國立臺灣大學電機資訊學院資訊工程研究所
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Master's Thesis

# Paired-EMS: 通過刺激拮抗肌肉對增強基於電擊肌肉刺激 (EMS) 的力回饋體驗

# Paired-EMS: Enhancing Electrical Muscle Stimulation (EMS)-based Force Feedback Experience by Stimulating Both Muscles in Antagonistic Pairs

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## MASTER'S THESIS ACCEPTANCE CERTIFICATE
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Paired-EMS：通過刺激拮抗肌肉對增強基於電擊肌肉刺激（EMS）的力回饋體驗

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本論文係鄭家宇君（學號 R11922117）在國立臺灣大學資訊工程學系完成之碩士學位論文，於民國 113 年 6 月 18 日承下列考試委員審查通過及口試及格，特此證明。

The undersigned, appointed by the Department of Computer Science and Information Engineering on 18 June 2024 have examined a Master's thesis entitled above presented by CHENG, CHIA-YU (student ID: R11922117) candidate and hereby certify that it is worthy of acceptance.

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分享最近的研究煩惱，關心我周遭發生的任何事情，給我物質和精神上的支助，讓我可以跨過這過程中每一個低潮。

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此碩士學位論文之大部分研究成果同時發表於人機互動領域頂尖會議—計算機人機介面會議 ACM CHI 2024，Paired-EMS: Enhancing Electrical Muscle Stimulation (EMS)-based Force Feedback Experience by Stimulating Both Muscles in Antagonistic Pairs [3]


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# 摘要

肌肉電擊刺激 (Electrical Muscle Stimulation, EMS) 已成為一種重要的可穿戴式觸覺回饋技術，能夠模擬多種虛擬環境中的力回饋體驗，例如拳擊衝擊力、虛擬物體的重量以及手推牆時的反作用力。為了模擬這些外力事件，EMS 往往刺激使用者實際激活的肌肉對面的肌肉（即拮抗肌），導致不自主的肌肉收縮和與現實世界不同的觸覺感受。在本研究中，我們提出了「Paired-EMS」的方法，同時刺激使用者激活的肌肉和先前 EMS 刺激的肌肉（即拮抗肌肉對），以增強外力回饋體驗。我們首先進行了一項小型的實驗 (n=8)，以幫助設計肌肉對的刺激強度，然後進行了一項使用者體驗實驗，評估「Paired-EMS」與先前 EMS 方法在靜力 (isometric) 和動力 (isotonic) 下使用者操作中的表現。實驗結果 (n=32) 顯示，「Paired-EMS」顯著提高了真實感、和諧感和娛樂性 ($p<.05$)，且舒適度結果相似 ($p>.36$)，總體上有 78% 的參與者更喜歡「Paired-EMS」($p<.01$)。

關鍵字：人機互動；虛擬實境；觸覺回饋裝置



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# Abstract

Electrical Muscle Stimulation (EMS) has emerged as a key wearable haptic feedback technology capable of simulating a wide range of force feedback, such as the impact force of boxing punches, the weight of virtual objects, and the reaction force from pushing on a wall. To simulate these external forces, EMS stimulates the muscles that oppose (i.e. antagonistic to) the actual muscles that users activate, causing involuntary muscle contraction and haptic sensations that differ from real-world experiences. In this work, we propose *Paired-EMS* which simultaneously stimulates both the muscles that users activate and that prior EMS stimulates (i.e. antagonistic muscle pairs) to enhance the external force feedback experience. We first conducted a small formative study ($n=8$) to help design the stimulation intensity of muscle pairs, then conducted a user experience study to evaluate *Paired-EMS* vs. prior EMS approaches for both *isometric* and *isotonic* user actions. Study results ($n=32$) showed that *Paired-EMS* significantly improved realism, harmony, and entertainment ($p<.05$) with similar comfort ($p>.36$), and was overall preferred by 78% of participants ($p<.01$).

**Keywords:** Human-centered computing; Virtual Reality; Haptic devices

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# Chapter 1

# Introduction

Electrical Muscle Stimulation (EMS) elicits muscle contraction using electric impulses that are delivered through electrodes on the skin near the muscles being stimulated. It has long been used for rehab and training [14], and has recently emerged as a key wearable technology for haptic and force feedback [17, 8, 19], as a small and lightweight EMS device can provide strong force feedback with low latency.

EMS has been used to enhance the haptic experience of a variety of external forces in VR, including: the impact force from boxing, baseball, football [17], sword fighting [8], falling marbles [20], the friction and weight from pushing [13] and lifting virtual objects [19], the recoil from shooting projectiles [28], and the reaction force from pushing against a wall [19], and even shaking hands with an avatar [11]. In order to simulate these external forces, EMS contracts the muscles along the direction of the external forces.

