



Kyoto Sangyo University

Doctoral Degree Thesis

Augmenting Human Ability through Electrical Muscle Stimulation in Interactive Systems

– Exploring the Applications and Potentials of EMS in Embodied Interaction –

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A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Computer Science

in the

**Division of Frontier Informatics
Kyoto Sangyo University**

December, 2025

Augmenting Human Ability through Electrical Muscle Stimulation in Interactive Systems

— *Exploring the Applications and Potentials of EMS in Embodied Interaction*

Summary

This dissertation systematically investigates how Electrical Muscle Stimulation (EMS) can augment human abilities within interactive systems. It explores EMS as a non-invasive interface that directly engages the human body to enhance sensorimotor control, coordination, and affective-physiological regulation. The work introduces an EMS system architecture and a stimulation efficiency model, followed by empirical studies validating its effectiveness in improving reaction time, finger precision, coordination, and stress regulation across various training contexts. Results demonstrate that EMS significantly facilitates skill acquisition and physiological stabilization. Based on these findings, the dissertation proposes the concept of “EMS-based Augmented HCI,” extending interaction from perceptual and cognitive domains to the bodily level. This paradigm establishes a theoretical and practical foundation for future applications of EMS in education, rehabilitation, entertainment, and emotional regulation, thereby broadening the scope of Human-Computer Interaction toward embodied augmentation and human-technology co-evolution.

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Chapter 1

Introduction

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1.1 Background: Emerging Trends in Augmented HCI

Human–Computer Interaction (HCI) is a discipline that studies the interactive relationship between humans and computer systems. Its goal is to optimize the interaction experience, improve work efficiency, and expand the possibilities of information acquisition and processing through technology and design [1]. Since its emergence in the 1970s, research in HCI has continuously evolved. In the early stages, the focus was mainly on computer usability and the development of graphical user interfaces, enabling non-expert users to effectively operate complex systems through keyboards, mice, and other devices [2, 3]. With the widespread adoption of mobile devices and the internet, research shifted toward ubiquitous computing, emphasizing interaction models across multiple devices and contexts to support access to information and communication any-time, anywhere. In recent years, with advances in speech recognition, gesture sensing, eye tracking, virtual reality (VR), and augmented reality (AR), the emphasis of HCI has further expanded to natural interaction, aiming to enable computers to better understand and adapt to human behaviors and intentions [4, 5]. Despite these achievements in interaction modalities and user experience, a common feature is that the human has

always been treated as the “operator”, rather than as the “augmented”.

Against this background, the concept of Human Augmentation has gradually been proposed in both academia and industry. Its core objective is not merely to improve the efficiency of information exchange between humans and computers, but to extend and enhance human physical, perceptual, and cognitive abilities through technology [6]. Research on human augmentation can generally be divided into four directions [7]: perceptual augmentation, such as enhancing vision, hearing, or touch to extend human sensory capacity; motor and coordination augmentation, such as improving strength, speed, precision, and skill learning through exoskeletons, brain–computer interfaces, or muscle stimulation; cognitive and decision augmentation, such as reducing cognitive load and improving decision-making efficiency through artificial intelligence and predictive systems; and physiological and affective regulation, such as using wearable sensors and biofeedback to monitor and adjust stress, fatigue, and emotional states in real time. These directions go beyond the traditional HCI focus on “optimizing the relationship between humans and computers,” positioning computers instead as tools and mediators for augmenting human capabilities themselves.

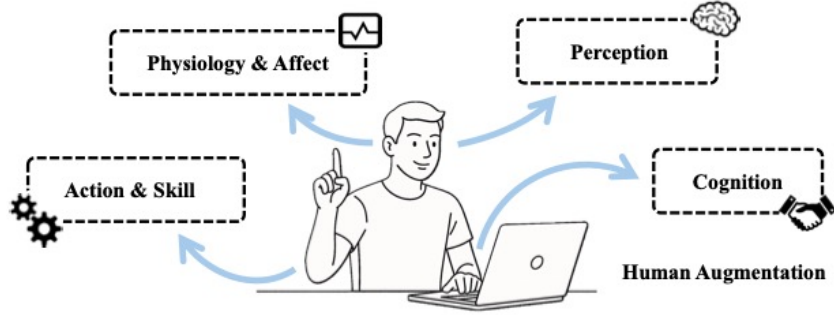


Figure 1.1: In this dissertation, Augmented HCI aims to enhance human perception, sensorimotor coordination, cognitive processes, and physiological and affective regulation through computer-based technologies.

