Mutual Masking and Perceptual Simultaneity in Electrical Muscle Stimulation and Vibration Haptics

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***Abstract*—Multimodal haptic feedback that combines electrical muscle stimulation (EMS) and vibrotactile signals can create richer, more immersive experiences than those using a single modality. EMS delivers kinesthetic feedback by inducing muscle contractions, simulating force sensations that complement tactile stimuli from mechanical vibrations. However, presenting these stimuli concurrently can lead to perceptual interference, where one modality masks or alters the perception of the other. Temporal alignment between stimuli is also critical, as asynchrony can affect the perceived quality of haptic sensations. To investigate these phenomena, we conducted three user studies with a total of 40 participants (12, 12, and 16, respectively), focusing on mutual masking effects and temporal order perception between EMS and vibration. Our findings suggest that vibration can alleviate the tingling and discomfort commonly associated with EMS, effectively mitigating these unwanted sensations. Conversely, the presence of EMS increases the Just Noticeable Difference (JND) in vibration frequency discrimination, indicating a decrease in sensitivity to vibratory changes. Additionally, participants generally perceived the stimuli as simultaneous when EMS preceded vibration by 100 to 200 milliseconds. We discuss these findings and present four design guidelines for multimodal haptic rendering with EMS and vibrations in user applications.**

***Index Terms*—Multimodal haptics, vibrotactile feedback, electrical muscle stimulation, simultaneity judgment, just noticeable difference, tactile masking, user study.**

I. Introduction

MULTIMODAL haptics is rapidly emerging as a powerful approach for interaction in virtual and augmented reality, teleoperation, and wearable assistive devices. By integrating different haptic modalities, such as vibrotactile feedback, thermal stimuli, and force feedback, designers can create sensations that feel richer, more immersive, and tailored to specific interaction goals compared to single-modality approaches [1]. Among these combinations, pairing electrical muscle stimulation (EMS) with vibrotactile feedback has become especially promising for rendering virtual collisions and impacts [2], [3]. EMS induces users' muscles to generate kinesthetic sensations, mimicking how humans naturally generate forces to move their limbs (e.g., [4], [5], [6], [7], [8]). Vibrotactile actuators complement this by delivering cutaneous cues that simulate being tapped or hit. These modalities have driven advances in sensing, actuation, and control for increasingly complex haptic interfaces.

Multimodal haptic systems offer enhanced sensory experiences, but their effectiveness depends on how the human perceptual system integrates concurrent stimuli. The human haptic perception system is inherently complex, relying on a combination of kinesthetic and cutaneous receptors that work together to interpret external stimuli. Each type of haptic feedback is typically delivered by a dedicated actuator, with its own physical properties and temporal characteristics. When multiple modalities are combined, interactions between these stimuli can lead to perceptual interference, a challenge that has received growing attention in recent studies [9], [10], [11]. Tactile masking [12], where one stimulus interferes with the perception of another, is one such phenomenon that must be considered in multimodal systems. In addition, synchrony between modalities plays a crucial role in shaping the overall quality and realism of perceived haptic sensations [13]. However, to our knowledge, no prior work has systematically and quantitatively examined mutual masking and perceived simultaneity between EMS and vibrotactile feedback across a range of frequencies, amplitudes, and temporal offsets commonly used in human–computer interaction.

To address this gap, we designed and conducted three controlled user studies with a total of 40 participants. These studies examined: (1) the masking of EMS sensations by vibration at intensities calibrated to just-cause-muscle-movement (Study I, n=12 participants); (2) the masking of vibration cues by EMS, assessed through changes in just noticeable differences (JNDs) in vibration frequency (Study II, n=12); and (3) the perceived simultaneity of EMS and vibration stimuli, measured using points of subjective simultaneity (PSS) and windows of simultaneity (WS) (Study III, n=16). In Study I, we found that larger vibration amplitudes significantly masked tingling and discomfort sensations typically associated with EMS, with EMS sensations becoming less dominant as vibration amplitude increased. In Study II, EMS interfered with users' ability to discriminate vibration frequencies, significantly increasing the JNDs, particularly at lower vibration frequencies and shorter EMS pulse widths. In Study III, participants perceived the two

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stimuli as simultaneous only when EMS preceded vibration by approximately 100–200 milliseconds (ms). The perceived simultaneity window varied widely across conditions, from 79 ms to 244 ms. Our contributions are:

1) Empirical data on mutual masking and simultaneity perception for EMS and vibrotactile feedback;
2) Four design guidelines for multimodal EMS and vibration rendering to minimize EMS-induced discomfort while preserving perceptual clarity and synchrony.

II. Related Work

We cover prior work on EMS and multimodal rendering as well as perceptual masking and temporal synchrony in haptics.

A. Electrical Muscle Stimulation

Early applications of EMS have a long history in fitness training [14] and rehabilitation [15], [16], [17]. More recently, EMS has attracted growing interest in human-computer interaction. For instance, PosessedHand [7] enables fine-grained control of multiple fingers for learning an instrument, and ElectricAuth [18] introduces an EMS-based biometric system that authenticates users via unique involuntary muscle responses. EMS has also been used to deliver haptic feedback in gaming [3], [4], [19], mixed reality [19], virtual reality [2], [3], [8], and teleoperation [20] environments. Additionally, EMS has been applied to convey various object properties during virtual interactions such as touching, grasping, and punching [8], [21].

A drawback of using EMS for user applications is an uncomfortable sensation on the user's skin. This occurs because electrical impulses must pass through tactile receptors before reaching the muscles to trigger movement [22], resulting in an unwanted and uncomfortable sensation often described as "tingling" [3], [23], [24], [25], [26], or "buzzing" [27] by researchers and participants in multiple studies. While some studies have reported qualitative comments that EMS sensations can be masked by concurrent haptic stimuli [3], [26], there is a lack of empirical work that systematically investigates these masking effects or develops strategies to mitigate EMS-induced discomfort. Our work addresses this gap by examining the conditions under which EMS-induced sensations can be attenuated through vibrotactile masking.

B. Multimodal Haptic Rendering

An emerging area in haptics is multimodal haptic rendering, which aims to enhance the quality of physical feedback by combining multiple types of haptic stimuli. Compared to unimodal approaches, multimodal rendering can produce richer and more nuanced sensations, leading to more realistic and immersive user experiences [28], [29]. Wang et al. [1] provide a comprehensive review of multimodal haptic devices and rendering techniques. In particular, vibrotactile feedback has often been integrated with other haptic modalities to enrich user experience and expand the expressive range of haptic systems. Previous work investigated combining vibrations with impact signals [30], thermal stimuli [31], [32], [33], kinesthetic feedback [34], [35], [36], [37], [38], [39], skin stretch [40] and electrical muscle stimulation [2]. For example, Park et al. [30] combined vibration and impact to more accurately reproduce virtual collisions than each stimulus alone. Lopes et al. [2] developed a wearable device called Impacto, which integrates impact and EMS to deliver realistic collision sensations to upper and lower limbs. In addition, EMS has been combined with other mechanisms such as the hanger reflex [41] and mechanical brakes [42] to support precise and complex movements. While prior studies focused on user applications of multimodal EMS rendering, our work examines the perceptual effects of combining vibration and EMS.

C. Perceptual Masking in Multimodal Haptics

Tactile masking occurs when a weaker tactile signal is perceptually suppressed by a stronger one, leaving only the more intense stimulus detectable [12], [43], [44]. Human tactile perception relies on four mechanoreceptor types, each tuned to a specific range or form of mechanical stimulation. Pacinian corpuscles are sensitive to high-frequency vibrations (80–450 Hz) [45], while Meissner's corpuscles respond to low-frequency vibrations and pressure in the range of 5–100 Hz [46], [47]. Tactile masking is most likely to occur when both stimuli activate the same mechanoreceptor channel [48].

