, one decimal); color scale also reflects per-row percentages.

exhibited fewer errors and clearer separation between levels. These results indicate that misclassifications did not occur randomly, but rather stemmed from perceptual difficulties in discriminating finely spaced step levels.

Qualitative reports from participants supported these patterns. Many noted that the ring finger was particularly difficult to judge because its movement was coupled with adjacent fingers, whereas the little finger, despite occasional discomfort at maximum step, was often easier to distinguish. Several participants reported that fine distinctions became harder when similar levels were presented consecutively, describing a residual sensation that carried over to the next trial. Others mentioned relying on relative comparison across trials rather than absolute sensation, especially for mid-level steps. These observations align with the confusion matrix analysis, suggesting that errors arise not from random guessing but from the inherent ambiguity of perceptual boundaries under EMS stimulation.

4 Discussion and Limitations

Our study evaluated the discriminability of EMS-induced finger flexion and found that recognition performance differed across conditions. Participants were generally able to identify stimulation steps correctly, and the 3-step condition yielded the highest accuracy, demonstrating that EMS-induced finger flexion can serve as a feasible channel for conveying multi-level information. As the number of steps increased, however, discrimination became more difficult. In the 5-step condition, recognition accuracy dropped to around 50% for the ring and index fingers, whereas the little and middle fingers maintained relatively higher accuracy.

These finger-specific differences can first be explained by the low recognition rates observed at the first step. For the index and ring fingers, participants often failed to detect or correctly classify the lowest stimulation level, which substantially reduced overall accuracy. This suggests that weak EMS contractions in these fingers provide less salient proprioceptive cues compared to the little and middle fingers. The relatively high accuracy of the little finger can be explained by its anatomical characteristics. The abductor digiti minimi is located superficially in the palm, directly beneath the skin, making it particularly responsive to surface electrode stimulation. As a result, even weak stimulation produced clear contractions and salient proprioceptive cues, which likely contributed to the higher accuracy. For the middle finger, Kooi et al. [15] reported that its lumbrical is the strongest and longest among the four fingers, likely allowing EMS to induce clearer flexion and supporting the higher accuracy observed here. By contrast, the lower accuracy of the ring finger can be attributed to its limited independence. Schieber and Santello [35] reported that the ring finger often moves together with adjacent fingers, which may have led to ambiguity in discrimination. Although anatomically independent, the index finger plays a central role in precision pinching with the thumb [15]. EMS-induced isolated flexion may therefore have deviated from habitual motor patterns, producing unstable perception. This is consistent with participant feedback: P16 noted that “the index finger bent in a way that felt different from usual,” suggesting that perceived unnaturalness contributed to reduced accuracy.

Error analysis further revealed that misclassifications were not random but concentrated between adjacent step levels, particularly between levels 2–3, 3–4, and 4–5 in the 5-step condition. This pattern is consistent with psychophysical findings that perceptual judgments often exhibit ambiguous categorical boundaries [6, 44], suggesting that EMS step discrimination is subject to the same constraints. Finally, visibility did not have a statistically significant effect on recognition accuracy, indicating that EMS interaction primarily relies on proprioceptive cues, with vision providing only limited reinforcement. Practically, this suggests that EMS systems can remain effective even in contexts where visibility is restricted or the visual channel is heavily loaded.

Taken together, these results suggest two key design principles for EMS-based interfaces. First, three steps represent the highest discriminable resolution, serving as a practical upper bound for EMS-based interaction. Second, the little and middle fingers should be prioritized for information delivery due to their higher discriminability, whereas the index finger should be assigned a lower priority. Overall, our findings show that up to 16 types of information can be conveyed across four fingers without visual attention, underscoring the strong potential of EMS-based finger interaction for body-centered information presentation.

Several limitations should be noted. The small sample size ($N=16$) limits generalizability, and only intensity modulation was examined. Future work should verify calibration objectively and explore multi-finger, temporal, and reference-free conditions. Because only one practice trial was given to reduce fatigue, adaptation may have been limited. Some participants described “unnatural” motion, reflecting a repeated loss of volitional control. This phenomenon should be regarded as a central design concern in EMS-based interfaces, as external stimulation may interfere with users’ natural motor control. Future research should examine how to balance effective feedback with the preservation of agency and comfort.

Beyond these limitations, our findings suggest that EMS-induced finger flexion is not merely a way to move the finger, but a flexible channel for conveying diverse information. EMS-based feedback can serve as a private and eyes-free notification modality where different fingers or intensities represent different meanings—for example, a light flexion of the little finger to signal an incoming message, or a stronger flexion of the middle finger to indicate urgency, or rhythmic patterns to provide navigation cues while cycling. It can also be used for skill training and rehabilitation, not only by guiding precise finger movements in piano or surgical training, but also by encoding the order, strength, or timing of these movements without visual distraction. Altogether, these application scenarios demonstrate that EMS can function as a body-centered display capable of encoding and delivering various types of information, thereby extending the design space of interaction beyond conventional haptic or visual modalities.

5 Conclusion

The results showed that, in the 3-step condition, all fingers achieved over 80% recognition accuracy, with the little finger reaching as high as 94%. Furthermore, the little and middle fingers enabled finer discrimination compared to the others, revealing finger-dependent differences in recognition accuracy. These findings indicate that

EMS-induced finger flexion can serve as a reliable information channel capable of conveying discrete information without relying on visual cues. These findings provide a foundation for using EMS as an information channel for subtle notifications or interactions where visual and auditory channels are overloaded. More broadly, this work positions EMS as a promising supplementary modality for embodied interaction, enriching the design space of future HCI systems.

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