Based on this concept, Augmented HCI has emerged as a new research trend in recent years [8]. The core idea of Augmented HCI goes beyond optimizing interaction interfaces to directly enhancing human abilities. It reframes computers not merely as tools for information processing, but as extensions of human functions. Rather than focusing solely on more efficient computer use, it ultimately seeks to improve human physical

and cognitive performance. This trend has already manifested in multiple fields—for example, the use of wearable devices and biofeedback to enhance performance in sports training, the use of augmented reality with bodily feedback to accelerate learning in education, and the integration of interaction technologies with physiological signals to aid recovery in rehabilitation medicine. The emergence of Augmented HCI marks a shift from “human-centered design” to “augmentation-centered design”: it is not only concerned with how humans can better use systems, but also with how humans themselves can be strengthened and extended through systems (Fig. 1.1).

Among the many technologies applicable to Augmented HCI, Electrical Muscle Stimulation (EMS) demonstrates unique advantages. EMS is a non-invasive technique that applies low-intensity electrical currents to target muscles to induce contractions or assist movements [9]. It is non-invasive and instantaneous, requiring neither surgery nor complex apparatus to directly act on muscles and generate visible motion. It provides direct bodily intervention: unlike visual or auditory cues, EMS delivers feedback or guidance by activating the muscles themselves, forming a highly intuitive “body-level interaction.” It is also highly controllable: by adjusting current intensity, pulse frequency, and pulse width, EMS can flexibly switch between “subtle cues” and “active movement induction.” Furthermore, EMS has multi-domain applicability: originally used in rehabilitation medicine, it has since been extended to sports training, interactive entertainment, and even artistic performance [10, 11, 12].

These characteristics make EMS an ideal technological approach for Augmented HCI. On the one hand, it can serve as an external cue that directly alters and shapes user movements, lowering the threshold for skill acquisition. On the other hand, it can help users acquire complex motor skills in a short time, with training effects partially retained even after stimulation is removed. Moreover, EMS can be integrated with physiological signals such as heart rate and respiration to achieve multi-level augmentation across perception, motor control, and affective regulation. Therefore, EMS is not only a new mode of interaction, but also a paradigm for exploring how human abilities can be augmented through technology in the context of human–computer interaction.

1.2 Research Motivation and Research Questions

Although EMS has already demonstrated its value in medical rehabilitation and shown great potential in motor learning, its possibilities within the broader context of HCI have not yet been systematically explored. Current HCI research remains primarily focused on providing cues and feedback through sensory channels such as vision, hearing, and touch. In contrast, interaction approaches that directly intervene in human movement and physiological states are still in the early stages of investigation [13, 14, 15]. The concept of Augmented HCI offers a new direction for addressing this gap—namely, how technology can directly enhance users’ abilities in motor control, skill acquisition, and physiological regulation. However, to fully realize the role of EMS in Augmented HCI, several research motivations and open questions must be addressed.

First, existing methods of skill learning and training typically rely on extensive repetition and long-term accumulation [16, 17]. Whether in the precision of operations in esports or the finger dexterity required in musical performance, the learning process depends heavily on individual perseverance and time investment. Such approaches are often inefficient and subject to considerable individual variability. By externally stimulating muscles, EMS can guide users to perform correct movement patterns within a short period of time. Therefore, it is important to investigate whether EMS can serve as an “accelerator” that effectively shortens the cycle of skill learning and enables users to achieve sustained improvement through short-term training.

Second, coordination training is central to many complex tasks [18, 19, 20]. For example, hand–eye coordination is essential in contexts such as gaming, sports, and surgery. However, traditional coordination training often lacks immediate bodily guidance, requiring users to gradually establish the mapping between perception and action through repeated trial and error. Through targeted stimulation of hand or finger muscles, EMS can provide precise movement prompts or guidance during bimanual or multi-finger tasks. Accordingly, it is necessary to explore whether EMS can help users more rapidly acquire complex hand–eye coordination patterns, thereby improving efficiency and accuracy in real-world tasks.

Third, in high-pressure and high-demand environments, emotional and physiological

states often play a decisive role in performance [21, 22, 23]. For instance, in esports competitions, players with excellent operational skills may still make errors due to tension and stress. Existing regulation methods—such as meditation, breathing exercises, or psychological counseling—are difficult to apply in real-time interactive scenarios. Integrating EMS with physiological signals, for example by detecting stress through heart rate and stimulating respiratory muscles to regulate breathing rhythms, may create a new mode of interaction. Hence, an important avenue of research is to examine whether EMS can be used within interactive systems to achieve real-time regulation of physiological and emotional states, thereby enhancing users’ stability and performance under pressure.