Masking effects can be undesirable when they suppress haptic cues essential for interaction or feedback [48], [49], [50]. For example, Lezkan and Drewing [50] showed that masking impedes the integration of haptic information during texture exploration. Vardar et al. [48] observed that masking stimuli elevate detection thresholds and impair the perception of tactile features such as edge sharpness. However, masking can also be advantageous in certain contexts. For example, in thermal referral and masking, combining vibrations with thermal input can shift the perceived location of the thermal sensation to the site of tactile stimulation [9], [51], [52], [53], expanding perceived thermal coverage across the skin without additional thermal actuators [9], [53]. Tanaka et al. [54] demonstrated a frequency-specific masking effect, where a vibration on the forearm could suppress the perception of a same-frequency vibration on the fingertip, which could be useful for the modification of perceived textures.

Others have combined mechanical and electrical tactile stimuli to improve perceptual outcomes. Yem and Kajimoto [55] used mechanical vibration to mask the vibrational component of an electrical stimulus and induce a pure pressure sensation. Mizuhara et al. [56] demonstrated that combining both can reduce the unnaturalness of electrical signals and amplify mechanical impact, achieving mutual enhancement. These studies focus on masking or modulating primary sensations. Our work extends this literature by examining masking between EMS and vibration, asking whether vibration can suppress the undesirable side effects of EMS (tingling and discomfort) rather than its primary kinesthetic feedback. Because EMS uses stronger currents than cutaneous electrical tactile stimulation, understanding these sensations supports practical applications and differentiates our work from prior research.

TABLE I
STUDY TOPICS AND PARAMETERS FOR THREE STUDIES

		Study 1	Study 2	Study 3
Study topic		Masking effects on EMS tingling and discomfort sensations by vibration	Masking effects on JND for vibration frequency by EMS	Perceived simultaneity between EMS and vibration
EMS	Pulse width	100, 150, 200, 250 μs	100, 250 μs	100, 250 μs
	Frequency	20, 50, 90, 120 Hz	20, 120 Hz	20, 120 Hz
	Duration	5 s	2 s	$\leq$ 1 s
Vibration	Frequency	170 Hz	100, 170 Hz	100, 170 Hz
	Amplitude	small (0.83 g), medium (1.72 g), large (2.54 g)	large (2.54 g)	medium (1.72 g), large (2.54 g)
	Duration	5 s	2 s	$\leq$ 1 s
Additional parameters		-	Comparison vibration frequencies: 12 values between [80Hz, 230Hz]	Delays: 19 values between [-330ms, 210ms]

D. Temporal Synchronization Across Modalities

In multimodal haptic rendering, precise onset synchronization between stimuli from different modalities is crucial for achieving the intended perceptual effects [57], [58]. While most multimodal haptic systems rely on internal piloting and manual adjustments to align stimulus timing [33], [59], a few recent studies have systematically investigated temporal perception. Park et al. [13] investigated the perceptual sensitivity to the simultaneity between impact and vibration stimuli, showing that simultaneity perception is affected by both vibration frequency and duration. Jodai et al. [60] examined the simultaneity window between thermal and tactile stimuli and found that perfect temporal alignment was not necessary; rather, the timing could be adjusted to increase the likelihood of perceived simultaneity. There is also research on onset synchronization between haptic and other sensory modalities. For example, Machulla et al. [61] demonstrated that synchrony judgments across visual, auditory, and tactile inputs are transitive and rely on a globally coherent internal representation of temporal alignment, underscoring the importance of precise timing in designing perceptually consistent multimodal systems. However, to our knowledge, little research has explored temporal synchrony between EMS and vibrotactile stimuli. Our work fills this gap by quantifying human sensitivity to the timing of EMS and vibrations, thereby supporting realistic and perceptually aligned multimodal haptic rendering.

III. Experiment Setup

We used the same apparatus and experimental setup for all three studies. Table I summarizes the study topics and parameters for all three studies. The experimental protocol was approved by the Arizona State University Institutional Review Board (IRB ID: STUDY00022028).

A. Apparatus

We developed the EMS feedback prototype based on an off-the-shelf EMS massage device (Beurer Medical EM49 EMS/TENS) for providing electrical muscle stimulation. We replicated a controller from the EMS Toolkit [62], which includes an Arduino Nano for precise control of the EMS output intensity and timing. The EMS Toolkit utilizes an electrically isolated circuit capable of switching EMS pulses on or off via a USB connection (Fig. 1). The resulting EMS stimulus is a sawtooth waveform, allowing pulse widths ranging from 80 μs to 450 μs and pulse frequencies between 1 Hz and 150 Hz. The EMS device enables users to control the intensity level by adjusting the peak amplitude of the waveform. Each intensity level corresponds to a fixed peak-to-peak current that is not affected by changes to the EMS frequency or pulse width. We measured this relationship at 100 Hz and 120 μs using an oscilloscope across a 1kΩ resistive load. The currents relevant to this study fall within the range of 9.6 mA to 32 mA. For one EMS channel, we used two 50 mm $\times$ 50 mm self-adhesive electrode pads.

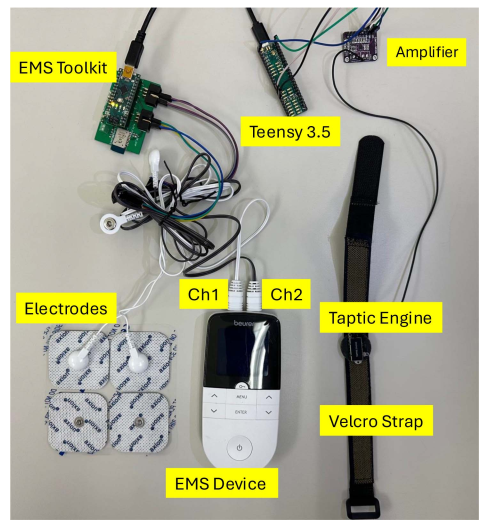

Fig. 1. Apparatus setup used for EMS and vibration stimulus delivery.

We generated sinusoidal vibrations using a Taptic Engine extracted from an iPhone 13 Pro Max with a Teensy 3.5 microcontroller. The Teensy synthesized sine waves at specified frequencies and amplitudes using its waveform generator and 12-bit digital-to-analog converter (DAC). Signals were amplified via a CJMCU-98306 MAX98306 Class D Amplifier and delivered to the motor. We measured the vibrations with an ADXL354CZ analog accelerometer connected to a NI USB-6353 DAQ, set at $\pm$8 g. The actuator was mounted directly on the accelerometer and fixed to a 10 g rigid mass with adhesive, totaling 20.5 g of moving mass. For skin contact, we attached the Taptic Engine to an adjustable Velcro strap. We used a Python script to

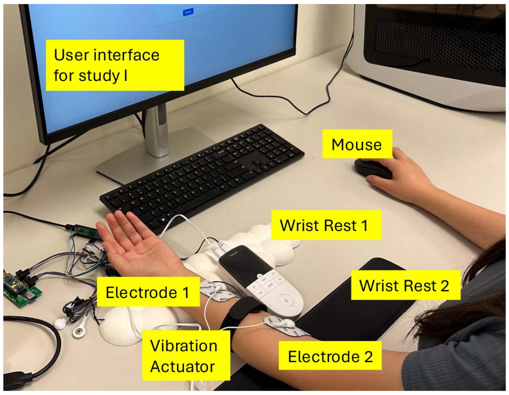

Fig. 2. Experimental setup for the three studies.

send simultaneous trigger commands to the Arduino Nano and Teensy 3.5, which serves as a communication bridge. The delays from this bridge were accounted for in our end-to-end latency measurements (Section VI-A). We ran the studies on a laptop, with an external monitor and mouse provided for participant input.

B. Actuators Placement

Fig. 2 shows the actuator placement and experimental environment across all three studies. We placed the EMS and vibration actuators on the forearm since most HCI EMS work focuses on the upper limbs and, in particular, the forearm muscles [3], [4], [5], [21], [63]. We targeted the flexor carpi radialis, a muscle responsible for bending the middle finger inward [63]. We placed a pair of electrodes 5 cm apart on the selected muscle on the left forearm, with the vibration actuator placed midway between them. This location ensured that the vibration was in close proximity to both EMS sites and aligned with common placements used in wearable devices. Two wrist rests supported the participant's forearm and kept the velcro strap of the vibration actuator from contacting the table, preventing unintended vibration dissipation.

