EMSTouch: Electrical Muscle Stimulation for Object Interaction and Social Touch in Extended Reality

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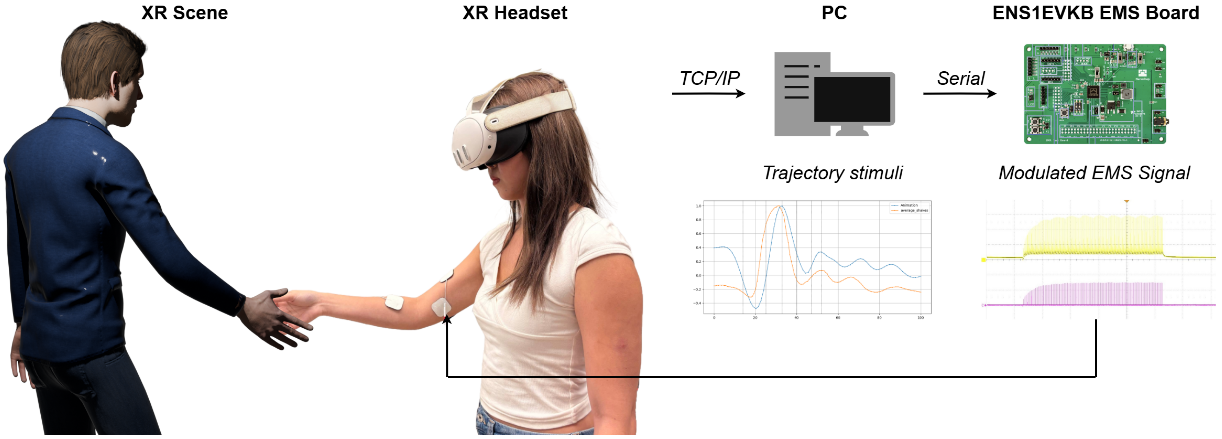

Figure 1: System design and implementation overview. The user engages in a virtual handshake with an avatar inside the XR environment. Interaction data are transmitted to a connected PC, which controls the EMS board via a serial connection. The board generates modulated EMS signals that stimulate electrodes on the user's arm, synchronizing the trajectory of the virtual handshake with the user's actual muscle movements.

Abstract

Electrical muscle stimulation (EMS) provides direct, felt feedback by actuating muscles, offering a novel haptic channel for extended reality (XR). We present EMSTouch, a system that augments XR scenes through controlled muscle activation for virtual object manipulation and handshake tasks. EMS was evaluated against vibrotactile and visual baselines, focusing on the perception of replayed socially meaningful gestures. In a user study (N=12), EMS feedback yielded higher realism scores than visual only interaction and produced greater naturalness and immersion than vibrotactile feedback. Findings highlight the realism–agency trade-off inherent in EMS-based interaction, showing how more realistic stimulation can influence autonomy. We further explore EMS in creative practice through a case study in XR art, where electromyography (EMG) captures the biodynamics of strokes during virtual sculpture creation and EMS replays the movements. Altogether, EMS emerges as a socially accepted feedback modality that elevates realism and immersion in both virtual interaction and creative expression.

CCS Concepts

- **Human-centered computing → Empirical studies in HCI**; *User interface design.*

Keywords

Extended reality, Electric muscle stimulation, Vibrotactile feedback, Interaction design

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1 Introduction

Extended Reality (XR) augments human perception by integrating digital elements into the physical world, primarily through visual and auditory channels. While sufficient for visualization, these modalities fall short of conveying the physicality of virtual objects due to the lack of tactile feedback. Vibrotactile feedback is a conventional solution to this problem, where vibrations signal interactions with digital content [9]. However, vibrotactile cues remain largely symbolic. Users must cognitively interpret a vibration and relate it to a virtual event rather than physically experiencing it, diluting the depth of immersion. To create more tangible feedback, kinesthetic devices such as wearable robots [7], exoskeletons [41], and pulley mechanisms [2] mechanically engage the body's positional and kinesthetic senses, simulating weight and resistance. Yet, these solutions present inherent drawbacks: they are often costly, cumbersome, and can introduce significant tensions with user agency, limiting acceptance and adoption.

This work explores Electrical Muscle Stimulation (EMS) as an alternative to connect virtual events with bodily sensation without relying on external mechanical constraints. Unlike exoskeletons that apply force to the body, EMS actuates the user's own neuromuscular system. The user's body itself becomes part of the haptic interface, offering a lightweight way to nudge the user's limbs according to the digital environment. This approach creates opportunities for interactions where the system participates in movement, for instance, stopping the user's hand at the surface of a virtual object or guiding the arm through a handshake-like motion, while retaining some degree of agency.

Electrical muscle stimulation also offers a practical lens to study embodied cognition, the principle that thought and action are inseparably linked to the body's sensorimotor systems [13]. By directly modulating muscular activity, EMS can shape the user's perception, agency, and interaction with extended realities [20]. In interactive contexts such as XR or artistic installations, it allows studying how neuromuscular and environmental feedback jointly structure experience.

Building on this foundation, we investigate EMS as a medium for embodied interaction in XR, with particular attention to how it shifts perceived realism and control. We introduce EMSTouch, a system that augments virtual scenes through controlled, adaptive muscle activation (see Figure 1). The system tracks the user's hands in a mixed reality environment and triggers EMS responses according to their relative position to the digital content. It relies on three primary components: (1) An XR application that tracks the users' hands; (2) a software system that converts the users' hands position into EMS signals relative to the digital environment; (3) a hardware EMS system that transmits the EMS signals to the user's limbs.

To investigate the impact of our system, we implement and evaluate EMSTouch in two scenarios. The first scenario emulates static physical constraints to evaluate the immersion and realism brought by the platform. When a user touches a virtual object floating in mid-air, an EMS signal triggers a wrist extension, simulating the "push-back" of a solid surface. The second scenario addresses reciprocal interactions through a social gesture with a digital avatar. Upon grasping the avatar's hand, the system actuates the user's arm in a guided shaking motion. While replaying a pre-recorded handshake motion, the non-rigid nature of EMS allows us to explore how users perceive and exercise their own agency in EMS-guided social interactions. Finally, building on these insights, we demonstrate the capabilities of EMSTouch to convey human gestures in an art installation. We record the surface electromyography (sEMG) signals from an artist drawing a digital structure using an XR drawing application. These signals are then replayed via EMS to the users as they touch the specific strokes, combining several channels to convey the artist's intent.