Moreover, the application of EMS in HCI also entails new challenges. For example, how can stimulation parameters be individualized? Can users maintain sufficient autonomy and agency while being partially “controlled”? Does long-term use pose any physical or psychological risks? These issues concern not only technical feasibility but also the sustainability of ethical and practical considerations. Therefore, it is crucial to investigate how EMS systems can be designed to enhance user abilities while ensuring comfort, safety, and ethical soundness.

Based on the above reflections, this dissertation establishes the following core research questions:

- RQ1 Can EMS, by directly driving muscles, effectively accelerate skill learning and produce both short-term and long-term retention?
- RQ2 Can EMS help users form more efficient perception–action coordination in complex tasks, thereby enhancing hand–eye coordination and multi-finger control?
- RQ3 Can EMS be integrated with physiological signals to regulate users’ emotional and physiological states in real time, thus improving performance in high-pressure scenarios?
- RQ4 In system design and application, how can EMS ensure feasibility and ethical acceptability in terms of individual differences, user agency, and long-term safety?

In summary, the motivation of this study is to transcend the traditional limitations of HCI that focus primarily on cues and feedback, and to explore the potential of EMS as an interaction technology that directly acts on the human body to augment human

ability. By addressing the above research questions, this dissertation aims to establish an EMS-driven framework for augmented interaction and to validate its effectiveness and feasibility in perceptual–motor training, coordination enhancement, and physiological regulation, thereby providing new theoretical and practical foundations for Augmented HCI.

1.3 Overview of the Dissertation Structure

Building upon the research objectives outlined in the previous sections, this section provides an overview of the dissertation structure. The dissertation is organized as follows.

Chapter 2 reviews the background and research progress of Augmented HCI, with a focus on directions of human augmentation and the current applications of EMS in rehabilitation, interaction, and skill training, while clarifying the interdisciplinary positioning of this study. Chapter 3 presents the overall research objectives and framework of the dissertation, explaining from a macro perspective how the different research questions and experimental systems are integrated into a unified paradigm of augmented human–computer interaction. Chapter 4 introduces the fundamental principles and system architecture of EMS, with detailed discussions on stimulation signal parameter adjustment mechanisms, efficiency modeling methods, and approaches for integrating EMS with interactive systems, thereby providing the technical foundation for subsequent experiments.

Chapters 5 to 7 form the core of the dissertation, presenting the applications and experimental results of EMS across different augmentation directions. Chapter 5 focuses on perceptual–motor augmentation, examining the role of EMS in timing training and precise finger control. Chapter 6 addresses coordination augmentation, showing how EMS can improve hand–eye coordination in bimanual tasks and validating its potential in complex skill training through musical instrument learning experiments. Chapter 7 centers on physiological and emotional regulation, integrating physiological states to propose and validate EMS-based methods for stress management and breathing rhythm control.

Chapter 8 provides an integrated discussion of the overall research outcomes and application prospects. It analyzes the empirical results in terms of feasibility, limitations, user experience, individual differences, and potential risks, and further examines the theoretical implications, design principles, and future application scenarios of EMS-based augmentation across domains such as training, entertainment, and psychological intervention, while also addressing ethical and social responsibility issues. Chapter 9 concludes the dissertation by summarizing the main technical, empirical, and conceptual contributions, articulating the paradigm of “EMS-based augmented interaction systems,” and outlining future research directions, including multimodal integration, multi-user interaction, and long-term adaptive interventions.

Through this structure, the dissertation progresses from theoretical foundations and system development to empirical validation, integrated discussion, and conceptual synthesis, ultimately establishing a comprehensive framework for EMS-based human augmentation in interactive systems.

Chapter 2

Literature Review

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2.1 Research Directions in Augmented HCI and Human Ability Enhancement

HCI, as an interdisciplinary field, emerged in the 1970s with the goal of understanding and improving how humans interact with computational systems [24]. Early research emphasized the usability of input/output devices, interface efficiency, and the reduction of users' cognitive and physical workload [25]. From command-line interfaces to graphical user interfaces (GUI), and later to mobile and touch-based interaction, the central objective of HCI has been to lower the communication cost between humans and computers and to design interfaces that align with human perceptual and cognitive characteristics [26, 27, 28].