C. EMS Calibration

We adopted the manual calibration procedures commonly used in EMS research [3], [62], [63], [64]. The experimenter introduced EMS and safety considerations and worked with participants to individually calibrate electrode placement and stimulation intensity based on differences in muscle size, skin conductivity, and other factors.

Location Calibration: To identify the correct electrode placement, participants were asked to perform an inward bending motion of the middle finger. The experimenter observed muscle contractions on the ventral side of the forearm and searched for the optimal EMS electrode positions by palpation. Then, the experimenter placed two electrodes over the muscle group associated with the target movement and used a default pulse width and frequency combination to confirm whether the stimulation elicited the expected motion. This spatial calibration was done once at the start of each study session.

Signal Calibration: We conducted signal calibration whenever the EMS pulse width or frequency changed during the study. Here, participants adjusted the intensity level themselves. We defined the *just-cause-muscle-movement* intensity level as the minimum EMS intensity that consistently produced a stable inward bend of the middle finger (beyond a minor twitch or fingertip jerk), without finger trembling. Participants were instructed to keep their muscles relaxed and were not asked to resist or suppress the movement during calibration.

IV. Study I: Masking Effects of Vibration on EMS At Just Cause Muscle Movement Intensity

The primary goal of this study is to investigate how vibration masks the tactile sensations (e.g., tingling, discomfort) produced by EMS on the skin to improve the overall comfort and usability of EMS-based haptic systems. We evaluated masking occurrence rates across four EMS pulse frequencies, four EMS pulse widths, and three vibration amplitudes with 12 participants (8 males, 4 females; mean age = 24.7 years, SD = 2.5) recruited through online advertisements at the author's institution. Recruitment criteria specified that participants should be free of neuropathy and skin injuries on their hands or forearms. Each participant received a $15 cash reward as compensation for a 70-minute study.

A. Study Design

EMS Stimuli: The EMS signal was a sawtooth waveform, and we selected four pulse widths: 100 μs, 150 μs, 200 μs, and 250 μs. The stimulation frequencies included 20 Hz, 50 Hz, 90 Hz, and 120 Hz. The selected frequencies and pulse widths cover a broad range of stimulation commonly utilized in HCI research (e.g., [4], [6], [7]) and are consistent with those available in off-the-shelf EMS devices frequently adopted in HCI applications (e.g., [6], [65]). *Vibration Stimuli.* We used three vibration amplitudes with the actuator's resonant frequency of 170 Hz. This frequency is within the Pacinian corpuscle detection range, ensuring reliable perception of vibrotactile stimuli [45]. In our internal tests, this frequency also exhibited the greatest potential to demonstrate masking effects. Based on our preliminary experiments with EMS and vibration stimuli, we selected three distinct amplitude levels—classified as small (0.83 g), medium (1.72 g), and large (2.54 g) on the dominant vibration axis.

Experiment Conditions: Each participant completed 48 trials: 4 pulse widths $\times$ 4 frequencies $\times$ 3 vibration amplitudes. The 16 pulse width–frequency combinations were randomized, with vibration amplitudes further randomized within each. EMS and vibration were delivered simultaneously for 5 seconds per trial.

B. Procedure

After signing a consent form, participants completed a background questionnaire that included their demographics (age, gender, educational background, and occupation) and prior experience with haptic technologies. They also received information about the experimental procedures. We did not present any information about the masking phenomenon to the participants to avoid any preconceived notions.

Next, participants experienced all pulse width–frequency combinations in a random order, calibrating the EMS intensity for each combination (see Signal Calibration in Section III-C). We recorded the calibrated intensity level they used for each condition. Once calibrated, the participant experienced the EMS-only condition for 5 seconds and answered three questions: (1) Rate the intensity of tingling or pain from EMS on a scale from 0 (none) to 10 (unbearable); (2) How uncomfortable was the EMS sensation on a scale from 0 (neutral) to 10 (extremely uncomfortable); (3) Identify the region where the EMS sensation was felt using a hand and arm diagram. The first two questions assessed distinct aspects of EMS sensations. Tingling was defined as the immediate physical cutaneous sensation evoked by electrical stimulation (e.g., buzzing, prickling), whereas discomfort was defined as the affective evaluation, reflecting how unpleasant or aversive it felt. Participants were instructed to treat these as separate dimensions and to rate each independently. During the study, if participants requested further clarification, the experimenter explained that "tingling" referred to the raw physical sensation, while "discomfort" referred to its emotional or aversive quality. For the last question, they selected as many points as they wanted by clicking on an image of the hand and arm. We followed prior subjective haptics studies in which participants were asked to indicate the regions where they perceived the stimulation [9], [66].

The participant then experienced the EMS stimulation combined with one vibration amplitude condition for 5 seconds and responded to four questions. The first three questions were the same as the EMS-only condition above. The last question asked (4) Which sensation dominated? (EMS / Vibration / Both equally). The same process was repeated for the other two vibration intensities before moving to the other pulse width-frequency combinations. Participants were required to take a 3-minute break after every four pulse width–frequency combinations. They could request additional breaks at any time if they experienced muscle or mental fatigue.

C. Results

We report results on participants' calibrated intensity levels for *just-cause-muscle-movement*, their ratings of tingling and discomfort, the reported locations of EMS sensation, and the perceived dominant sensation. We use an alpha level of 0.05 for statistical significance and apply a Bonferroni correction for post hoc tests.

1) Calibrated Intensity Levels: Fig. 3 shows the average intensity trends across participants, grouped by EMS frequency and pulse width, respectively. The required intensity decreases with frequency initially, then increases, suggesting a U-shape relationship. In contrast, there is a consistent decrease in intensity as pulse width increases, indicating that larger pulse widths more efficiently elicit movement at lower stimulation intensities. Our primary hypothesis was that the calibrated EMS intensity would differ across EMS frequencies and pulse widths. The calibrated intensity values met the assumptions of normality and sphericity, allowing for a two-way repeated-measures ANOVA. The results revealed significant main effects of EMS frequency ($F(1,11) = 23.439$, $p<.001$, $\eta_p^2 = .681$) and EMS pulse width ($F(1,11) = 92.661$, $p<.001$, $\eta_p^2 = .894$), on the calibrated minimum intensity levels required to induce finger flexion. Bonferroni-corrected tests showed that 20 Hz required larger intensities than 50 Hz ($p<.001$) and 90 Hz ($p = .019$), but not 120 Hz ($p = 1.00$). The 50 Hz condition produced the lowest intensities, differing significantly from 90 Hz ($p = .001$) and 120 Hz ($p<.001$). Intensities at 90 Hz and 120 Hz also differed significantly ($p = .013$). For EMS pulse width, all pairwise comparisons on the required intensity were statistically significant ($p \leq .003$) except for 200 μs and 250 μs conditions. These results confirmed our primary hypothesis.

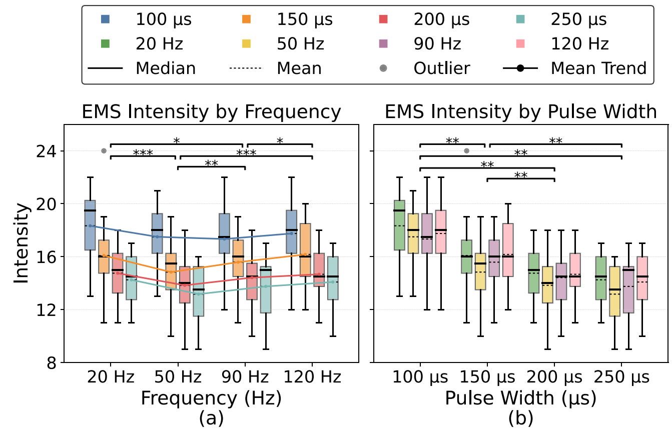

Fig. 3. Distribution of calibrated EMS intensity levels for different (a) EMS frequency and (b) EMS pulse width, corresponding to the EMS calibration in Section IV-B. The y-axis shows the device's intensity level, corresponding to the peak-to-peak current measured at 100 Hz and 120 μs with a 1kΩ resistive load. The current values for intensity levels 9–24 are 9.6, 10.8, 12, 13, 14, 15.6, 17, 18.4, 20, 22, 23.6, 25.4, 27.2, 28.2, 30, and 32 mA, respectively. The top lines indicate statistically significant Bonferroni-corrected pairwise comparisons: $^*p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$.