Figure 1.1(a) shows an example of a user physically receiving a punch in boxing, and the user activating the triceps muscle to counter the external force [26, 30]. To simulate such external force, EMS contracts the *biceps* muscles to pull the forearm towards the body, which is different from the actual muscles that users activate to counter the boxing punch, which is the *triceps* muscles. For EMS to simulate external forces, it fundamentally has to stimulate the muscles that are antagonistic to the user-activated muscles, causing involuntary contraction of muscles that should be in a more relaxed state. This discrepancy results in haptic sensations that differ from real-world experiences.

We present *Paired-EMS*, which enhances EMS-based external force feedback by stim-


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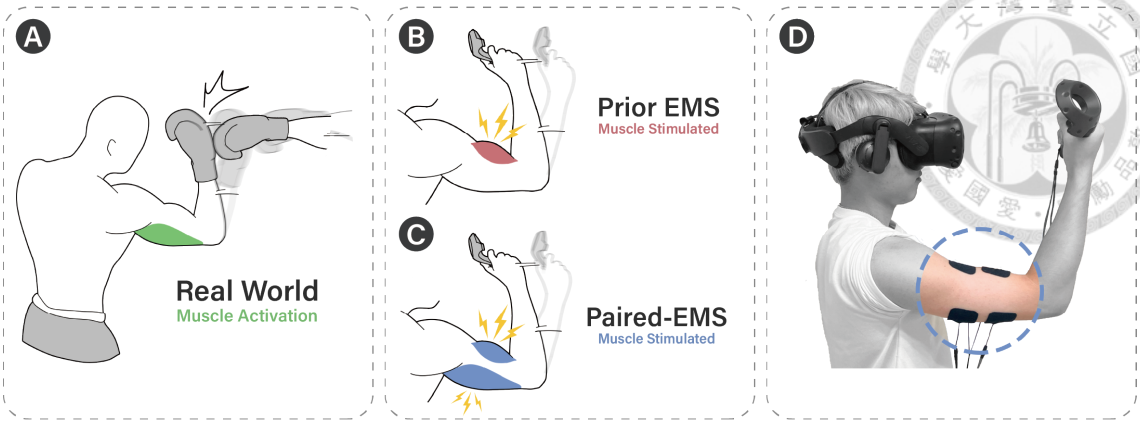


Figure 1.1: Muscles activated by users to counter external forces in the real world vs. the muscles stimulated by EMS to provide force feedback in VR: (a) A user physically receiving a punch in boxing, and activates the *triceps brachii* muscle to counter the external force from the punch; (b) Prior EMS techniques contract the *biceps brachii* muscle to pull the forearm towards the body to simulate the effect of external forces; (c) We present Paired-EMS, which enhances EMS-based external force feedback by stimulating the *agonist muscles* that users actively contract and the *antagonist muscles* that prior EMS work stimulates; (d) Actual placement of electrodes on the *antagonistic muscle pair* of biceps and triceps muscles.

ulating both the *agonist muscles* that users activate and their *antagonistic muscles* that prior EMS work stimulates to mimic external forces, as shown in Figure 1.1(c). To explore the intensity designs for the user-activated muscles for actions that span both *isometric* (i.e. maintaining muscle lengths) and *isotonic* (i.e. changing muscle lengths) actions, we conducted a small formative study in a VR boxing game for blocking and punching actions with 8 participants. Based on the findings, we conducted a summative study to evaluate the external force feedback experience of *Paired-EMS* vs. prior EMS in a VR boxing game for both blocking (isometric) and punching (isotonic) actions with 32 participants. Results showed that *Paired-EMS* significantly improved realism, harmony, and entertainment ($p<.05$) with similar comfort ($p>.36$), and was overall preferred by 78% of participants ($p<.01$).


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# Chapter 2

# Related Work

EMS generates electrical impulses that mimic the action potential that comes from the central nervous system, causing the muscles to contract, and delivers the impulses through electrodes on the skin near the muscles being stimulated. It has been used for a wide range of purposes, ranging from physical rehabilitation [31], sports training [29], to a variety of applications in human-computer interaction, including: guiding users in tutorial systems to execute complex tasks such as musical instrument performance [5, 32], mathematical notation and chart plotting [21], running posture [22], and speeding up human's reaction time [9, 10].