Despite substantial progress, traditional HCI has primarily focused on improving the efficiency and naturalness of information exchange, without directly engaging with the question of how technology might extend or enhance human physical, perceptual, or cognitive abilities. Discussions on human enhancement have long existed in related fields such as cybernetics, human factors, wearable computing, and ubiquitous computing. For

example, Mann’s early work on wearable computing [29] and Maes’s research on cognitive augmentation [30] both explored how technology could function as an extension of human capabilities. Within the HCI community, this line of thinking was further articulated by Rekimoto, who framed Human Augmentation as a design perspective that emphasizes using technology to expand human abilities rather than merely supporting task execution [8]. With rapid advances in sensors, wearable devices, artificial intelligence, and biotechnology, this perspective has gained increasing visibility in HCI and ubiquitous computing research [31].

This shift has contributed to the emergence of a research direction often referred to as Augmented HCI, which positions technology as an active component that intervenes in or complements human perceptual, motor, cognitive, and physiological processes. Rather than viewing technology solely as an external tool, Augmented HCI conceptualizes interactive systems as extensions of the human body and mind.



Figure 2.1: Examples of Augmented HCI. (a) JackIn: a vision augmentation system based on a third-person perspective [32]. (b) A wearable robotic limb that enhances human capabilities [33]. (c) Electrical muscle stimulation training that improves reaction time [34].

Existing work on human augmentation spans several complementary research directions (Fig. 2.1). The first is *Perceptual Augmentation*, which aims to expand or enhance human sensory experience. Augmented reality (AR) overlays virtual cues onto physical scenes to support complex tasks [35], while haptic interfaces provide force or texture feedback to enrich tactile perception [36]. The second is *Motor and Coordination Augmentation*, which includes exoskeletons, supernumerary robotic limbs, brain–computer interfaces, and electrical stimulation systems designed to enhance strength, dexterity, or sensorimotor coordination [33, 37, 38]. The third is *Cognitive Augmentation*, where computational tools support memory, attention, decision-making, and learning by reducing cognitive load or offering real-time guidance [39]. The fourth is *Physiological*

and *Affective Augmentation*, which leverages biofeedback, wearable sensors, and intelligent interventions to maintain optimal performance under fatigue, stress, or fluctuating emotional states [40, 41].

Together, these directions form the foundation of Augmented HCI, reflecting a broader shift from designing efficient interfaces toward designing technologies that actively reshape human capabilities. This shift is evident across multiple domains. For example, wearable sensing and feedback systems are used to improve athletic performance [42], and interactive training systems leverage bodily cues to accelerate skill acquisition [43]. Such applications demonstrate that augmentation is no longer a purely conceptual vision but has begun to influence real-world practices.

Within this broader landscape, EMS represents a unique modality for augmentation. Because EMS can directly modulate muscle activation, it offers the ability to guide movement, support coordination, and integrate with perceptual or cognitive processes. Building on these trends, the present dissertation systematically examines EMS as a means of augmenting human abilities and clarifies its role within the framework of Augmented HCI.

2.2 Development and Applications of Electrical Muscle Stimulation

As a technique that induces muscle contractions by applying low-intensity electrical currents to the surface of the skin, EMS was first widely applied in the field of rehabilitation medicine to help patients with impaired motor functions caused by injury, surgery, or disease recover muscle strength and motor abilities [44, 45]. In neurorehabilitation, EMS is often implemented in the form of Functional Electrical Stimulation (FES), in which electrical currents are applied while the patient performs specific actions to promote coordinated activity between nerves and muscles [46, 47]. The goals of such applications are to prevent muscle atrophy, promote blood circulation, and improve motor functions through long-term training, thereby partially restoring the ability to perform activities of daily living [48].

With the proliferation of portable stimulation devices and advances in electrode

materials, the applications of EMS have gradually expanded into sports training and performance optimization. In sports science, EMS has been used to enhance muscle strength, increase reaction speed, and promote recovery. For example, Seyri et al. [49] demonstrated that EMS interventions significantly improved physical performance in both untrained and trained individuals, including athletes. Similarly, Babault et al. [50] reported that long-term EMS training led to significant improvements in muscle strength and explosive power among elite athletes.