2) Tingling and Discomfort Ratings: Our primary hypothesis was that increasing vibration amplitude would reduce EMS-induced tingling and discomfort, while the secondary hypothesis proposed that EMS frequency and pulse width would also affect these ratings. The tingling and discomfort ratings met the assumption of normality but violated the assumption of sphericity; therefore, we ran a three-way repeated-measures ANOVA with Greenhouse–Geisser correction. The results showed significant main effects for both EMS frequency and vibration amplitude on both tingling and discomfort ratings and an interaction effect between EMS pulse width and frequency on discomfort ratings (Table II). Fig. 4 shows the average tingling and discomfort ratings across different EMS frequencies and vibration amplitudes.

Tingling ratings increased consistently with EMS frequency (20 Hz: $M = 4.456$, $SD = .455$; 50 Hz: $M = 5.103$, $SD = .366$; 90 Hz: $M = 5.208$, $SD = .406$; 120 Hz: $M = 5.867$, $SD = .404$). Discomfort ratings followed a similar increasing trend but remained lower than the tingling ratings (20 Hz: $M = 3.876$, $SD = .372$; 50 Hz: $M = 4.462$, $SD = .357$; 90 Hz: $M = 4.379$, $SD = .402$; 120 Hz: $M = 4.834$, $SD = .434$). Bonferroni-adjusted

TABLE II
THREE-WAY REPEATED-MEASURES ANOVA RESULTS FOR TINGLING AND DISCOMFORT RATINGS FOR EMS PULSE WIDTH (PW), EMS FREQUENCY (EF), AND VIBRATION AMPLITUDE (VA)

Factors	Measures	$F(1, 11)$	p	η_p^2
PW	Tingling	.662	.581	.057
	Discomfort	.169	.916	.015
EF	Tingling	**4.364**	**.042**	**.284**
	Discomfort	**4.049**	**.015**	**.269**
VA	Tingling	**32.425**	**<.001**	**.747**
	Discomfort	**9.053**	**.005**	**.451**
PW*EF	Tingling	1.878	.064	.146
	Discomfort	**2.375**	**.018**	**.178**
PW*VA	Tingling	2.018	.127	.155
	Discomfort	.908	.522	.076
EF*VA	Tingling	1.322	.279	.107
	Discomfort	.614	.611	.053
PW*EF*VA	Tingling	1.296	.154	.105
	Discomfort	1.327	.133	.108

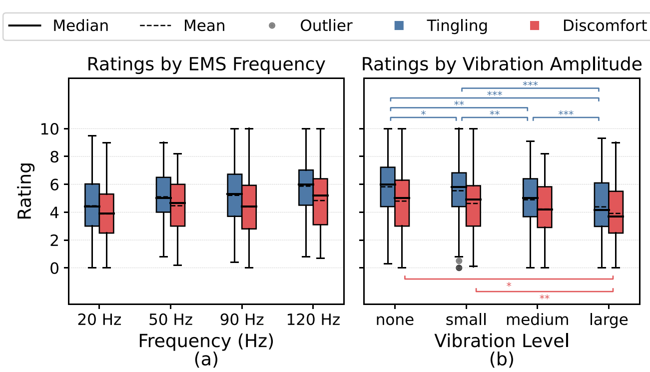

Fig. 4. Distribution of tingling and discomfort ratings across (a) four EMS frequencies and (b) four vibration amplitudes, reported in Section IV-B. Participants rated the tingling sensation from 0 (none) to 10 (unbearable) and the discomfort level from 0 (neutral) to 10 (extremely uncomfortable). The top (blue) and bottom (red) lines indicate statistically significant differences using Bonferroni-adjusted post-hoc pairwise comparisons: *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

pairwise comparisons revealed no significant differences among EMS frequency conditions for tingling or discomfort.

Vibration amplitude also had a significant main effect on tingling and discomfort. As vibration amplitude increased, both tingling and discomfort ratings decreased. Tingling ratings were highest when no vibration was present ($M = 5.822$, $SD = .364$) and decreased with increasing amplitude (small: $M = 5.539$, $SD = .316$; medium: $M = 4.892$, $SD = .344$; large: $M = 4.382$, $SD = .357$). A similar trend was observed for discomfort ratings: no vibration ($M = 4.795$, $SD = .395$), small ($M = 4.624$, $SD = .343$), medium ($M = 4.223$, $SD = .382$), and large ($M = 3.909$, $SD = .366$). Bonferroni-adjusted post-hoc pairwise comparisons revealed that all pairs of vibration amplitude conditions differed significantly in tingling ratings ($p<.046$). For discomfort ratings, significant differences were observed between the no-vibration and large-vibration conditions ($p = .035$), as well as between the small-vibration and large-vibration conditions ($p = .008$).

Also, the interaction between EMS frequency and EMS pulse width had a significant effect on discomfort ratings. Bonferroni-corrected simple effects revealed that when the EMS pulse width was 150 μs, discomfort ratings at 20 Hz ($M = 3.419$, $SD = .532$) were significantly lower than at both 50 Hz ($M = 4.373$, $SD = .566$, $p = .011$) and 90 Hz ($M = 4.873$, $SD = .660$, $p = .010$). No significant EMS frequency effects were found at other pulse widths, and pulse width effects were not significant at any EMS frequency level. A bar chart illustrating the interaction effect is provided in Fig. 1 in the Supplementary Materials. Hence, we confirmed our primary hypothesis that increasing vibration amplitude reduces EMS tingling and discomfort, and we partially supported our secondary hypothesis that EMS frequency and pulse width influence discomfort.

3) Perceived Location of EMS Sensation: Given the significant main effects of EMS frequency and vibration amplitude on tingling and discomfort ratings, we overlaid participants' selections for the EMS sensation region across EMS frequency and vibration amplitude conditions (Fig. 5, see Fig. 2 in the Supplementary Materials for condition-specific plots). As vibration amplitude increased, participants reported feeling EMS not only at the electrode contact points but also in the region between the electrodes, indicating that the EMS sensation became more dispersed. This spatial dispersion might have contributed to the reduction in tingling and discomfort reported above, as the sensation was distributed over a broader area. In contrast, for a fixed vibration amplitude, increasing EMS frequency led to a more localized sensation concentrated at the electrode sites, which corresponds to increased tingling and discomfort. This pattern was consistent with the ANOVA results for both tingling and discomfort ratings.

4) Dominant Sensation: We aggregated responses for dominant sensations (see Fig. 3 in the Supplementary Materials for the plot). Each vibration condition included 192 responses (16 cells $\times$ 12 participants). At lower vibration amplitudes, participants reported a more balanced perception of EMS and vibration sensations. As the vibration amplitude increased, the EMS sensation was increasingly masked and vibration became the dominant percept.

V. STUDY II: MASKING EFFECTS OF EMS ON JND FOR VIBRATION FREQUENCY

We investigated how EMS influences the ability to discriminate subtle differences or just noticeable differences (JND) for vibration frequency. We recruited 12 new participants (9 males, 3 females; mean age = 24.1 years, SD = 2.5). Recruiting and compensation were the same as in Study I.

A. Study Design

EMS Stimuli: We selected two pulse widths (100 μs and 250 μs) and two frequencies (20 Hz and 120 Hz) for several reasons. First, Study I showed that 20 Hz and 120 Hz represented the lowest and highest ends of tingling and discomfort ratings, respectively. Second, prior research [67] indicated that these parameters produced the most distinct qualitative sensations.