Combining proprioceptive and kinesthetic input and output (I/O) capabilities, Pose-IO [18] enables users to communicate through the pose of their wrists via the proprioceptive sense alone, without visual or auditory senses, by sensing the wrist poses controlled by EMS and by performing input gestures via flexing their wrists, sensed using a 3-axis accelerometer. bioSync [23] created specially designed electrodes capable of simultaneously performing Electromyography (EMG) biosignal measurements and EMS via the same electrodes, to enable sharing of kinesthetic experiences between two people, and was extended to applying EMS to both wrist flexors and extensors at the same time to convey joint stiffness [24]. Our work differs in that we enhance the experience of active, external force feedback.

EMS has also been used for a variety of force feedback in VR [25, 4, 17, 28, 20, 19, 8, 13, 11]. We highlight several example scenarios from these prior works in Figure 2.1,


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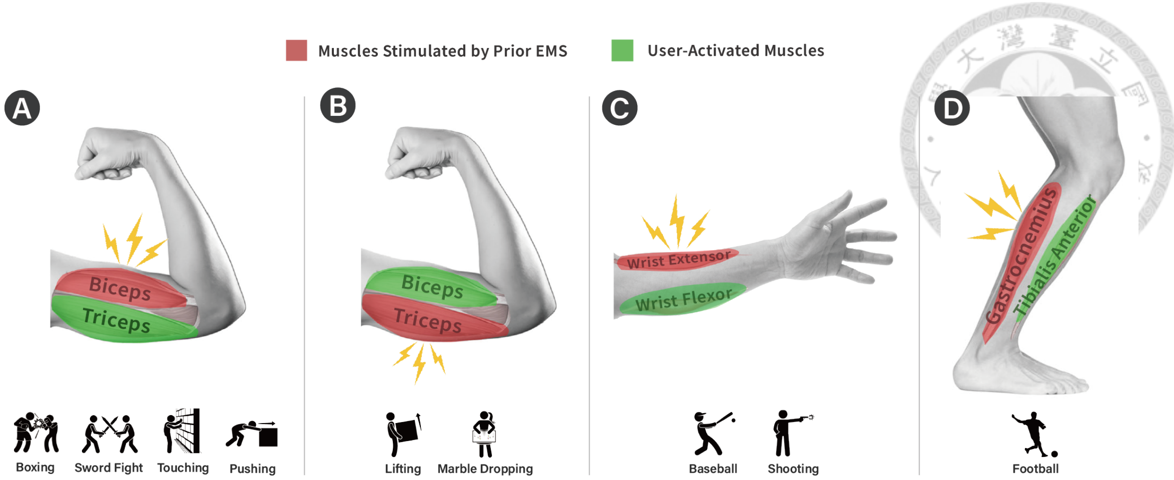


Figure 2.1: Summary of muscles stimulated by prior EMS work to simulate external forces (colored dark red) vs. the muscles that users actually activate in these scenarios in the real world (colored light green): (a) *biceps* vs. *triceps*, e.g. boxing [17], sword fighting [8], touching walls [19], and pushing objects [13]; (b) *triceps* vs. *biceps*, e.g. lifting heavy objects [19] and catching falling marbles [20]; (c) *wrist extensor* vs. *wrist flexor*, e.g. hitting baseballs [17] and recoil from shooting projectiles [28]; (d) *gastrocnemius* vs. *tibialis anterior* muscles, e.g. kicking footballs [17].

grouped by the muscles that are stimulated through EMS. The muscles colored light green show the agonist muscles that users activate, while the muscles colored dark red show the antagonist muscles stimulated by these prior EMS works. Figure 2.1(a) illustrates scenarios in which EMS stimulates the biceps while the user activates the triceps, such as simulating impact forces during boxing [17] and sword fighting [8], friction when pushing objects [13, 20], and reaction force when pushing against a wall [19]. Figure 2.1(b) shows the triceps being stimulated while the user activates the biceps, including lifting virtual objects [19] and playing a game involving the catching of falling marbles within the context of mixed reality[20]. Figure 2.1(c) shows the wrist extensor being stimulated by EMS while the user activates the wrist flexor, such as hitting a baseball [17] and experiencing recoil from shooting projectiles [28]. Figure 2.1(d) shows the calf muscles, specifically gastrocnemius, being stimulated by EMS to simulate the inertial force of a football when kicked by users [17], while users activate the tibialis anterior muscle. Other EMS applications simultaneously stimulate multiple muscles across the body that are not in antagonistic pairs, to raise players' arms and forearms upon the arrival of explosion shockwaves and when virtual avatars shake hands with the players [11].