We conduct a user study (N=12) to quantify how neuromuscular feedback influences user perception of presence, agency, and embodiment compared to visual-only and vibrotactile baselines in the first two scenarios. Our findings indicate that EMS significantly improves engagement and realism over audiovisual feedback. In the social handshake scenario, EMS outperforms vibrotactile feedback in naturalness and immersion. Our evaluation also raises the complex question of agency in mixed digital-physical experiences. While EMSTouch successfully provides tangibility to the virtual content, it requires balancing "nudging" and "forcing" to maintain the user's sense of autonomy in creative XR environments, Finally, applying EMSTouch to conveying artists' intents in XR art yields several practical findings for real-world implementation. Participants emphasized the importance of visual feedback in reinforcing immersion, as well as the need to normalize EMS signal intensity to create a more integrated experience.

The rest of this paper is organised as follows. After reviewing the closest related works, we describe the design of EMSTouch as well as its implementation in the two scenarios in Section 3. Section 4 presents our evaluation procedure and its results, respectively. Finally, Section 5 presents a case study of using EMS to convey a digital artist's intent in XR painting.

2 Background

Electrical muscle stimulation (EMS) is a technique used to elicit muscle contraction by delivering modulated electrical signals through electrodes placed on the surface of the skin, directly above the target muscle. It is used for therapeutic rehabilitation [3], strength training [36], and in learning to play musical instruments [28], where controlled stimulation can support motor learning and coordination. With the availability of compact EMS hardware and experimental toolkits [33], EMS has recently been explored as an output modality in human–machine interaction [40]. EMS represents a paradigm shift in haptic feedback, by transitioning from external mechanical actuators to the user's own musculoskeletal system as the primary output medium. This approach enables portable, wearable systems that can render complex sensations such as weight, impact, and resistance in intangible contexts while keeping the user's palms entirely free for natural gesture interaction.

Designing EMS systems remains challenging: stimulation can cause discomfort or fatigue, electrode placement must be precise to avoid unintended muscle activation, and safety concerns such as skin irritation or excessive current must be carefully managed. Beyond these technical and physiological challenges, the involuntary nature of EMS-induced contractions introduces a critical experiential dimension: users may perceive a disruption of agency, leading to an uncanny or unsettling interactions. Addressing the balance between effective haptic feedback and the preservation of user control is central to advancing EMS as a reliable modality for human–machine interfaces.

EMS delivers short electrical impulses through surface electrodes placed on the skin above target muscles. These pulses depolarize motor neurons and cause the underlying muscle fibers to contract, effectively mimicking the neural signals that normally originate in the central nervous system. By varying pulse amplitude, frequency, and duration, practitioners can control contraction strength, timing, and sensation, allowing EMS to produce subtle guidance or stronger, task-oriented actuation [32].

Historically, EMS has been applied in physical therapy and rehabilitation to prevent atrophy, restore motor function, and assist recovery after injury or immobilization [31]. In sports and fitness, EMS is used as a supplemental training tool to target specific muscle groups and enhance conditioning [18].

More recently, EMS has attracted interest in human–computer interaction and XR as a way to provide embodied haptic feedback—conveying resistance, motion cues, or social touch—by directly actuating the user's muscles rather than relying solely on surface vibration or force devices.

Early explorations of interaction in virtual environments used conventional 3D game engines such as Quake3 controlled via standard input devices, providing a baseline for studying user behavior in digital spaces [21]. Building on this, researchers began to investigate electrical muscle stimulation as a novel haptic interface. Lopes et al. [25] combined EMS with solenoid-based tactile feedback to simulate hitting and being hit in VR, showing that multimodal stimulation produced more convincing sensations than either technique alone. Another game-cented EMS-based haptic interface [12] has been developed for mixed reality tennis game, where muscle contractions proportional to collision impact allowed users to feel as though they were striking a real ball with a racket. Additionally, EMS has been explored in ubiquitous mobile context. Mobile force feedback was achieved by actuating forearm muscles directly via EMS, enabling compact prototypes mounted on mobile phones and yielding stronger user preference compared to vibrotactile feedback [24] for scenarios of mobile gaming.

Beyond impact simulation, EMS has been used to guide and shape user actions. Electrocutscenes [19] applied EMS to synchronize users' involuntary movements with avatar actions in VR cutscenes, significantly increasing perceived presence compared to vibrotactile feedback. Another work, Affordance++ [26] extends object affordances by dynamically guiding motion, multi-step processes, and time-dependent behaviors through electrical muscle stimulation of the user's arms. This approach enabled participants to operate devices with weak natural affordances and avoid unsafe interactions, such as hot cups. In training contexts, Pfeiffer et al. [34] introduced WONDER, a virtual environment augmented with EMS feedback, showing that push–pull guidance improved workflow recall and was preferred by participants. ErgoPulse [17] extended EMS to lower-body biomechanics, simulating locomotion cues in VR and broadening the scope of embodied haptics beyond upper-limb interactions.

Another stream of work has focused on EMS for simulating physical properties of virtual objects. Lee et al. [22] analyzed force response characteristics of forearm extensor muscles, validating a simplified model for EMS-based haptic rendering and identifying peak force and response time dependencies on stimulation parameters. Harris et al. [14] further explored EMS for virtual wall sensations, showing that priming muscles with low-intensity stimulation and using co-contraction improved responsiveness and damping during wall interactions. EMS is a haptic modality that can be used for impact simulation, action guidance, training support, and physical property rendering.

More recent explorations highlight EMS as a tool for embodied social and creative interaction. Emotion Actuator [15] demonstrated how EMS can convey affective states, showing its potential for social interaction in XR through embodied emotional feedback. Electroencephalography (EEG) signals from one person are classified to determine their emotional state and then transmitted to another individual as a sign-language gesture (elicited through EMS) corresponding to that emotion. EMS Painter [8] investigated co-creation of visual art using EMS guidance, illustrating how muscle-level haptics can support creative expression.

EMS-based interfaces provide compact, low-cost, and physiologically grounded feedback that surpasses vibrotactile alternatives in realism and user preference. However, challenges remain in modeling muscle responses accurately, ensuring comfort, and integrating EMS seamlessly into XR scenarios.