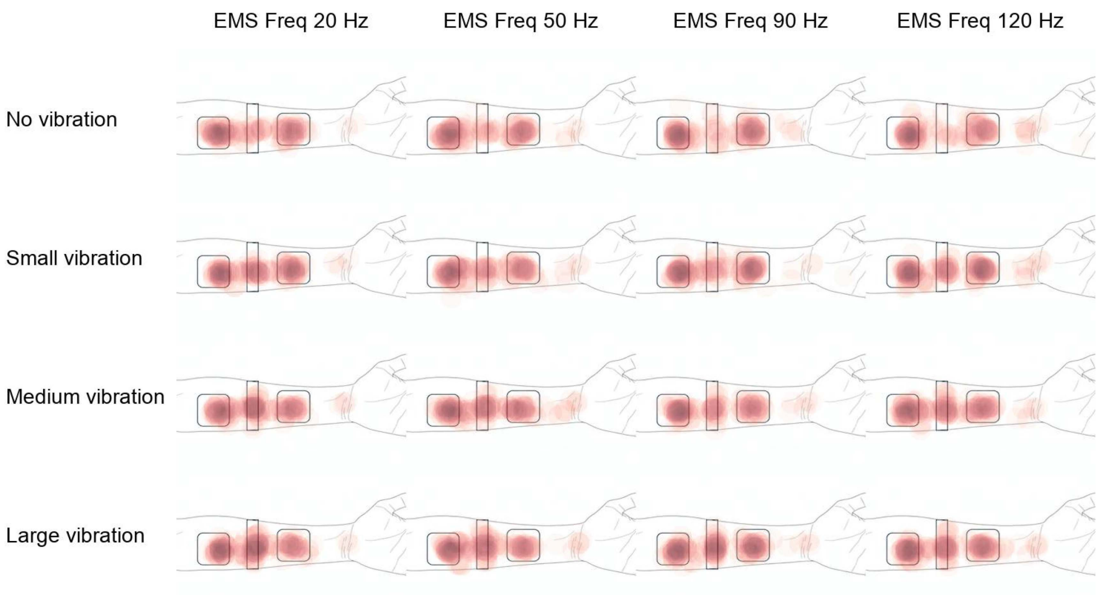

Fig. 5. Reported EMS sensation regions across varying EMS frequencies and vibration amplitudes. A darker color represents more selections by participants over that area. The areas outlined in black represent the EMS electrodes (squares) and the vibration actuator's velcro strip (rectangle).

Third, we reduced the number of conditions in Study II to keep the total session within 70 minutes.

Vibration Stimuli: We used 100 Hz and 170 Hz as two reference vibration frequencies, selected through pilot testing, which confirmed they were reliably distinguishable even with concurrent EMS stimulation. Moreover, they span the range commonly used in vibrotactile studies and align with the physiological sensitivities of mechanoreceptors in human skin. Meissner's corpuscles are mostly sensitive to low-frequency, low-intensity stimuli in the range of approximately 5–100 Hz [46], [47]. Pacinian corpuscles, in contrast, respond to high frequency vibrations typically between 80–450 Hz [45]. JNDs were measured using the method of limits due to its efficiency and proven reliability [68]. In this method, the participant feels a reference and comparison stimulus in pairs and selects whether the comparison stimulus has a lower, equal, or higher value than the reference stimulus. We generated a set of 12 comparison stimuli, ranging from 80 Hz to 230 Hz in approximately 10% intervals: 80, 88, 97, 107, 118, 130, 143, 157, 173, 190, 209, and 230 Hz. The reference and comparison stimuli were all delivered at the same amplitude of 2.54 g.

B. Procedure

After completing a demographic questionnaire, the participant wore noise-canceling headphones and proceeded to a practice session. This session used a reference vibration frequency of 130 Hz and consisted of two series: one increasing series starting from 80 Hz and one decreasing series starting from 230 Hz. The EMS stimulus used in the practice trials had a pulse width of 150 μs and a frequency of 50 Hz. Participants did not know that the session was for practice. We excluded this data from the final analysis.

The main experiment included two sessions for the two reference frequencies, each repeated twice in counterbalanced order. Each session comprised eight series (4 EMS conditions $\times$ 2 orders). In each series, comparison frequencies increased from 80 Hz or decreased from 230 Hz across 12 trials. Each trial consisted of a reference-comparison stimulus pair with 1s interval between them. In both the reference and comparison stimuli, EMS and vibration were presented simultaneously for 2 seconds. Participants judged whether the comparison felt "lower," "equal," or "greater" than the reference.

A series ended when the participant submitted two consecutive "greater" responses in an increasing series or two "lower" responses in a decreasing series. We required two consistent responses to mask the experimental mechanism but analyzed only the first "greater" or "lower" response. A single "greater" or "lower" response was sufficient when the response was the last selection in a series. In all cases, there was a single transition point and participants could replay the stimuli if needed. Participants had to take a 5-minute break between the two sessions. Each participant completed a total of 384 trials.

C. Results

We calculated the JNDs for each reference frequency by dividing the differential thresholds from the method of limits by the reference frequency [68]. Table III shows the average with standard deviations of JNDs across the participants under different conditions. Our primary hypothesis was that JND would differ depending on the EMS pulse widths, EMS frequencies, and vibration reference frequencies. The JND values met the assumptions of normality and sphericity. Table IV shows the results of the three-way repeated-measures ANOVA. The detailed mean and standard deviation values for each condition are provided in Table 1 of the Supplementary Material. Since

TABLE III
MEAN ± SD OF JND VALUES ACROSS EMS PARAMETER COMBINATIONS AND VIBRATION REFERENCE FREQUENCIES (N = 12 PER CONDITION)

		Vibration Reference Frequency	
EMS PW (μs)	**EMS Freq. (Hz)**	**100 Hz**	**170 Hz**
100	20	36.54% ± 19.16%	19.78% ± 6.21%
	120	38.86% ± 16.33%	20.44% ± 6.88%
250	20	24.58% ± 13.98%	22.51% ± 7.20%
	120	31.89% ± 19.02%	18.97% ± 7.05%

TABLE IV
RESULTS OF THE THREE-WAY REPEATED-MEASURES ANOVA FOR EMS PULSE WIDTH (PW) AND VIBRATION REFERENCE FREQUENCY (VRF)

Parameter	Test Result	η_p^2	Comparison
PW	F(1,11)=5.76, p=.035	.344	100 μs > 250 μs
VRF	F(1,11)=18.21, p=.001	.623	100 Hz > 170 Hz
PW × VRF	F(1,11)=6.11, p=.031	.357	100 μs: 100 Hz > 170 Hz (p=.001) 250 μs: 100 Hz > 170 Hz (p=.025) 100 Hz: 100 μs > 250 μs (p=.022) 170 Hz: n.s. (p=.695)

EMS frequency did not show a significant effect, we partially confirmed our hypothesis that EMS pulse width and vibration reference frequency would influence the JND values.

VI. Study III: Perceptual Simultaneity Between EMS and Vibration Stimuli

This study aimed to quantify the human performance of perceiving EMS and vibration stimuli as occurring at the same time. We obtained the points of subjective simultaneity (PSSs) and the thresholds of simultaneity detection (TSDs) for combinations of four EMS signals and four vibration stimuli. We recruited 16 new participants (9 males, 7 females; mean age = 24.6 years, SD = 2.5). Recruiting and compensation were the same as in Study I.

A. Latency Measurements

To control EMS–vibration delay, we measured actuation latencies ($\tau_{\text{vib}}^{\text{actuation}}$, $\tau_{\text{ems}}^{\text{actuation}}$) using a unified command trigger and recording them simultaneously with a high-speed camera. For the EMS circuit, we wired an LED to visualize its activation. The latency calculation for both began at the video frame showing the command's execution (when the experimenter hit the "Enter" button). $\tau_{\text{vib}}^{\text{actuation}}$ was the time until the first frame of actuator movement, while $\tau_{\text{ems}}^{\text{actuation}}$ was the time until the first frame of the LED illuminating, which signifies current delivery to the skin. Across 50 trials per stimulus, $\tau_{\text{vib}}^{\text{actuation}}$ was 27 ms and $\tau_{\text{ems}}^{\text{actuation}}$was 141 ms, causing vibration to lead EMS by 114 ms. We compensated for this by delaying the command for the vibration signal by 114 ms.

In terms of EMS activation, there are two additional delays to consider. First, once the electrical current reaches the skin, there is a delay before it excites the muscle. According to the literature, this excitation latency $\tau_{\text{ems}}^{\text{excitation}}$ is typically within 10 ms across the general population on their limbs [69], [70]. Second, there is a delay of $\tau_{\text{ems}}^{\text{movement}}$ between muscle contraction and the actual onset of physical (finger) movement. This delay varies significantly across individuals, ranging approximately from 30 ms to 100 ms [71]. In our study, EMS onset was defined as the moment the electrical signal reached the skin. The actuation delay $\tau_{\text{ems}}^{\text{actuation}}$ was used to manipulate delay windows between EMS and vibration. This excludes subsequent muscle excitation and physical movement delays, which we discuss in Section VII.