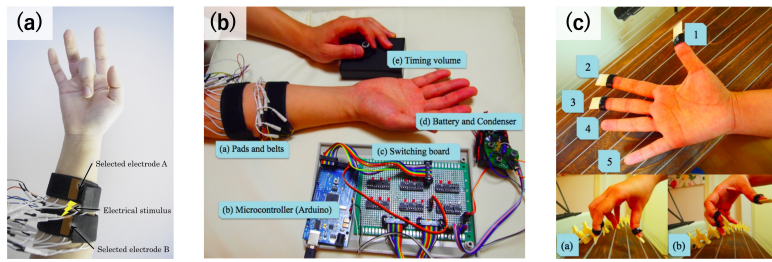


Figure 2.2: PossessedHand system proposed by Tamaki et al. [51] (a) Electrode configuration. (b) System controller. (c) Finger movement control via electrical stimulation using the PossessedHand.

When introduced into HCI research, EMS was first explored as a novel modality for feedback and control. Early studies focused on using EMS as an alternative to conventional haptic feedback, such as generating force sensations or movement sensations on the skin and muscles, thereby assisting users in improving their motor control performance [52]. Building on this, researchers began to experiment with directly driving users' actions through EMS to expand the diversity of interaction methods [53]. A representative example is the PossessedHand system proposed by Tamaki et al. [51, 54], which stimulates different muscle groups in the hand to control finger movements, allowing users to passively perform more complex and flexible gestures that they would otherwise find difficult to execute (Fig. 2.2). Such studies demonstrate the unique potential of EMS in action guidance and interaction control, laying the groundwork for its extension from rehabilitation and training technologies to interactive technologies.

In summary, the research and applications of EMS have gradually expanded from medical rehabilitation to sports science and, subsequently, to exploratory work in interactive systems. Its uniqueness lies in combining non-invasiveness, safety, and the ability

to directly drive muscle activity, enabling it to serve not only as a practical tool in medicine and training, but also as a novel control and feedback channel in interaction research. This developmental trajectory provides an important technical and research foundation for further exploring the potential of EMS in Augmented HCI.

2.3 Interdisciplinary Integration and Research Positioning

As a technique that directly acts on human muscles, the research and application of EMS are inherently interdisciplinary. Different disciplines provide the theoretical foundations and practical pathways for the development of EMS, while HCI offers new contexts and methodologies for integrating these outcomes into applied scenarios.

In engineering and computing, research has primarily focused on the hardware design and signal control mechanisms of EMS systems, with the aim of enabling efficient stimulation of specific muscle groups and seamless integration into interactive systems. For example, Jovičić et al. proposed a wireless distributed functional electrical stimulation system capable of controlling multiple channels simultaneously, providing more flexible stimulation strategies and significantly improving the practicality of rehabilitation training [55]. In the domain of interactive systems, Lopes et al. developed the Muscle Plotter, which demonstrated how EMS could be used as a spatial output medium by stimulating different muscle groups to generate tactile sensations on the skin, thereby extending the application of EMS in interaction design [56]. In addition, early research on upper-limb functional electrical stimulation laid important foundations for EMS signal control by exploring how multi-channel stimulation could achieve fine-grained motor control [57]. Meanwhile, the development of intelligent wearable systems has further promoted the miniaturization and portability of EMS technologies. For example, in lower-limb robotics, Mohammed et al. discussed how functional electrical stimulation could be integrated with wearable mechanical structures to achieve intelligent control of limb movement, thereby enhancing system flexibility and providing new directions for combining EMS with wearable augmentation devices [58].

In medicine and rehabilitation, researchers have focused on the role of EMS in muscle maintenance, blood circulation, and long-term neural recovery. Clinical studies have

shown that EMS can effectively prevent disuse muscle atrophy, particularly in patients who are bedridden or in states of impaired consciousness, helping to maintain muscle activity and delay functional decline [59, 60]. Moreover, low-frequency electrical stimulation has been demonstrated to increase muscle strength and improve local blood supply in patients with chronic heart failure [61], while graded stimulation has been applied to enhance muscle hemodynamics in healthy individuals [62]. These findings establish the medical value of EMS for maintaining basic physiological functions. In neurorehabilitation, Li et al. proposed combining electromyographic (EMG) signals with FES to improve motor recovery in stroke patients, showing that this “bio-signal-driven plus external stimulation” model was more effective for restoring motor function [63]. Similarly, Fu et al. demonstrated through experimental research that EMS can accelerate functional recovery following nerve injury [64]. More importantly, recent studies in neuroscience have revealed the relationship between EMS and neural plasticity. Carson et al. showed that combining external stimulation with voluntary motor intent can induce adaptive changes in the motor cortex, thereby facilitating motor learning and cortical reorganization [65]. In addition, Gondin et al. confirmed that electrical stimulation training has positive effects on neural drive and muscle structure [66]. This mechanism provides a scientific explanation for the long-term effects of EMS and establishes a theoretical foundation for its extension from rehabilitation medicine to skill learning and performance optimization.