Our work differs from prior external force feedback EMS studies in that we addition-


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ally stimulate the *agonist muscles* to *antagonistic muscles* stimulated by prior EMS work, and evaluated the experience for both isometric and isotonic user actions.



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# Chapter 3

# Formative, Intensity Preference Study

To explore the feasibility of Paired-EMS, we conducted a small formative study to collect user preference and feedback on stimulation intensity for the user-activated muscles for both isometric and isotonic actions. We explored three levels of stimulation intensity, ranging from minimum detectable to maximum acceptable:

- *Minimum (detectable)* intensity corresponds to the minimum intensity for the user-activated muscles at which users can distinguish between *Paired-EMS* vs. prior EMS.
- *Medium* intensity corresponds to the maximum intensity without inducing involuntary limb movement by the agonist, user-activated muscles. ( i.e., imply muscle activation without joint movement.)
- *Maximum (acceptable)* intensity corresponds to the highest intensity without experiencing pain and discomfort during *Paired-EMS*.

For VR scenarios, we selected the most popular category of EMS force feedback as summarized in Figure 2.1, which simulates external forces applied to the hands toward users. We selected boxing as it has both isometric (blocking) and isotonic (punching) actions and is popular among these scenarios.


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## 3.1 Apparatus

We used two channels of an FDA-approved, 4-channel EMS device (iSTIM EV-805) to generate safe and adjustable waveforms, and controlled the delivery to users using an Arduino Uno board with relay switches. Two pairs of 5 cm × 5 cm electrodes were attached to the biceps and triceps muscles on each participant's dominant hand.

We also used the same techniques as prior studies [9, 18] to mask out the tingling sensation caused by EMS, we applied vibrotactile feedback at the site of electrodes. Specifically, we used a vibrotactile haptic sleeve, bHaptics Tactosy for Arms, [1] worn on top of the electrodes, which synchronously vibrated with EMS impulses to mitigate the tingling sensation. In addition, to provide tactile feedback at the contact points of boxing, similar to Impacto [17], we re-purposed and placed a vibrotactile band [2], bHaptics TactVisor, on the fist.

Participants wore an HTC Vive Pro 2 VR headset and played a commercial VR boxing game, *The Thrill of the Fight* [16]. We used HapticSeer [15] and OpenVR API to listen to blocking and punching actions based on the VR controller's vibration signals. When users receive or deliver a punch, we use the relay switch to provide muscle stimulation.

## 3.2 Study Procedure, Calibration, and Participants

After an explanation of experimental procedures, participants were asked to wear boxing gloves and engage in punching and blocking exercises for 10 times each with an experimenter. This real-world, hands-on experience helps form the basis for assessing force feedback designs.

We then helped participants to attach electrodes to their biceps and triceps and wear the vibrotactile devices. Calibration for EMS and vibrotactile was performed for each participant individually, as each participant sat on a chair and assumed a relaxed, blocking posture. For EMS, calibration was conducted for the biceps first, then for the three intensity levels for the triceps. The calibration process for the biceps was based on prior EMS studies [20, 19], which started at the lowest current intensity and gradually increased by


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1 $mA$ until the upper bound that remained comfortable and pain-free was identified. The pulse frequency was set to 120 $Hz$ with a pulse width of 100 $\mu s$ based on findings from a pilot study with 4 users. For the triceps, the current intensity was also gradually increased by 1 $mA$ until the three levels: minimum (detectable), medium, and maximum (acceptable), were found.

The calibration of the intensity of vibration motors for the Bhaptics sleeve followed the procedure mentioned in *Preemptive Action* [9]: (1) We calibrated EMS to tingle the skin but not strongly enough to actuate the arm. (2) We actuated the vibration motors, which vibrated the participant’s biceps and triceps respectively. (3) We asked the participant to say when they felt skin tingling among the vibrations. (4) We turned on the EMS at a random point in time. (5) If participant still felt the skin tingling, we lowered the EMS (never below the point of tingling) and increased the intensity of the vibrations. (6) We ensured all participants’ responses to this were below or around random (<=50%).

After the completion of calibration, participants played the VR boxing game. For each action type, blocking or punching, users experienced three levels of *Paired-EMS* intensity: *minimum (detectable)*, *medium*, and *maximum (acceptable)*, for one minute each, in counter-balanced ordering. After experiencing all three intensity levels for each action type, we collected participants’ most preferred intensity and qualitative feedback.

We recruited 8 participants (3 males and 5 females) with ages 19-26 years (mean = 23, SD = 2.3). All participants were right-handed, and 2 participants had previously experienced EMS.