B. Study Design

EMS Stimuli: We used the same pulse widths (100 μs and 250 μs) and frequencies (20 Hz and 120 Hz) as in Study II.

Vibration Stimuli: We used the same two vibration frequencies (100 Hz and 170 Hz) as in Study II. For vibration amplitude, two levels were used: 8.3 g and 12.6 g, corresponding to the medium and large vibration conditions from Study I.

Haptic Delays: The two stimuli were temporally separated by inserting one of 19 predetermined delay values: −330, −300, −270, −240, −210, −180, −150, −120, −90, −60, −30, 0, 30, 60, 90, 120, 150, 180, 210 ms. These delay values were selected based on pilot testing to ensure that the probability of simultaneity perception would be very low or close to zero at the extreme delay values. A negative delay indicates that the EMS stimulus preceded the vibration stimulus, a positive delay indicates that EMS followed the vibration, and a delay of zero indicates simultaneous onset of both stimuli. To avoid influencing their simultaneity judgments, both haptic stimuli were designed to end at the same time and the total duration from the onset of the first stimulus to the end of both stimuli was 1 s.

Experiment Conditions: Overall, each participant completed 304 trials: 2 (pulse widths) × 2 (pulse frequencies) × 2 (vibration frequencies) × 2 (vibration amplitudes) × 19 (delay windows). The presentation order was randomized.

C. Procedure

After a background questionnaire, participants completed three sessions: training, practice, and main. The training session was designed to familiarize participants with EMS and vibration stimuli. After spatial calibration, the experimenter calibrated the signal for a randomly selected EMS pulse width–frequency combination and played the signal multiple times. We instructed participants to focus on the moment the electrical sensation reached their skin, rather than on the resulting finger movement. One vibration amplitude–frequency combination was also presented repeatedly in the same manner. The training session lasted approximately two minutes. Next, participants completed a practice session that mirrored the structure of the main session. Using the EMS and vibration settings from the training session, participants experienced multimodal haptic stimuli with delays randomly selected from the 19 predefined values. After each trial, they were asked to assess the simultaneity of the two stimuli by selecting one of three options on the study interface: "EMS first," "Same time," or "Vibration first." The practice session consisted of 19 trials. The main session included all 16 EMS and vibration conditions, each presented with 19 trials, resulting in a comprehensive evaluation of delay perception across parameter

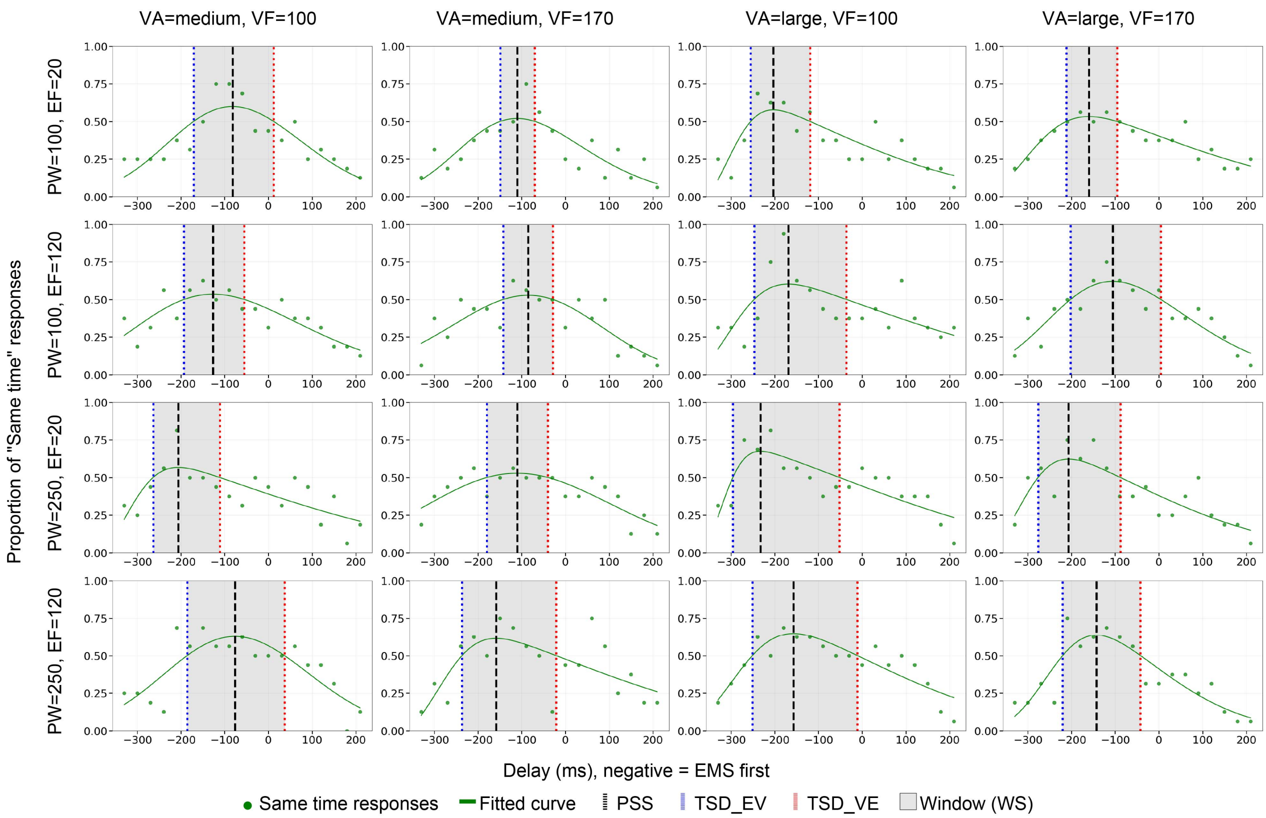

Fig. 6. Psychometric functions estimated for simultaneity under 16 conditions. A negative delay indicates a lead of the EMS stimulus. Each row is for the same EMS pulse width and frequency, while each column is for the same vibration amplitude and frequency. Abbreviations: PW, EMS pulse width; EF, EMS frequency; VA, vibration amplitude; VF, vibration frequency.

combinations. Participants were required to take a 3-minute break after every four EMS and vibration conditions.

D. Data Analysis

1) Psychometric Model: For every EMS $\times$ Vibration stimulus combination (16 cells), responses were recoded as SIMULT $= 1$ for *"Same time"* and SIMULT $= 0$ for *"EMS first"* or *"Vibration first"*. Each condition included 19 stimulus-onset asynchronies (SOAs; $\Delta t \in \{-330, \ldots, 210\}$ ms), yielding a 19point *simultaneity profile* $p(\Delta t)$ representing the proportion of "same" judgments. 16 participant responses were collected per delay. We followed other simultaneity judgment studies [13], [72], [73], fitting the response data with a function obtained from the difference of two cumulative Gaussian distributions:

$$P_{\text{same}}(\Delta t) = \frac{1}{2}\left[\text{erf}\left(\frac{\Delta t - \mu_1}{\sqrt{2}\,\sigma_1}\right) - \text{erf}\left(\frac{\Delta t - \mu_2}{\sqrt{2}\,\sigma_2}\right)\right], \quad (1)$$

where μ_1, σ_1 and μ_2, σ_2 govern the location and spread of the EMSlead and Vibrationlead flanks, respectively, and $\text{erf}(\cdot)$ is the Gaussian error function. Following prior work, we estimated the four parameters with bounded Levenberg-Marquardt nonlinear leastsquares to capture asymmetries.

2) Derived Metrics: We derived the point of subjective simultaneity (PSS) from the fitted psychometric function, representing the temporal offset perceived as most simultaneous. To account for stimulus order effects, we calculated two 50%-correct thresholds of detection: TSD_{VE} (vibration first) and TSD_{EV} (EMS first). These thresholds capture asymmetries in simultaneity perception depending on which stimulus precedes the other. The just noticeable differences (JNDs) were defined as the absolute differences between the PSS and each TSD. The sum of the two JNDs constitutes the window of simultaneity (WS), which indicates the temporal range within which stimuli are perceived as simultaneous.