In behavioral science and psychology, the focus has been on skill acquisition, cognitive regulation, and the influence of emotional states on task performance. Motor learning theory suggests that the acquisition of motor skills typically depends on iterative adjustments in perception–action mapping and the gradual consolidation of stable motor memory through feedback. The integration of EMS into this process can provide additional external signals, thereby reducing trial-and-error costs and accelerating the formation of correct movement patterns. For instance, Kasahara et al. demonstrated that maintaining user autonomy during EMS-based training not only improved the learning experience but also reduced reaction times once EMS was removed, highlighting the importance of balancing external stimulation with voluntary control [34]. Beyond skill learning, EMS has also been investigated as a medium for communication and infor-

mation transfer. Dingler et al. introduced the concept of EMS Icons, where muscle stimulation conveys analogical signals to help users understand and execute commands more efficiently [67]. This illustrates how EMS can function not only as a tool for motor guidance but also as a channel for communication and cognitive cues. Furthermore, psychological studies emphasize the role of emotions and physiological states in performance. Hoolahan et al. reported that combining EMS with virtual reality influenced users' emotional experiences and significantly affected both effort levels and muscle fatigue [68]. Similarly, Harvey et al. noted that functional electrical stimulation can generate psychological benefits in both rehabilitation and experimental settings, including increased motivation, improved concentration, and reduced anxiety [69]. Together, these findings suggest that EMS can serve as a body-level intervention that influences cognition and emotional states either directly or indirectly through its integration with physiological and psychological processes.

Building on these multidisciplinary findings, the present research positions itself as an effort to integrate engineering, medicine, and behavioral science within a unified framework oriented toward human augmentation. Unlike traditional HCI, which emphasizes usability of interfaces and devices, this research focuses on how EMS can directly expand users' capability boundaries at the bodily level. Within this process, engineering and computing provide the technical implementation through hardware and algorithms, medicine elucidates the physiological mechanisms and safety boundaries, behavioral science explains the psychological processes of learning and regulation, and HCI supplies the methodological and application-oriented design context.

Therefore, the positioning of this dissertation can be summarized as follows: grounded in the technical implementations of computer science and engineering, and informed by physiological mechanisms from medicine and learning models from behavioral science, it establishes an interdisciplinary framework for EMS-based augmented human-computer interaction. Through this framework, the dissertation aims to explore how EMS can contribute to skill acquisition, coordination enhancement, and emotional regulation, thereby providing new research directions and application practices for Augmented HCI.

Chapter 3

Research Scope and Methodological Framework

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3.1 Research Scope and Positioning

The overarching goal of this research is to explore the potential of Augmented HCI through the application of EMS, and to propose and validate an interdisciplinary research framework with EMS at its core. In traditional HCI research, the primary focus of system design has been on improving interface usability and interaction efficiency, while the user's body and abilities have often been regarded as fixed boundary conditions. However, with the emergence of the concept of Human Augmentation, the scope of HCI has expanded to include how technology can directly alter and enhance human capabilities. Building on this shift, the present study seeks to clarify the role of EMS in augmenting human skills and regulating physiological states, and to establish a corresponding theoretical and practical framework.

The scope of this research can be defined in several dimensions. First, at the technical

level, it focuses on the application of non-invasive EMS, employing surface electrodes and low-intensity currents to stimulate specific muscle groups. Unlike implantable neural stimulation or clinical applications of FES, the EMS systems developed in this research are designed for experimental and interactive scenarios with ordinary users, emphasizing wearability, programmability, and everyday usability rather than long-term therapeutic objectives in clinical rehabilitation. Second, with regard to research participants, the study primarily involves healthy individuals and examines the role of EMS in skill acquisition, hand-eye coordination, fine finger control, and the regulation of emotions and physiological states. The experimental contexts include training games, musical instrument practice, and task performance under stress, demonstrating the generalizability and adaptability of EMS across different task domains.