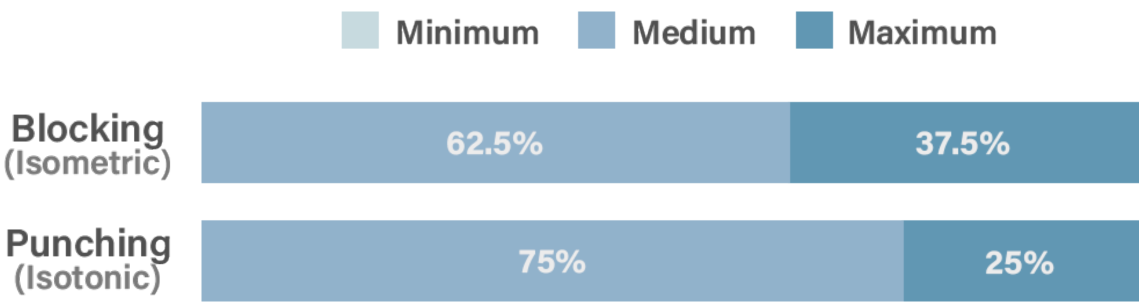


Figure 3.1: Most-preferred Paired-EMS intensity levels for the triceps muscles for: blocking (isometric) and punching (isotonic) actions in VR boxing.


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## 3.3 Results

Figure 3.1 shows the distribution of most-preferred intensity levels for the triceps muscles, with most participants preferring the *medium* level: 62.5% for blocking and 75% for punching. All remaining participants most-preferred the *maximum (acceptable)* level, with no participants preferring *minimum (detectable)*.

In terms of qualitative feedback, participants liked the ”more balanced” sensations for their chosen intensity levels. More than half of the participants felt the *medium* intensity most balanced so they preferred it (P1, P2, P3, P4, P5, P8). Some reported that the *maximum (acceptable)* intensity was too strong and interfered with their intended fist movement (P1, P2, P4, P5, P8), while a few mentioned that the *maximum (acceptable)* intensity felt closest to the strength experienced on the biceps, hence perceiving a more balanced sensation (P6, P7). Most of the participants indicated that the *minimum (detectable)* intensity was too weak compared to the other two intensities (P1, P2, P3, P6, P7, P8).

Consequently, we determined that the *medium* intensity would be employed to stimulate the user-activated muscles due to its favorable balance of sensory perception within the VR context.


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# Chapter 4

# User Experience Evaluation

To help understand how *Paired-EMS* user experience compares with prior EMS work, we conducted a summative user experience evaluation with 32 participants. The study used a within-subjects, counter-balanced design to compare user experience for *Paired-EMS* vs. a baseline of prior EMS work, i.e. EMS for both biceps and triceps (at the most-preferred, *medium* intensity) vs. a baseline of EMS for only the biceps.

For the tactile feedback on the fist, 16 participants used a solenoid actuator based on the Impacto design [17], as depicted in Figure 4.1(a). 16 participants used the more-accessible vibrotactile band used in our formative study, illustrated in Figure 4.1(b), which used coin-style Eccentric Rotating Mass (ERM) actuators. The former, solenoid-based approach delivers stronger feedback, while the latter is lighter, more compact, and more widely used.

## 4.1 Apparatus, Procedure, and Participants

Apart from the solenoid device, the rest of the apparatus was identical to that used in our formative study. The study procedure is also based on the formative study, with the following changes:

- **Calibration** for the triceps muscles identified only the

  ”medium” level, which was most-preferred intensity level. The same biceps inten-


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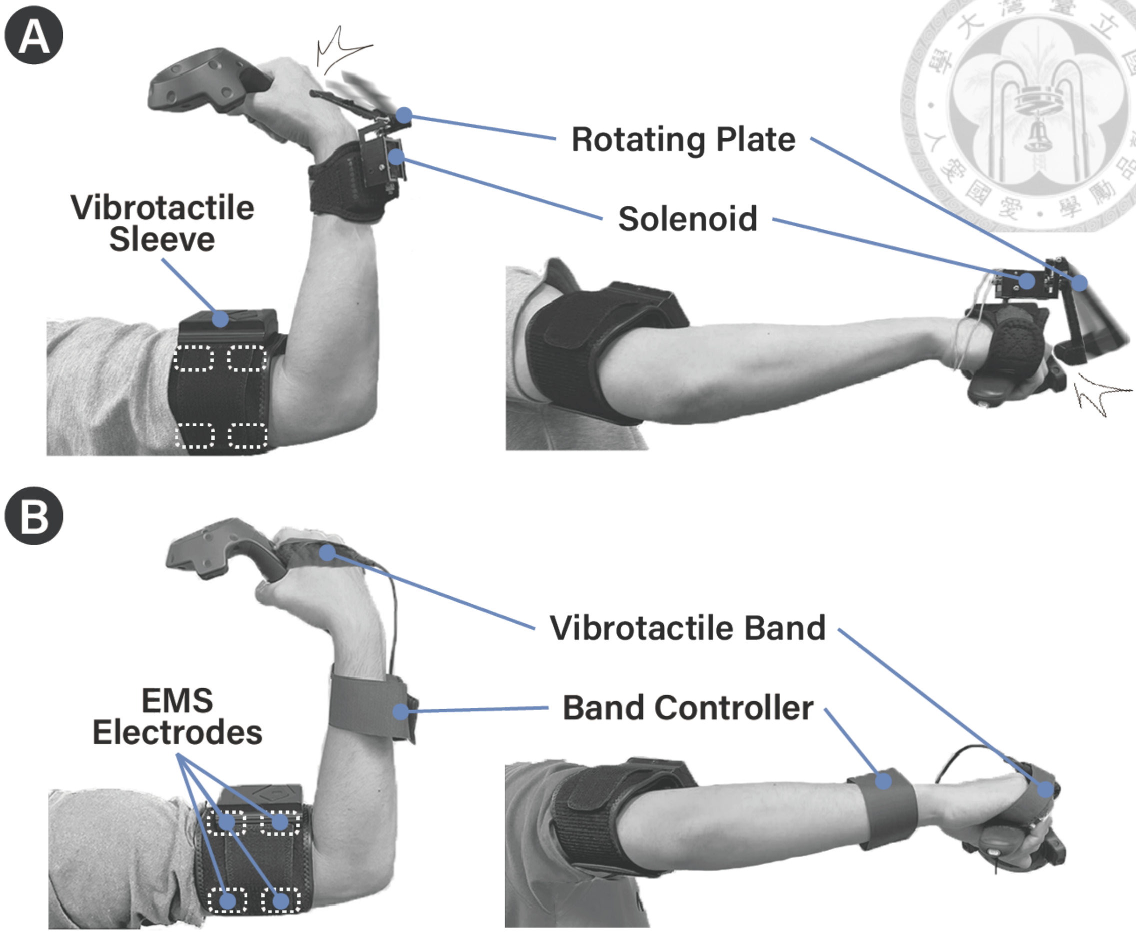


Figure 4.1: The tactile devices worn by participants for the study. All 32 participants wore a *vibrotactile sleeve* to mask out the tingling sensation caused by EMS. For tactile feedback on the fist and forearm, 16 users used (a) a *solenoid actuator* design based on pulling a rotating plate to hit the user, based on the design in Impacto [17]; and the other 16 users used (b) *ERM-based vibrotactile band*.

sity was used for both Paired-EMS and the baseline.

- **Tasks and Preference Rating**: for each group of 16 participants, the study was a 2 x 2 design, with two action types (blocking and punching) and two feedback types. For each action type, participants experienced both types of feedback then provided preference ratings for realism, harmony, entertainment, comfort, and overall preference, by first choosing a preferred feedback type then rating the degree of difference on a 5-point scale [6].

We recruited 32 participants, 13 females and 19 males, with ages ranging from 18 to 30 years old (mean = 22.8, SD = 2.9). 6 participants have had prior boxing experiences, and one of them is an amateur boxer. 3 participants were left-handed.


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For calibration, the biceps intensity averaged 19.32 $mA$ ($\sigma$ = 7.43), and the triceps intensity averaged 9.45 $mA$ ($\sigma$ = 3.69) across all 32 participants.