3) Inferential Statistics: We estimated psychometric functions for each participant and computed their individual PSS. To examine how different stimulus parameters influence perceived simultaneity, we conducted a repeated-measures ANOVA with four within-subject factors. Our primary hypothesis was that PSS would differ across EMS pulse widths, frequencies, vibration amplitudes, and frequencies.

E. Results

Fig. 6 shows the psychometric functions obtained in the 16 experimental conditions. Table V presents the PSS, TSDs, and JNDs computed from each function.

The PSS values consistently showed negative delays, indicating that participants generally perceived the stimuli as simultaneous when EMS preceded vibration. The largest negative shift in PSS was -232.751 ms, while the smallest negative shift was -76.343 ms. Most other conditions exhibited negative shifts in

TABLE V

PSYCHOMETRIC MEASURES ACROSS EMS AND VIBRATION CONDITIONS. ABBREVIATIONS: PW, EMS PULSE WIDTH; EF, EMS FREQUENCY; VA, VIBRATION AMPLITUDE; VF: VIBRATION FREQUENCY; PSS, POINT OF SUBJECTIVE SIMULTANEITY; TSD, THRESHOLD OF DETECTION; JND, JUST NOTICEABLE DIFFERENCE; WS, WINDOW OF SIMULTANEITY; EV, EMS FIRST; VE, VIBRATION FIRST.

PW (μs)	EF (Hz)	VA	VF (Hz)	PSS (ms)	TSD (ms)		JND (ms)		WS (ms)
					EV	VE	EV	VE	
100	20	medium	100	-82.016	-171.161	11.991	89.145	94.007	183.152
			170	-110.650	-149.280	-70.130	38.629	40.520	79.150
		large	100	-203.307	-255.173	-119.295	51.866	84.012	135.878
			170	-160.355	-211.681	-95.793	51.326	64.562	115.888
	120	medium	100	-126.588	-193.312	-55.273	66.723	71.316	138.039
			170	-84.987	-142.256	-28.799	57.269	56.188	113.457
		large	100	-169.270	-247.069	-36.093	77.799	133.177	210.975
			170	-105.788	-202.226	4.427	96.438	110.215	206.653
250	20	medium	100	-206.278	-263.817	-111.461	57.539	94.817	152.356
			170	-110.650	-179.535	-40.415	68.884	70.235	139.120
		large	100	-232.751	-295.963	-52.031	63.212	180.720	243.932
			170	-206.818	-276.513	-88.229	69.695	118.589	188.284
	120	medium	100	-76.343	-185.748	36.843	109.405	113.187	222.591
			170	-158.734	-236.803	-21.506	78.069	137.229	215.298
		large	100	-157.384	-251.391	-10.970	94.007	146.413	240.420
			170	-143.067	-220.325	-42.306	77.259	100.760	178.019

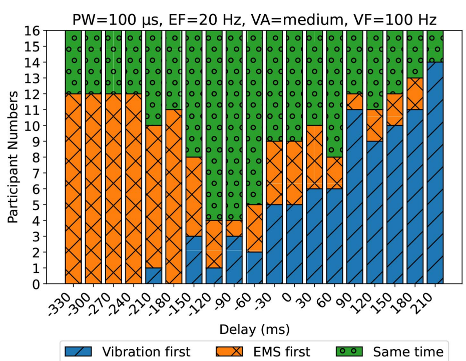

Fig. 7. Stacked bar charts in the experiment for participants' responses under one of the 16 conditions. Abbreviations: PW, EMS pulse width; EF, EMS frequency; VA, vibration amplitude; VF, vibration frequency.

PSS between approximately −100 and −200 ms. Values for the window of simultaneity (WS) varied notably across conditions as well, with the narrowest window being 79.150 ms and the broadest window measuring 243.932 ms. The ANOVA results revealed a significant main effect of EMS frequency on PSS values ($F(1, 11) = 4.599, p = .049, \eta_p^2 = .235$). Specifically, the 20 Hz EMS frequency condition ($M = -121.924, SD = 17.591$) produced a larger negative shift compared to the 120 Hz EMS frequency ($M = -86.015$, $SD = 21.243$). No other main effects or interaction effects reached statistical significance. The hypothesis was partially confirmed, as PSS differed for only one of the four factors.

Fig. 7 presents a stacked bar chart for the condition with 100 μs pulse width, 20 Hz EMS, medium vibration amplitude, and 100 Hz vibration frequency. Charts for all 16 conditions are provided in Fig. 4 in the Supplementary Materials. The "Same time" responses (green) form a U-shaped distribution, with the lowest point(s) indicating the delay where most participants perceived the two haptic stimuli as simultaneous.

VII. DISCUSSION

A. Reflection on Study Results

Findings from the three studies revealed several consistent perceptual trends for EMS and vibration parameters. Study I showed that higher EMS pulse widths (200–250 μs) and low- to mid-range EMS frequencies (50–90 Hz) required lower calibrated *just-cause-muscle-movement* intensities. Because lower current amplitudes correspond to weaker cutaneous activation, these parameter settings are expected to reduce surface tingling. Lower EMS frequencies (20–50 Hz) combined with higher vibration amplitudes (1.72–2.54 g at 170 Hz) further reduced the perceived discomfort and tingling caused by EMS. Study II showed that EMS pulse width can reduce human sensitivity to vibration frequency and increase vibration JND. Yet, higher vibration reference frequency (170 Hz at 2.54 g) and the wider EMS pulse widths (250 μs) did not increase vibration frequency discrimination thresholds much. Finally, Study III showed that the lower EMS frequency (20 Hz) resulted in broader simultaneity windows between EMS and vibration, meaning participants tolerated greater temporal offsets before perceiving the two as asynchronous. The three studies consistently suggest that higher pulse widths and low-to-mid EMS frequencies promote efficient muscle movement, greater comfort, and clearer simultaneity perception, while higher vibration frequencies and amplitudes enhance both comfort and frequency discrimination.

When both EMS and vibration stimuli are meant to convey information in an application, several perceptual trade-offs emerge. Combining the two modalities can yield positive outcomes, as shown in Study I, where vibration reduced EMS-induced discomfort. However, this benefit comes with two notable drawbacks. First, vibration discriminability can decrease when EMS is active, lowering its information bandwidthparticularly at lower vibration frequencies. Second, achieving perceptual simultaneity between EMS and vibration is challenging, as demonstrated in Study III. Synchrony requires EMS to precede vibration by roughly 100–200 ms, which is challenging to maintain in real-time applications due to individual differences in neural latency and hardware timing constraints. Although designers could attempt to optimize for both comfort and perceptual resolution, doing so confines them to a narrow parameter range (for instance, around a 170 Hz vibration reference frequency) and reduces expressiveness and information bandwidth. Beyond this range, achieving a balance between comfort, discriminability, and temporal precision demands careful trade-offs and calibration.

Our study findings align with established neurophysiological principles. Concurrent vibration reduced EMS-induced tingling, consistent with the Gate Control Theory of Pain, where activation of large-diameter A-β fibers by the vibration stimulus inhibits nociceptive transmission from smaller afferents activated by the electrical current [74], [75], [76]. Moreover, vibration altered the perceived location of EMS, causing the sensation to spread and become less localized, which is an effect akin to masking and referral phenomena observed in thermal and vibration multimodal haptics [9], [53]. In Study II, EMS impaired vibration frequency discrimination even when vibration dominated the overall percept. While vibration selectively activates large-diameter A-β fibers (e.g., Pacinian corpuscles) that encode frequency with high fidelity, EMS broadly excites both cutaneous and motor afferents, including A-β, A-δ, and possibly C fibers, introducing neural noise into the somatosensory system. This non-specific activation likely reduced the signal-to-noise ratio of Pacinian-mediated coding, thereby degrading frequency discriminability despite vibration's perceptual dominance [76]. In Study III, the need for EMS to precede vibration reflects differences in afferent pathways. Vibration signals, mediated by A-β fibers, reach awareness faster than EMS, which activates a broader afferent population requiring more central integration [77]. Moreover, electrical stimulation frequency affects afferent recruitment: higher frequencies preferentially activate A-β fibers, while lower or mixed frequencies engage a broader population, potentially slowing perception and increasing simultaneity variability [78]. These mechanisms explain our findings based on the broader literature on sensory integration principles and enhance their relevance and generalizability to multisensory perception and design.