3 System Design and Implementation

The system is designed to integrate virtual reality with electrical muscle stimulation, enabling synchronized physical feedback during immersive interactions. Object and avatar interactions in XR are transmitted to a PC over the local network, which controls an EMS board via a serial connection. The board produces modulated EMS signals that stimulate electrodes on the user's arm, synchronizing muscle activation with the XR experience (see Figure 1). This section examines how user actions within the virtual environment are captured and translated into physical feedback through electrical muscle stimulation.

3.1 Interaction and Feedback Design

Our study considers two representative XR scenarios: interaction with a virtual cube and a virtual handshake. In the cube scenario, participants engage with a simple geometric object that could be freely touched and manipulated, as shown in Figure 2a. The Meta Quest's built-in hand tracking system continuously monitors the position and contour of the user's right hand. The system measures the distance between the center of the palm and the center of the object as the primary input for triggering haptic feedback.

When the hand approaches the cube, feedback is activated and modulated according to proximity. As the user touches the cube, EMS stimulation induces finger extension against the virtual surface. The closer the hand moves toward the cube, the stronger the feedback becomes pulling fingers more upward. The side of the cube is $2 \times D_{max}$, where $D_{max} = 10cm$. The feedback starts at the distance D_{max} from the center of the palm to the center of the cube,

(a) Cube interaction scenario

(b) Handshake scenario

Figure 2: XR scenes

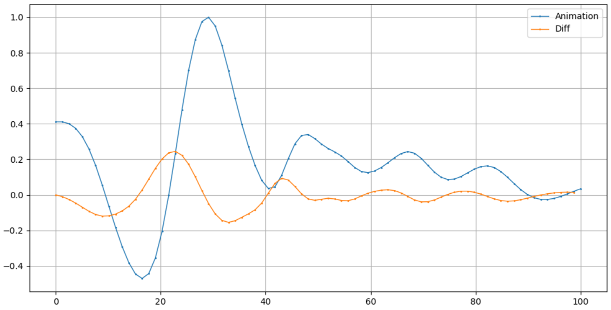


Figure 3: The motion path and the differences between consecutive positions for the handshake animation. The x-axis represents time (in steps of 1/30 s ≈ 33 ms), while the y-axis shows normalized distance values scaled between −1 and 1

and the intensity $A_{applied}$ increases according to a proportional formula:

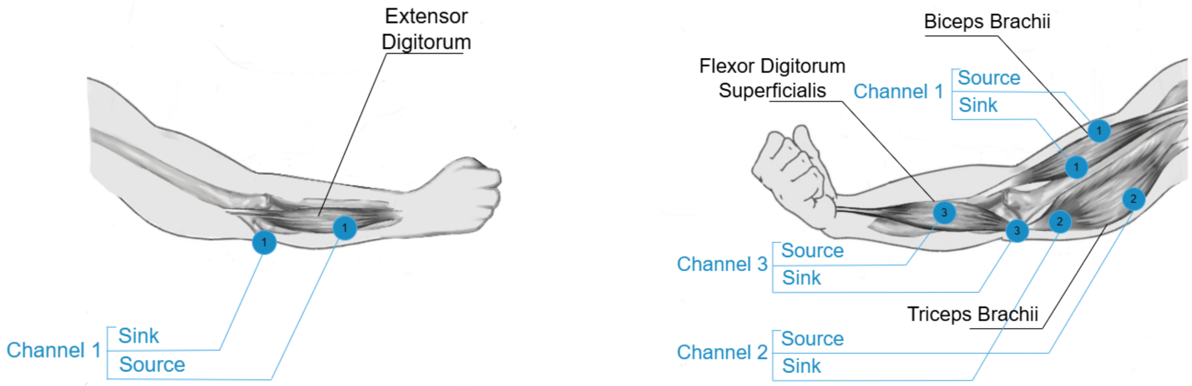
$$A_{applied} = A_{min} + \frac{(D_{max} - d)}{D_{max}}(A_{max} - A_{min}),$$

where d is the current distance, A_{min} and A_{max} are the minimal and maximum stimulation currents, respectively, the value of which are established in the Section 3.3. The evoked gesture is designed to simulate a counterforce, as if the user is pressing their fingers against the surface of a physical cube. The intensity of the vibrotactile feedback would increase according to the same formula; however, in contrast to the electrical stimulation, the vibrotactile feedback is just a notification of encounter rather than the actual physical impact of the virtual surface.

In the handshake scenario, a virtual avatar extends its right hand toward the participant, inviting a gesture of social touch (see Figure 2b). When the participant's right hand enters the proximity of the avatar's hand, the system initiates a handshake animation accompanied by the corresponding stimulation pattern. The handshake takes 3.33 seconds, characterised by four damping up/down motions lasting 0.66 seconds each (as shown in Figure 3). The pairing of visual motion and neuromuscular feedback is designed to reproduce the bipartite nature of a handshake, where the sensation arises from the negotiation of forces between two agents rather than from unilateral movement alone.

To generate the feedback sequence, we extract the sequence of z-coordinates from the avatar's handshake animation (see Figure 3). For both haptic and EMS modalities, feedback intensity is mapped proportionally to the avatar's hand position to ensure the physical sensation evolves synchronously with the visual gesture. For the EMS feedback specifically, we compute the incremental differentials along this trajectory and linearly scale them to the full range of stimulation intensities. Positive differentials (upward motion) trigger extension-related muscle activation, while negative differentials (downward motion) elicit arm flexion. This mapping reproduces the alternating dynamics of a handshake, providing a felt rhythm that mirrors the avatar's motion and transforms the interaction into a physically embodied experience.

To further enhance realism, we simulate the sensation of hand grip by actuating finger flexion during the handshake interaction. The intensity of this grasp is modulated according to the trajectory: the strongest grip occurs at points of directional change — corresponding to zero differential, while the weakest grip is applied during continuous slopes. This design ensures that the grasp is felt most pronounced at moments of transition, echoing the tightening and loosening that characterizes natural handshakes [27]. The effect functions as a metaphor for grasp rather than a direct squeeze: a subtle counter-reaction (or nudging) stimulus encourages the fingers to flex in response to perceived pressure. Unlike the continuous upward and downward palm compression of a real handshake, which can be achieved in soft-robotic handshake [10], this electric stimulation evokes reactive engagement.