In terms of disciplinary positioning, this research is inherently interdisciplinary. Computer science and engineering provide the hardware architecture and signal control methods necessary for stable and adjustable EMS operation. Medicine and neuroscience contribute theoretical insights into muscle contraction, neural plasticity, and physiological regulation, revealing how EMS can influence human functions in both short- and long-term dimensions. Behavioral science and psychology supply models and explanatory frameworks for skill learning and emotional regulation, enabling the experimental results to be situated within broader contexts of motor learning and cognitive regulation. By integrating findings across these fields, this study emphasizes not only technical feasibility, but also the combined outcomes of user experience, learning performance, and psychological well-being.

Therefore, the positioning of this dissertation can be summarized as follows: under the technical conditions of non-invasive EMS, it investigates the role of EMS in augmenting perceptual-motor ability, coordination, and physiological regulation, and proposes an interdisciplinary framework for augmented human-computer interaction. Through this positioning, the dissertation both responds to the broader shift in HCI from interface design to human augmentation, and provides theoretical and empirical foundations for the future application of EMS in domains such as education, entertainment, rehabilitation, and psychological intervention.

3.2 Conceptual Framework for EMS-Based Augmented HCI

Within the field of Augmented HCI, EMS is distinctive in its ability to directly intervene at the bodily level, influencing both motor execution and physiological regulation. Unlike conventional interaction modalities that rely primarily on visual, auditory, or tactile cues, EMS applies electrical stimulation to targeted muscle groups, thereby functioning simultaneously as an action cue, a means of motor induction, and a potential pathway for modulating physiological and affective states.

To systematically describe the role of EMS in human augmentation, this study proposes a conceptual framework (Fig. 3.1) consisting of three core dimensions: Sensorimotor Augmentation, Coordination Augmentation, and Affective and Physiological State Augmentation.

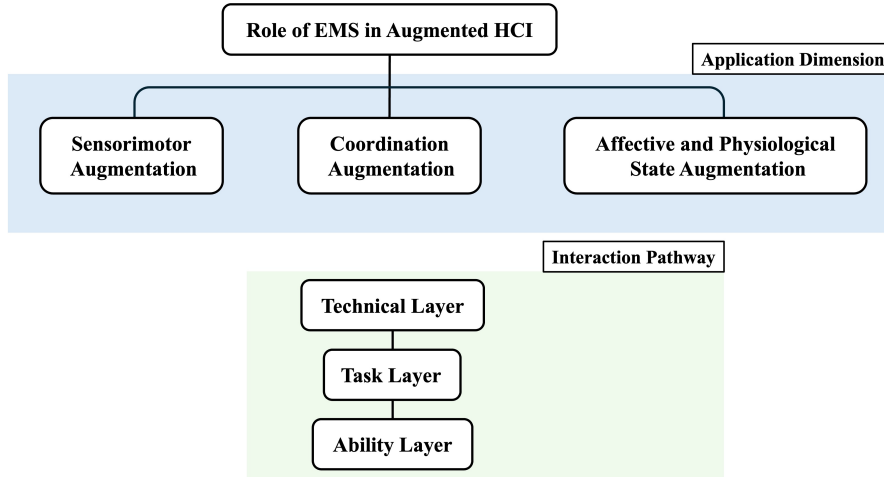


Figure 3.1: A conceptual framework for EMS-based Augmented HCI.

The first dimension, Sensorimotor Augmentation, emphasizes the enhancement of motor precision, timing, and reaction speed. This dimension addresses how EMS can provide immediate bodily-level feedback that facilitates the acquisition of accurate motor patterns and reduces the reliance on repetitive trial-and-error.

The second dimension, Coordination Augmentation, focuses on complex multi-limb and perceptual-motor tasks that require the integration of multiple channels of information. By providing targeted stimulation at critical moments, EMS has the potential to support users in establishing more efficient coordination across body parts, thereby

accelerating the process of mastering complex motor interactions.

The third dimension, Affective and Physiological State Augmentation, highlights the regulation of performance under conditions of stress, fatigue, or high cognitive load. EMS, when combined with physiological signals such as heart rate or respiration, can be explored as a bodily-level intervention to help stabilize users' internal states, enabling more consistent performance across demanding contexts.

Based on these three dimensions, this research proposes a three-layer integrative framework that articulates the pathways through which EMS contributes to Augmented HCI. At the technical layer, EMS hardware systems, stimulation parameters, and safety mechanisms provide the foundation for reliable application. At the task layer, EMS is embedded within interactive contexts that serve as platforms for testing and validation. At the ability layer, the ultimate focus lies in the augmentation of human capacities such as motor precision, coordination, and emotional or physiological regulation. This layered framework allows EMS to be conceptualized not merely as a technical intervention, but as a bridge between engineering design and the expansion of human capability.