## 4.2 Results and Discussion

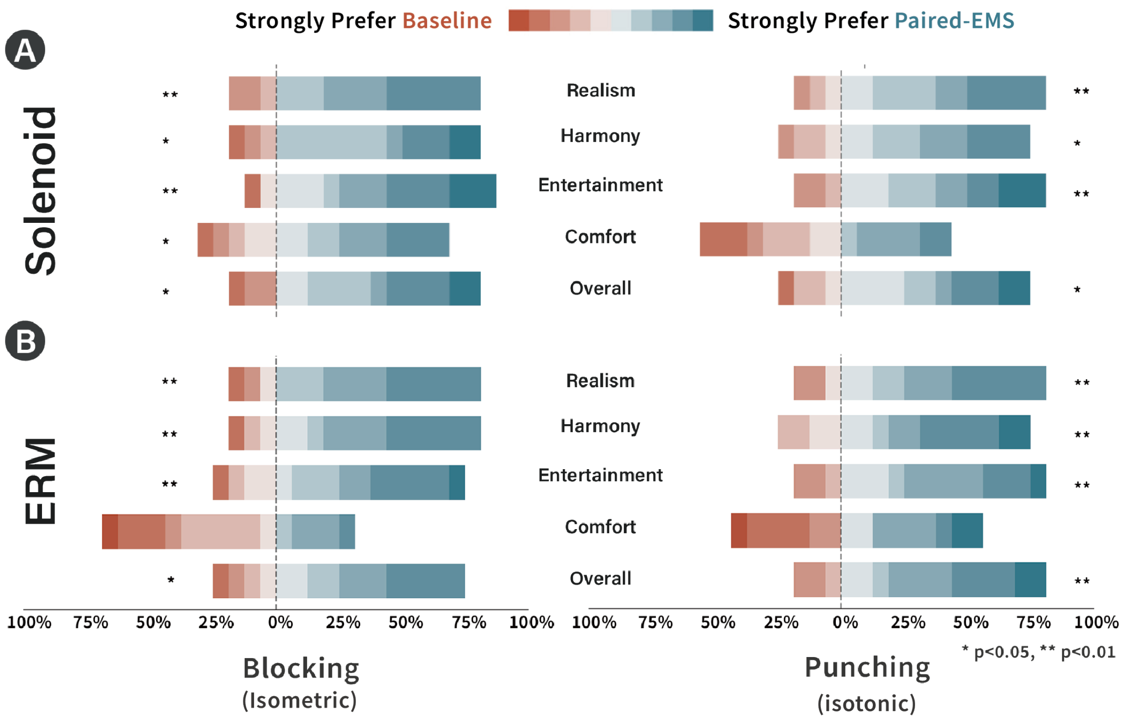


Figure 4.2: The distribution of user preference for baseline vs. Paired-EMS, for *realism*, *harmony*, *entertainment*, *comfort*, and *overall preference* when performing Blocking (isometric) and Punching (isotonic) actions for (a) a solenoid actuator based tactile feedback, and (b) ERM actuators based tactile feedback. Participants significantly preferred Paired-EMS for *realism*, *harmony*, *entertainment*, and *overall* with large effect sizes.

Figure 4.2 shows the distribution of user preferences for realism, harmony, entertainment, comfort, and overall preference across each feedback type, with 16 participants in each.

The non-parametric, Friedman test showed a significant difference between two methods for all metrics (p < .01). The preference results were similar for solenoid and ERM for the fist, when analyzed separately. Effect size of each pairwise comparison is calculated as $r = \frac{Z}{\sqrt{N}}$ and interpreted using guidelines of $0.1 \sim 0.3$ (small effect), $0.3 \sim 0.5$ (moderate effect), and $\geq 0.5$ (large effect) [27].

Results show that participants preferred *Paired-EMS*, whether in both action types or


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both feedback types. In the solenoid/blocking scenario, 87% of participants expressed a preference for *Paired-EMS* in terms of entertainment, 81% for realism, harmony, and overall preference, and 68% for comfort. In the solenoid/punching scenario, 81% of participants favored *Paired-EMS* for realism and entertainment and overall preference, 75% for harmony, and 43% for comfort. In the ERM/blocking scenario, 81% of participants expressed a preference for *Paired-EMS* in terms of realism and harmony, 75% for entertainment, 31% for comfort, and 75% for overall preference. In the ERM/punching scenario, 81% of participants favored *Paired-EMS* for realism, entertainment, and overall preference, 75% for harmony, and 56% for comfort.

Significant enhancements were observed in both action types and both feedback types for realism (p = 0.0045 solenoid/blocking, 0.0048 solenoid/punching, 0.0075 ERM/blocking, 0.0048 ERM/punching), harmony (p = 0.015, 0.012, 0.006, 0.0041), entertainment (p = 0.0024, 0.0099, 0.0086, 0.0093), and overall preference (p = 0.0048, 0.026, 0.021, 0.0052) vs. the baseline, all with large effect sizes ($r \geq 0.5$). For comfort, 50% of 32 users preferred *Paired-EMS* (p>.36). Interestingly, some of the users that preferred baseline for comfort preferred *Paired-EMS* overall. Their rationale was that despite the expanded stimulation, the overall intensity remained within an acceptable threshold, contributing to their preference for a more realistic and engaging experience.