(a) Cube interaction scenario. Right hand, lateral view

(b) Handshake scenario: Right hand, medial view

Figure 4: Electrode placement for EMS feedback

The design emphasizes naturalness and immersion, while balancing system guidance with user agency. In both scenarios, the animation and corresponding feedback are terminated once the user's hand moves sufficiently far from the avatar's hand.

3.2 Muscle Activation and Electrode Placement

To elicit finger flexion (for the handshake grasp) and extension (for virtual cube counter-force), we followed electrode placement guidelines established in prior work [4], which emphasize targeting specific forearm muscles to achieve reliable and repeatable actuation. Accurate placement is critical in EMS research, as small deviations can lead to unintended muscle activation, discomfort, or reduced control fidelity [40].

In the cube manipulation scenario, which required simulation of finger extension, the target muscle was the *extensor digitorum*, located in the posterior compartment of the forearm, on the lateral aspect near the elbow (see Figure 4a). The source electrode was positioned directly above the extensor digitorum, while the sink electrode was placed at the elbow. This configuration has been shown to reliably produce finger extension movements [4], making it well suited for simulating the sensation of pressing against a rigid surface in XR.

In the handshake scenario, the goal was to augment the grasp through nudging the finger flexion. For this, we targeted the *flexor digitorum superficialis*, located in the anterior compartment of the forearm, on its medial aspect (see Figure 4b). The source electrode was positioned above the flexor digitorum superficialis, while the sink electrode was placed at the elbow.

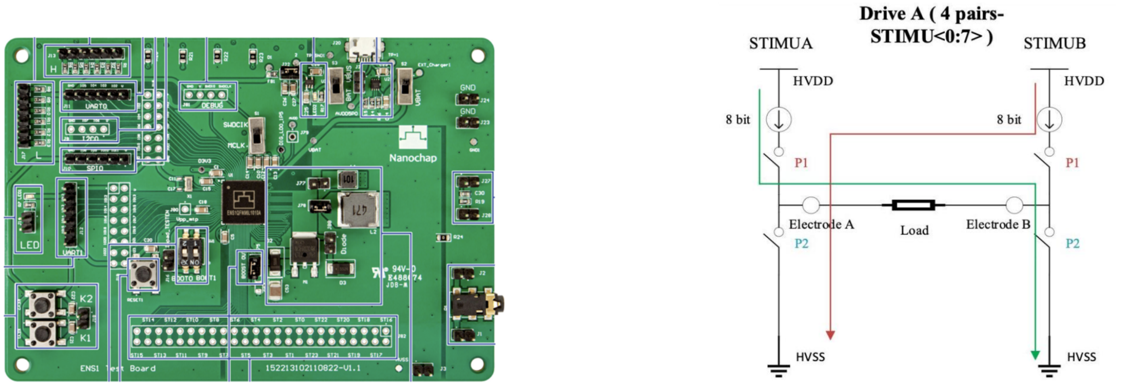
Flexion and extension of the arm during the handshake were achieved by stimulating the *biceps brachii* and *triceps brachii*, respectively [40]. For the biceps, the source electrode was placed proximal to the muscle belly when flexed, and the sink electrode distal to the belly. For the triceps, the source and sink electrodes were positioned above and below the muscle belly (Figure 4b). This arrangement allowed us to reproduce the alternating contraction and relaxation cycles characteristic of a handshake, where flexion and extension are dynamically coordinated.

3.3 Implementation

We employed the Oculus Quest 3 as the XR platform, with interactive scenes developed in Unity. Two separate Unity scenes were created to represent the interaction scenarios. In both cases, hand tracking (High Frequency at 60Hz) and hand contour visualization were enabled, and passthrough mode was activated to support extended reality. The first scene contained a virtual cube that could be freely dragged and manipulated, while the second scene featured a static virtual avatar extending its right hand for a handshake.

A routine continuously calculated the distance between the user's right hand and the interactive target, either the cube's center or the avatar's hand. The headset and the connected PC communicated via an ad hoc network hosted on the PC. When the distance fell below a predefined threshold, the value, expressed in Unity units (meters), was packaged into a TCP message with an indicative prefix and transmitted to the PC. In the virtual avatar scene an motion-capture animation of the handshake was played when the user's hand enters the proximity of the avatar's hand. The position of the avatar's hand and the user's hand are not synchronized. The end of the interaction is triggered either by the animation completion or if the distance between the user's and the avatar's hand exceeds a threshold of 10cm.

The PC hosted a Python web server, which relayed data either through serial UART to the EMS hardware or via Bluetooth to a Myo band [39] for vibrotactile feedback. The Myo armband's features a built-in Eccentric Rotating Mass (ERM) motor, that can modulate the perceived vibration intensity by rapidly adjusting the motor's activation. Depending on the scenario, different routines were invoked to process the received distance. In the cube interaction case, the intensity of vibration or electrical stimulation was adjusted proportionally to the distance between the hand and the cube. In the handshake scenario, a static stimulation pattern was replayed each time. Vibration strength and timing were encoded in a simple array, while EMS parameters were preloaded from a file. The preloaded file contained intensity values for three channels (hand squeeze, triceps for extension, and biceps for flexion), with each point timestamped at intervals of $1/60$ seconds. In both scenarios,



(a) ENS1EVKB Development Circuit Board

(b) Schematic of electrical stimulation peripheral configured in Mode A

Figure 5: EMS Stimulation board

once the end-of-interaction message was received, the feedback - whether vibrotactile or EMS - was abruptly terminated to ensure clear task boundaries and consistent user experience.

A ENS1EVKB Development Circuit Board (see Figure 5a) containing an ENS001 microcontroller from Nanochap Electronics Co. Ltd [1] is used to generate the EMS stimuli in the tests. The ENS001 microcontroller features a Cortex-M0 core, digital communication interfaces including UART, an electrical stimulation peripheral powered by an integrated voltage boost converter.

We configure the electrical stimulation peripheral to operate in Mode A (see Figure 5b), which enables precise control of multiple electrode pairs. In this configuration, four pairs of electrodes are available, each connected in an H-bridge arrangement. The H-bridge design allows bidirectional current flow between the electrodes, ensuring that stimulation can be applied symmetrically and that muscle activation can be modulated with greater flexibility. This bidirectional capability is particularly important for alternating contraction and relaxation cycles, as it prevents charge buildup and reduces the risk of skin irritation.