B. Design Guidelines

Our findings offer four actionable guidelines for designing haptic systems involving EMS and vibration.

First, designers can optimize both movement efficiency and perceptual comfort by using high EMS pulse widths (e.g., 250 μs) and mid-range EMS frequencies (e.g., 50-90 Hz). As shown in Study I, higher EMS pulse widths and mid-range EMS frequencies require lower current intensities to elicit visible muscle contractions, achieving effective kinesthetic feedback with reduced painfulness. This combination optimizes two design goals: efficient muscle activation and perceptual comfort. This result aligns with previous qualitative research [67], which reported that EMS pulse width and frequency influence the calibrated EMS intensity level required to produce movement and the words (e.g., tapping vs. vibrating) people use to describe the sensation. However, Knibbe et al. [67] did not examine user discomfort or quantitatively assess how variations in EMS parameters affect it. Our findings extend prior qualitative studies by identifying a practical range of pulse width and frequency values that jointly minimize current thresholds and discomfort, providing an actionable guideline for the design of HCI-based EMS applications.

Second, designers can reduce tingling and discomfort sensations by adding vibration between the EMS electrodes at amplitudes between 1.72 g to 2.54 g, and by using lower EMS frequencies (e.g., 20-50 Hz). In Study I, larger vibration amplitudes and lower EMS frequencies significantly reduced EMS-induced tingling and discomfort, effectively mitigating the cutaneous pain and enhancing comfort in multimodal haptic experience. Although vibration can sometimes feel unpleasant, our parameters (170 Hz and 0.83 to 2.54 g) were within a comfortable range based on prior findings. Prior work suggested that increasing vibration amplitude generally led to an increase in valence and arousal [79], [80], [81]. Additionally, prior work has shown that a 60 Hz vibration frequency often evoked more negative feelings, while higher frequencies like 175 Hz were perceived as more pleasant and smoother [79], [82]. These prior findings suggest that the parameters used in our study are unlikely to induce negative emotional responses. Prior work has also demonstrated that vibration duration also influenced emotional responses, with longer vibrations typically perceived as more alarming than shorter ones [31]. Since in our work several seconds (less than 5 seconds) were sufficient for EMS to induce muscle contraction, the duration of vibration used to mitigate discomfort was relatively short, reducing the chance of significant discomfort or annoyance.

Third, designers can preserve frequency discrimination performance near unimodal JND levels by using higher vibration frequencies (e.g., 170 Hz); if lower frequencies are necessary, they should apply larger frequency gaps to ensure perceptible differences. In Study II, EMS stimulation increased JNDs for vibration frequency discrimination, particularly at the lower reference frequency. When the reference frequency was 100 Hz, JNDs ranged from 24.58% to 38.86%, depending on EMS pulse width and frequency. In contrast, when the reference frequency was 170 Hz, JNDs remained consistently around 20% across EMS parameter variations. For comparison, prior research on unimodal vibrotactile perception reported a typical frequency JND of 18%, a threshold that held consistently across reference frequencies, vibration amplitudes, and actuator types when other parameters were controlled [83]. These findings suggested that EMS imposed a perceptual masking effect on vibration frequency discrimination, especially at lower frequencies.

Finally, EMS should be activated approximately 100–200 ms before vibration to achieve a perception of synchrony. Study III revealed that participants generally perceived EMS and vibration as simultaneous only when EMS preceded vibration by approximately 100–200 ms, with JNDs ranging from 38 to 180 ms. We instructed the participants to use the moment the electrical signal was felt on the skin, rather than the point of actual finger movement, as the EMS onset. In prior work, physiological excitation latency and electromechanical delay typically ranged from 40 to 210 ms in the general population, as discussed in Section VI-A. Even when accounting for these factors, our results indicated that EMS should precede vibration by a meaningful margin. These findings suggested that EMS–vibration coordination has a more relaxed temporal timeline compared to other multisensory haptic pairings. For example, impact–vibration, audio–tactile, visual–tactile, and visual–auditory interactions typically required temporal alignment within roughly $\pm$ 30–100 ms [13], [61], [73], [84], [85], [86], [87], [88], [89], whereas thermal–tactile feedback exhibits an broader acceptable temporal window of approximately 1000 ms [60]. While our results suggest EMS-vibration coordination can tolerate a relatively broad temporal window, achieving this synchronization in practice is challenging due to inherent EMS hardware delays and inter-user variability. Therefore, the 100–200 ms offset should be regarded as an approximate target rather than a strict design rule, with further calibration applied to suit each application context.

C. Limitations and Future Work

In Study I, EMS intensity was individually calibrated while vibration amplitude was fixed, leading to variability in absolute tingling and discomfort ratings across participants. Thus, results should be interpreted in terms of relative rating reduction rather than absolute rating levels. Also, as higher vibration amplitudes increasingly masked the EMS sensation, participants may have struggled to distinguish between the two feedback types, reducing EMS localization accuracy despite reference trials and explicit instructions. Thus, it remains unclear whether the EMS sensation was perceived at the vibration site or if participants could not discriminate them.

In Study II, the reference vibration frequency range (80–230 Hz) was limited by the Taptic Engine's operating range and did not fully cover both Meissner's and Pacinian corpuscle sensitivities. Alternative actuators such as the Haptuator Redesign and Mark II-D were tested but found less suitable due to their bulkier form and poorer skin contact. Future work should explore broader frequency ranges and actuator types. Another limitation is that we did not match the perceived vibration intensities. Because perceived vibration strength varies with frequency even at a fixed physical amplitude [90], [91], [92], participants may have perceived certain frequencies as stronger or weaker, independent of the actual frequency difference. This perceptual bias could have influenced JNDs, as participants might rely on intensity cues rather than pure frequency discrimination. We used a fixed amplitude of 2.54 g to avoid the extensive calibration required for equal-intensity matching; therefore, the reported JNDs represent a "best-case" scenario since perceived intensity differences may have facilitated performance. Future work should incorporate perceptual calibration across frequencies to address this limitation.

In study III, each participant provided only one judgment per condition and delay to keep the session length manageable (1 h). A multi-repetition design was infeasible due to time and fatigue constraints. As a first exploratory study in this area, we prioritized breadth to map a broad practical parameter space for EMS and vibration in application design, which limited our ability to capture individual variability. The 30-ms SOA step size offered broad coverage but limited resolution near the perceptual threshold. In addition, we did not control or match perceived intensities between EMS and vibration, as these modalities differ qualitatively. In our internal testing, we found intensity matching challenging. Also, EMS was individually calibrated, further complicating alignment. Pilot testing ensured both stimuli were perceptible and distinguishable, though perceived strength likely varied across participants, influencing PSS and WS estimates. Participants were instructed to use the initial tingling as the EMS onset cue, but adherence could not be verified. Future work should employ finer-grained SOA steps and multi-session designs to enhance precision and leverage the identified significant effect of EMS frequency for deeper investigations.

All three studies shared several limitations. Muscle fatigue from repeated trials may have reduced sensitivity to tingling and vibration despite scheduled and optional rest breaks. Although participants were monitored and given 3–5 minute rests between trial blocks, shorter intervals constrained by study duration may not fully prevent fatigue effects. Future studies could systematically investigate how muscle fatigue influences perceptual masking and the perception of simultaneity in EMS. In addition, we tested a limited set of EMS and vibration parameters, using only one muscle and one vibration site. Future work should expand parameter space and stimulation sites to assess broader applicability.

VIII. Conclusion

This study examined mutual masking and perceptual simultaneity between EMS and vibration. Large-amplitude vibration reduced EMS-induced discomfort, while EMS impaired vibration frequency discrimination at low frequencies. Perceived simultaneity required EMS to precede vibration by 100–200 ms. These findings support design guidelines for minimizing discomfort, preserving perceptual fidelity, and achieving temporal coherence in multimodal haptic systems.

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