**Qualitative Feedback** More than half of the participants expressed that experiencing simultaneous stimulation of both biceps and triceps felt more realistic (P2, P3, P5~P8, P10~P14, P16, P18~ P20, P24, P27, P29). "It matched the sensation of exerting force to resist the experimenter's attacks during the interaction phase." (P3) Half of the participants informed that the baseline stimulation primarily concentrated on the biceps, resulting in an imbalanced sensation. In contrast, *Paired-EMS* provided stimulation to both biceps and triceps, creating a more natural sensation (P2, P3, P7, P8, P10, P12~P14, P16, P18, P19, P24, P25, P27, P31). "When an opponent threw a punch, there was a subconscious tendency to resist. The force feedback from Paired-EMS gave me the sensation that I was resisting." (P8) Some participants reported that *Paired-EMS* better reproduced the tingling sensation spreading throughout the entire arm, as experienced in real-world boxing sce-


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narios (P1, P5, P10, P15, P23, P31). ”Paired-EMS felt more like being hit by a fist, but the sensation from the baseline was just like getting shocked by the stimulation” (P15) A few participants perceived stronger force feedback when experiencing *Paired-EMS* (P0, P7, P9, P13, P18, P27). Some participants found that *Paired-EMS* allowed them to focus more on the game and less on the stimulation of the biceps (P10, P14, P27). On the other hand, some believed that the baseline stimulation, primarily stimulating the biceps, was more comfortable (P5, P7, P9, P11, P14), while most of these participants also found the baseline experience was less realistic, leading them to prefer *Paired-EMS* (P5, P7, P9, P11, P15, P16, P18, P23, P25, P26, P30). Contrarily, a few participants said that although *Paired-EMS* was more realistic, they still preferred the more comfortable Baseline stimulation (P2, P6, P13).


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# Chapter 5

# Discussion

The study results showed that most users preferred *Paired-EMS* over prior EMS approaches. There are two possible reasons for the enhanced experience: (1) *Paired-EMS* masks the incongruence of involuntary activation of the antagonistic muscles by stimulating the user-activated muscle. In the case of boxing, the stimulation to the biceps becomes less noticeable with *Paired-EMS*; and (2) *Paired-EMS* provides higher total stimulation, making it especially suitable for high-intensity feedback scenarios. In boxing, stronger feedback than the maximum (pain-free) contraction that the biceps can tolerate can further enhance the feedback experience, which is provided by *Paired-EMS*'s additional, additive stimulation via triceps.

An interesting observation in our study is that some participants preferred *Paired-EMS* over the baseline, even though they reported a lower sense of comfort compared to the baseline. We recognize that this outcome may be task-dependent, influenced by the specific user experience in the boxing game employed in our study, so we believe that similar scenarios involving high-impact force, such as sword fighting or shooting games, also hold promising potential as the application of *Paired-EMS*.

Future research directions include exploring the stimulation of additional muscles involved in various movements to enhance realism further while maintaining user comfort within acceptable intensity levels. For instance, in addition to stimulating the triceps, it may be beneficial to stimulate muscles like the anterior deltoid or upper trapezius, which are highly active during boxing. However, increasing the number of muscles stimulated


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may also result in users experiencing more discomfort due to heightened stimulation.

As different users have different preferences in VR gaming experiences, with some seeking more realistic while others prefer a comfortable and relaxed gaming experience, the challenge lies in determining how to stimulate the maximum number of user-activated muscles while maintaining user comfort within acceptable intensity levels. Finding the optimal balance between realism and comfort is a topic worthy of future exploration.

Lastly, the calibration time required may increase because *Paired-EMS* stimulates more muscles compared to the prior EMS methods. Recent research has proposed magnetic muscle stimulation [33], which results in ∼50% less discomfort caused by tingling than EMS, and the implementation of automatic calibration methods [7, 12], which can help us streamline the calibration process. These advancements hold the potential to make *Paired-EMS* more practical for widespread use.


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# Chapter 6

# Conclusions

In this work, we introduced a novel approach to EMS named *Paired-EMS* aimed at enhancing the force feedback experience in VR environments. Prior EMS methods primarily stimulate muscles that are antagonistic to the user-activated muscles to simulate external forces, resulting in haptic sensations that differ from real-world experiences. In contrast, *Paired-EMS* simultaneously stimulates both muscles in antagonistic pairs, thereby increasing the realism of force feedback. The study results demonstrated that *Paired-EMS* significantly outperformed prior EMS methods in terms of realism, harmony, and entertainment, and it was preferred by the majority of participants. In summary, our study presents a new approach to EMS for VR external force applications, enhancing the user experience and offering valuable insights for future interactive experience designs.



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