The peripheral incorporates a built-in voltage converter, which we configure to generate a stimulation voltage of 45 V. This voltage level provides sufficient headroom to elicit reliable muscle contractions across different participants while remaining within safe operational limits established in prior EMS research. Current delivery is managed by an 8-bit programmable current source, which we configure to operate within a range of 0 mA to 13 mA.

We utilize up to three channels of the board with the following waveform parameters [40]: biphasic rectangular pulse with a width of 400 µs, positive-negative gap of 50 µs, stimulation period of 16000 µs, amplitude between 3 mA to 9 mA. These parameters were determined through preliminary calibration tests with two participants. During these tests, pulse width and amplitude were iteratively tuned to achieve clear, repeatable muscle activation without discomfort or fatigue. The biphasic waveform was selected to minimize net charge transfer and reduce the risk of skin irritation, while the relatively short inter-pulse gap ensured stable contraction without perceptible jitter. The amplitude range was found to provide sufficient actuation for both subtle gestures (e.g., finger flexion) and larger movements (e.g., elbow extension), while still allowing participants to maintain a sense of comfort and control.

This distributed architecture introduces multi-system latency, including the Quest 3 hand tracking latency, local TCP network transmission, Python processing, and UART serial communication. However, because both the visual rendering and the physics triggers execute directly on the headset before sending actuation commands to the PC, the end-to-end delay remains within acceptable bounds for immersive haptics, in the same order as the interframe time. As later observed in our evaluation data (see Figure 8a), the physical actuation of the user's muscles exhibited a tight synchronicity with the visual animation, reflecting a minimal induced motion delay of approximately 10–20 ms, successfully preserving the illusion of immediate physical embodiment.

4 Evaluation

The objective of this user study is to assess immersion, realism, and social acceptance when employing EMS-based feedback, in comparison to visual-only and vibrotactile modalities.

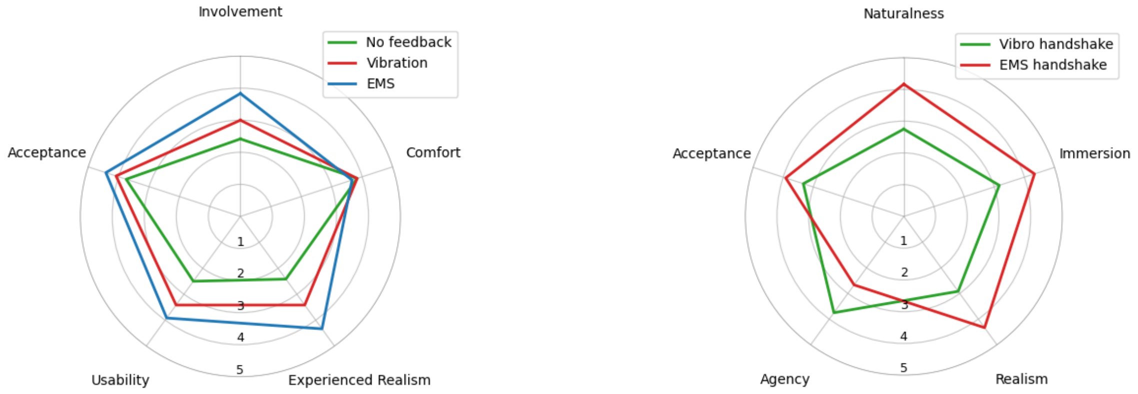
4.1 Participants and Apparatus

We invited 12 participants (10 male, 2 female) to participate in the EMS experiments developed for this study. Participants were aged between 19 and 37 years ($\bar{M}_A$=26.8, σ_A = 5.4), all right-handed.

The experiment considers three conditions: (1) audiovisual-only XR with a Meta Quest 3 headset; (2) Vibrotactile feedback, with a vibration on the arm band; (3) EMS feedback in the configurations developed for the specific scenario (see Section 3). Participants go through the three conditions in the cube-touching scenario. In the handshake scenario, participants only undergo the EMSTouch and vibrotactile conditions due to the difficulty of synchronizing a handshake without some form of haptic feedback. We counterbalance the order of conditions for participants through full permutations to reduce the order and learning effects.

4.2 Procedure

Participants in the user study completed the following procedure:



(a) Mean score for touch scenario

(b) Mean score for handshake scenario

Figure 6: Survey results for the interaction and handshake scenarios

(1) Briefing and consent. The experiment conductor explained the study objectives, modalities, risks, and stop rights. Participants reviewed and were asked to sign a consent form.

(2) Equipment setup. Participants put on and adjust the XR headset. For haptic feedback, the wearable band is placed around the participant's forearm. For EMS feedback scenarios, electrodes were positioned on the target muscles. Users were asked to maintain relaxed arm positions that matched those later used in the experimental tasks. Activation was verified through an iterative calibration process in which electrode placement was carefully adjusted based on both visual confirmation of intended gestures and participants' self-reports. During this procedure, stimulation intensity was gradually tuned to achieve clear and comfortable activation of the target muscles, ensuring that the elicited movements matched the intended gestures. In some cases, misplaced electrodes led to either insufficient activation or unintended effects such as localized discomfort, requiring repositioning and re-tuning before verified muscle activation could be established.

(3) Comfort calibration. For the EMS-based feedback scenario, the intensity of the stimulation was increased gradually to achieve actuation of the required muscles while maintaining a comfortable level of sensations. Participants were instructed to withdraw their hand from the virtual objects if they experienced any discomfort during EMS stimulation. In such cases, the EMS stimulus was immediately terminated. For the vibrotactile baseline condition, vibration intensity was verified to be clearly perceptible to the user.

(4) Virtual object tasks. Participants performed simple tasks (e.g., reach and grasp the virtual cube) in XR under different counterbalanced feedback conditions: visual-only, vibration, and EMS.

(5) Virtual handshake interaction. Participants experienced a handshake interaction in XR using two feedback types: EMS and vibrotactile. The order of feedback type was counterbalanced for each participant.

(6) Self-administered questionnaire. After completing each scenario, participants filled out a questionnaire adapted from the IGroup Presence Questionnaire (IPQ) [35], assessing their sense of presence in the virtual environment, perceived realism, acceptance and immersion (on 5-point Likert scale).

The protocol was reviewed and approved by the Human and Artifacts Research Ethics Committee of the Hong Kong University of Science and Technology (Protocol no. : HREP-2025-0641).

4.3 Results

Figure 6a illustrates the results from the questionnaire, showing mean scores for Involvement ("I've felt like I was really touching the cube"), Comfort ("The experience was comfortable throughout"), Experienced realism ("The feedback made the cube interaction more realistic"), Usability ("The feedback made it easier to interact with the cube"), and Acceptance ("I would be willing to use this type of feedback in future AR/VR applications") for the cube interaction scenario on 5-point Likert scale. As expected, Vibrotactile ($\bar{M}$=3.83, σ=0.83) and Visual ($\bar{M}$=3.83, σ=1.19) perceived to be more comfortable than EMS ($\bar{M}$=3.66, σ=0.88), as visual feedback requires no additional hardware and vibrotactile feedback was delivered through a small wearable band. Apart from that, EMS feedback showed higher scores in involvement ($\bar{M}$=3.83, σ=0.88 versus $\bar{M}$=2.41, σ = 0.99 for visual and $\bar{M}$=3, σ=1.20 for vibrotactile), realism ($\bar{M}$=4.33, σ=1.15 versus $\bar{M}$=2.41, σ=1.16 for visual and $\bar{M}$=3.41, σ=1.08 for vibrotactile), and usability ($\bar{M}$=3.91, σ=1.08 versus $\bar{M}$=2.5, σ=1.24 for visual and $\bar{M}$=3.41, σ=1.08 for vibrotactile). The acceptance (or willingness to use) was highest with EMS ($\bar{M}$=4.41, σ=0.51), followed by vibrotactile ($\bar{M}$=4.08, σ=0.99) and visual feedback ($\bar{M}$=3.75, σ=1.35).

To analyze the 5-point scale responses across the three conditions, we treated the data as interval data by averaging them. Parametric analyses like the ANOVA are robust for Likert-type scales in such cases[6, 29]. A repeated-measures ANOVA revealed a significant main effect of condition (visual, vibrotactile, EMS) on **involvement**, $F(2, 22)$=8.11, p=0.002. Because the assumption of sphericity

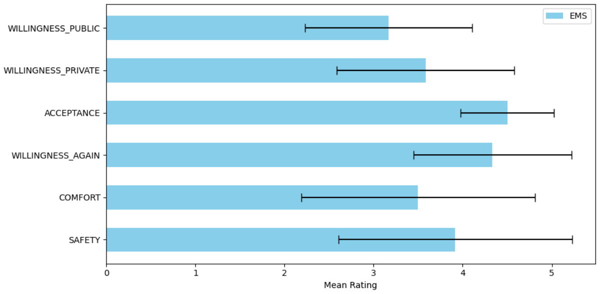


Figure 7: Survey results on general acceptance and comfort of EMS technology

was violated, Greenhouse–Geisser correction was applied (ϵ=0.89). Post-hoc pairwise comparisons (Bonferroni-corrected) indicated that involvement was significantly higher in the EMS condition compared to the Visual condition (p=0.029), whereas differences between EMS and vibrotactile (p=0.208) and between vibrotactile and visual (p=0.330) were not significant. Similarly, condition had significant effect on **realism**($F(2,22)$=14.61, p<0.001, with correction of ϵ=0.80) and Bonferroni-corrected pairwise comparison revealing realism ratings were significantly higher in the EMS condition compared to the Visual condition (p=0.02) and difference between EMS and vibrotactile did not reach significance (p=0.101).

Figure 6b shows results of the questionnaire, showing mean scores for Naturalness ("I felt like I was shaking hands with another person"), Immersion ("The feedback increased my feeling of immersion"), Realism ("The feedback improved the realism of the handshake"), Agency ("I felt in control of the handshake experience"), and Acceptance for the handshake scenario. The evaluated sense of agency (EMS condition: $\bar{M}$=2.66, σ=1.07, vibrotactile condition: $\bar{M}$=3.75, σ=0.75) suggests that externally controlled muscle activation diminished participants' perceived ability to initiate and regulate their own movements. Naturalness ratings were higher for EMS ($\bar{M}$=4.16, σ=0.93) compared to vibration ($\bar{M}$=2.75, σ=1.05). Similarly, immersion ($\bar{M}$=4.33, σ=0.93 vs. $\bar{M}$=3.16, σ=1.26) and realism ($\bar{M}$=4.33, σ=0.98 vs. $\bar{M}$=2.91, σ=0.99) were rated higher under EMS. Acceptance ratings showed a smaller difference (EMS: $\bar{M}$=3.91, σ=0.99; Vibration: $\bar{M}$=3.33, σ=1.21).

Wilcoxon signed-rank tests were conducted to compare EMS and vibrotactile feedback conditions for handshake scenario. Results indicated that EMS-modulated handshake was rated significantly higher than vibration handshake in **naturalness** (W=3.00, p=0.011), **immersion** (W=6.00, p=0.014), and **realism** (W=2.50, p=0.006), while agency was significantly lower (W=2.50, p=0.015).

Across all participants, the number of completed handshake cycles was higher under EMS feedback ($\bar{M}$=11.0, σ=3.8) than under vibrotactile feedback ($\bar{M}$=7.9, σ=2.0). This indicates that EMS made the interaction more sustained and engaging, reflecting a higher level of user involvement.

4.4 Discussion

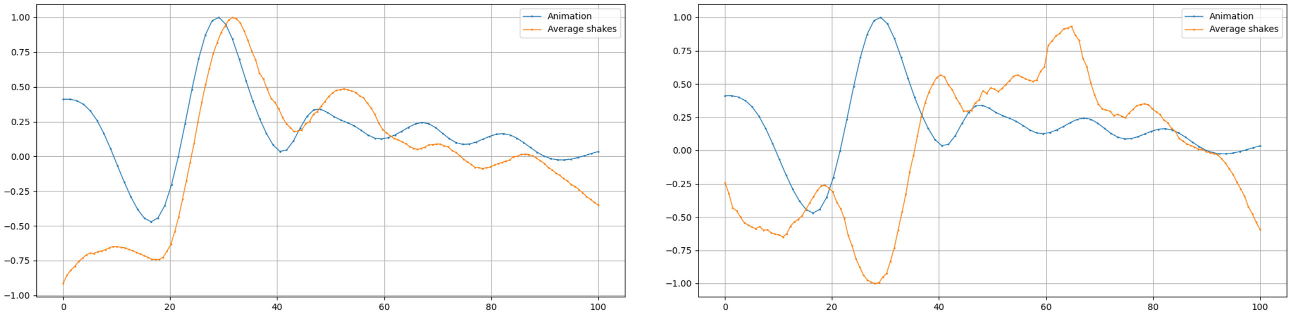
4.4.1 Limitations of the study. Our study has two primary limitations. First, the small sample size (N=12) restricts this to an exploratory evaluation; larger studies are needed to validate the findings. Second, the participant pool included mostly young participants and only two female participants. Because EMS perception and muscle recruitment are sensitive to anatomical differences, such as skin impedance, subcutaneous fat distribution, and muscle mass, our comfort and acceptance ratings may not generalize to female users. Future evaluations should use demographically balanced cohorts to ensure the viability and inclusivity of EMS haptic interfaces across a broader population.

4.4.2 Perceived Comfort and System Acceptance. Following the completion of all experimental sessions, we conducted an additional survey to capture participants' perceptions and attitudes toward the EMS feedback (see Figure 7). The evaluation results highlight that participants generally perceived the system as safe ($\bar{M}$=3.92, σ=1.31) and moderately comfortable ($\bar{M}$=3.50, σ=1.31), aligning with prior studies that report acceptable levels of comfort and perceived safety [19]. Acceptance was particularly strong ($\bar{M}$=4.5, σ=0.52), and willingness to use the system again was high ($\bar{M}$=4.33, σ=0.89), suggesting positive user attitudes toward repeated engagement. However, willingness varied across contexts: participants expressed greater readiness to use the system in private ($\bar{M}$=3.58, σ=0.99) than in public ($\bar{M}$=3.17, σ=0.94), with the Wilcoxon test confirming a statistically significant difference (p=0.025). This distinction underscores the importance of situating EMS-based interfaces within appropriate usage scenarios, as public deployment may introduce social or contextual barriers despite strong overall acceptance.

Regarding the qualitative feedback on safety and comfort, several important observations can be reported. As part of our protocol, we informed participants that they could withdraw at any time and periodically checked their comfort level during the experiment. None of the participants expressed the need to withdraw, which suggests that the procedures were broadly tolerable. However, a small number of individuals declined participation due to unpleasant prior experiences with EMS technology. Among those who did participate (N = 12), one individual explicitly noted that although they understood the system was safe, "it didn't *feel* safe." It highlights the role of personal history and perception in shaping willingness to engage as well subjective level of comfort.

During the calibration phase, several participants reported discomfort, including localized discomfort and a sensation described as "bone vibration." In such cases, electrode placement was adjusted and recalibrated until reliable activation could be achieved without adverse effects. This iterative process was essential to balance usability with participant comfort, but it affects the convenience of EMS technology overall, as active users need to calibrate every time.

Only one participant reported experiencing continuous light muscle discomfort following the completion of the experiment. The discomfort was transient, lasting for approximately fifteen minutes. While this isolated case did not result in lasting harm, it highlights the need for ongoing monitoring of post-session effects and for clear communication of expected sensations to participants.



(a) Comparison between the original animation trajectory and induced movements of the user's hand averaged across all participants for EMS-controlled handshake

(b) Comparison between the original animation trajectory and voluntary movements of the user's hand averaged across all participants for vibrotactile-augmented handshake

Figure 8: Induced and voluntary trajectory comparison

In summary, prior negative perceptions and stigma, reports of discomfort or adverse effects during calibration, as well as the overall convenience and comfort of use, hinder the broader use and acceptance of EMS technology.

4.4.3 *Perceived and Expected Agency.*

A key issue affecting the acceptance is the perception of agency. As shown in Section 4.3, participants reported lower perceived agency with EMS feedback compared to vibrotactile stimulation. The figure 8a illustrates that EMS-induced hand movements, averaged across participants, were strongly guided, exhibiting four distinctive peaks along the original animation trajectory with a delay of 10–20 ms. In contrast, voluntary movements during the handshake (as depicted in Figure 8b) with vibrotactile feedback did not display such synchronicity. While this reduction in agency may be problematic in some contexts, in the case of a handshake, it is less critical, as the gesture inherently involves two individuals jointly shaping the trajectory.

EMS feedback produces highly realistic, physically guided movements that closely replicate the dynamics of a handshake, yet realism comes at the cost of perceived autonomy, as participants often felt "forced" into action. This contrast highlights a design dilemma: systems that maximize realism may risk undermining user agency, while those that prioritize agency may deliver less immersive or convincing experiences [11]. The challenge for future work is to balance these dimensions, identifying contexts where realism justifies reduced agency and contexts where preserving agency is paramount, such as precise control tasks or personal interactions.

4.4.4 *Future Works.*

Several concrete avenues for improvement on EMS for tactile feedback in XR emerge from this study.

First, to mitigate the diminished sense of agency, future iterations could implement dynamic agency adaptation via impedance-control logic. By integrating sEMG sensors to detect if a user is intentionally resisting the induced movement, the system could dynamically lower EMS intensity, thereby preserving user autonomy when necessary.

Second, while we compared EMS and vibrotactile feedback in isolation, blending multiple modalities is a promising direction. Vibrotactile feedback excels at rendering high-frequency cutaneous cues (e.g., the initial impact or texture of a surface), whereas EMS is ideal for low-frequency kinesthetic actuation (e.g., sustained pushback). Fusing both modalities could maximize realism without compromising comfort [25].

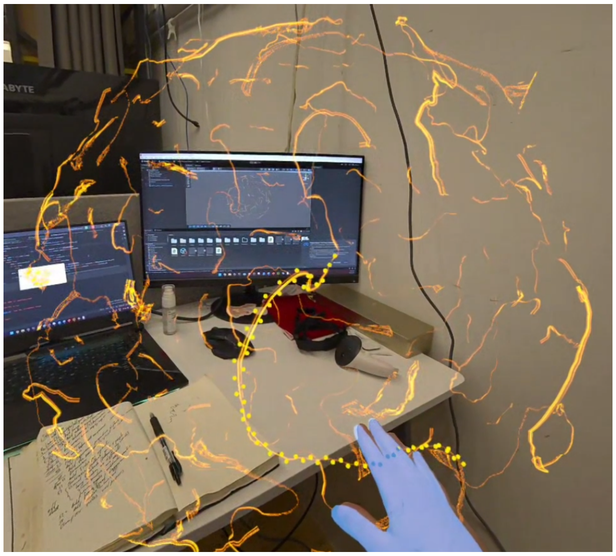


Figure 9: Interaction with XR sculpture

Finally, our cube interaction mapping relied on a linear equation for resistance. Future work should explore the integration of non-linear mathematical profiles, such as exponential or logarithmic curves—to simulate virtual objects with varying material properties, enabling users to physically distinguish between soft bodies and rigid constraints.

5 Case study: Conveying Artistic Intent in XR

In this section, we explore how EMS can be used in XR art to create shared embodied experiences. We aim to prototype an interaction where an artist's muscle activity is captured and replayed, allowing observers to both see and physically feel the gestures that shaped the virtual sculpture. To investigate how tangibility can be integrated into XR art, we prototype a virtual sculpture scenario enhanced with EMS feedback that carries the artist's creative intent. Our work focuses on the conversion of surface electromyography (sEMG) to EMS as a medium for gesture replay and tangibility in artistic contexts.

An artist's intentions are central to the creation, interpretation, and appreciation of artworks [23]. Whether planned or spontaneous, these intentions retroactively shape how a work is understood. One way to reconstruct this intent is through the detailed documentation of the artist's bodily states during the creative process. This link is especially evident in practices like Chinese calligraphy [16]. While codified techniques govern stroke creation, the artist's stance, breath, and movement carry intent into the final piece [38]. Chinese calligraphy appreciation has been characterized as "following the brush" — mentally reconstructing the artist's movement by analyzing the gestural information carried by the strokes [37]. Our work builds onto this concept by capturing the electrical signatures of an artist's gestures and enabling viewers to relive them through a neuromuscular replay. The augmented sculpture becomes self-guiding, with each stroke carrying the dynamics and muscular effort that brought it into being.

To build our prototype, we collaborated with artist Brian Lau [1], who is known for blending digital and physical experiences [5]. The artist first created a 3D digital sculpture using a custom XR painting application. During this process, we captured sEMG signals from his forearm corresponding to each 3D stroke using a Myo band [39]. These sEMG signals are then converted to EMS for the audience to experience the artist's intent while exploring the XR work.

For the sEMG-to-EMS conversion, we adopt the approach of mirror therapy [30], in which EMG signals recorded from the healthy muscles of one arm are transformed into EMS and applied to the contralateral impaired arm. The transformation pipeline consists of several stages of filtering, rectification, and electrode mapping. Specifically, signals from the eight sEMG electrodes of the MyoBand are first processed with a band-pass filter in the range of 20–90 Hz, then rectified, and subsequently smoothed with a low-pass filter capped at 5 Hz. Finally, signals from the eight sEMG electrodes are mapped to four EMS electrodes by averaging pairs of neighboring channels.

We consider an asynchronous interaction where the sculpture is first created (with corresponding sEMG patterns captured) and then experienced later in XR. The viewer's forearm muscles are actuated according to the captured patterns, transforming the act of watching into a shared, embodied experience

This experience contrasts with prior works that explored EMS for artistic sharing. For instance, EMSPainter [8] considers real-time interaction between the painter and the audience, enabling the co-creation of art with the audience actively diverting the artist's strokes through an EMS interface. Another machine-mediated human-to-human interaction transfers emotions [15] with the help of EMS. Psychological states deduced from electroencephalography are transformed into sign-language gestures and replayed through EMS. Comparatively, our work focuses on the direct, asynchronous replay of muscle actuations within the same domain, requiring no complex mapping between input and output.

We presented this experience to a small audience of five people as a design probe to gather qualitative feedback on gesture replay in artistic contexts. Participants highlighted that visual feedback was crucial, as long strokes are difficult to follow without additional cues. To address this, we introduced a visual augmentation in which each stroke is highlighted by a sequence of dots appearing alongside the trajectory, synchronized with the replay of sEMG signals. Furthermore, participants noted that the intensity of electric strokes fluctuated noticeably from one gesture to the next. This observation underscores the need for a strategy that preserves salient hand movements while normalizing intensity across the input space, ensuring both expressiveness and consistency in the replay experience.

Our exploration opens up several avenues for future work. The feedback suggests that forearm sEMG alone is insufficient. As mentioned earlier, the entire body movement contributes to the strokes, and forearm sEMG only provides a partial view into the artist's full intent. The whole body must be captured and replayed through a ghostly avatar, allowing appreciation to unfold as a full-bodied reenactment of the artist's intentions.

Furthermore, when an artist embeds their intent into an artwork through EMG/EMS, it creates a new haptic language without a real-world equivalent. We understand EMS-assisted touch and gestures, such as touching a cube or experiencing a handshake, because we have a baseline of lived experience. However, we have no prior context for this new form of conveying intent. Haptics are also only one part of this new language. While a visual feedback was requested by participants to better track the gesture, intent can also be conveyed through sounds, smells, and other sensory modalities, all facilited through XR.

6 Conclusion

This work explored the opportunities of electrical muscle stimulation (EMS) as a feedback modality for XR. We introduce EMSTouch, a system augmenting virtual scenes through controlled muscle activation. EMS improved user involvement, realism, and usability compared to visual-only and vibrotactile feedback. In particular, EMS feedback significantly enhanced the sense of presence during virtual object interactions and outperformed vibrotactile feedback in the handshake scenario, yielding higher ratings of naturalness, immersion, and realism. Although comfort ratings were slightly lower than for vibrotactile and visual feedback, acceptance was highest for EMS, reflecting the appeal of its novelty and immersive qualities. Extending these principles into a creative context, our artistic case study further showed that EMS can serve as a new medium for conveying an artist's intent, allowing observers to physically feel the gestures behind a work of art. These findings highlight EMS as a promising modality for enriching embodiment in XR applications, while also underscoring the need to address

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[1] https://artrio.org/

concerns about reduced agency and comfort to ensure broader adoption.

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