In summary, this conceptual framework positions EMS as a multidimensional augmentation tool that operates across sensorimotor, coordinative, and affective domains. By situating EMS within a structured theoretical model, the dissertation establishes the foundation for subsequent empirical studies that will examine its feasibility and effectiveness in practice.

3.3 Methodological Approach

To systematically investigate the potential of EMS in Augmented HCI, this study constructs a multi-layered methodological framework (Fig. 3.2). This framework integrates experimental design, system development, interdisciplinary theoretical grounding, and multimodal data analysis, ensuring progress in both technological feasibility and the enhancement of human capabilities.

First, in terms of experimental design, the study employs a combination of controlled and multifactorial approaches. By setting conditions with and without EMS, performance differences can be compared to identify the role of stimulation in learning

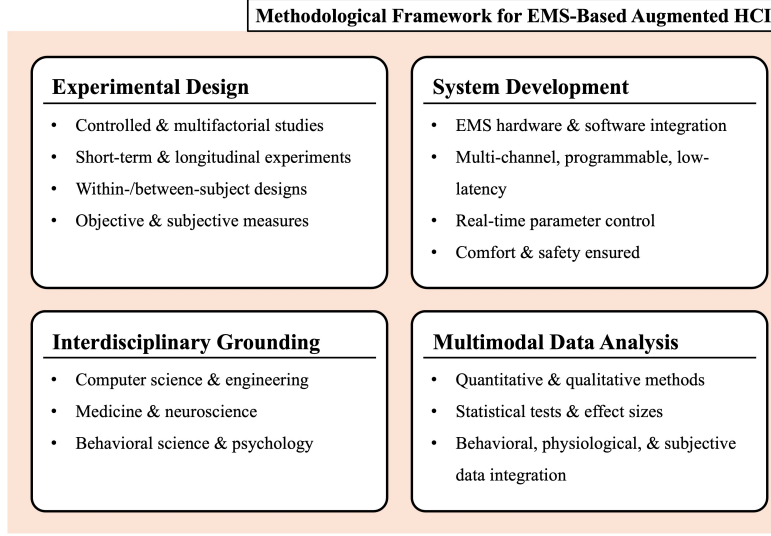


Figure 3.2: Methodological framework for EMS-based Augmented HCI.

efficiency, coordination, and state regulation. The experiments include both short-term studies, which focus on the immediate impact of stimulation, and longitudinal studies, which examine retention and transfer effects over time. Both within-subject designs (the same participants tested under different conditions) and between-subject designs (different groups tested under distinct conditions) are applied to increase statistical power and interpretability. In all experiments, objective measures (e.g., accuracy, timing, physiological signals) are collected alongside subjective assessments (e.g., perceived effort, fatigue, stress levels), ensuring a comprehensive evaluation of EMS effects.

Second, in terms of system development, this research builds multiple EMS-enabled interactive systems. On the hardware side, the systems are based on commercial stimulation devices, supplemented by customized electrodes, relay modules, and control circuits to achieve multi-channel, programmable, and low-latency outputs. Special emphasis is placed on electrode material conductivity, comfort, and safety to ensure stable performance during extended use. On the software side, real-time communication interfaces are implemented to control stimulation parameters (e.g., current intensity, pulse frequency, pulse width) and embed EMS into interactive task environments. The integration of hardware and software creates an extensible platform that enables EMS to be adapted across diverse experimental contexts and task types.

Third, from an interdisciplinary perspective, this study draws upon insights from

computer science and engineering, medicine and neuroscience, as well as behavioral science and psychology. Computer science and engineering contribute system architecture and signal control mechanisms, ensuring safety and repeatability. Medicine and neuroscience provide theoretical foundations regarding muscle contraction, neural plasticity, and the physiological effects of stimulation, defining safe operating ranges for EMS. Behavioral science and psychology offer models of skill acquisition, motor learning, and affective regulation, which serve as interpretive frameworks for experimental results. For example, motor learning theories explain how EMS may reduce trial-and-error processes to accelerate the formation of correct movement patterns, while affective regulation theories help interpret EMS effects on stress and anxiety. Through this integration, the study ensures both scientific rigor in experiment design and theoretical depth in result interpretation.

Finally, in terms of data analysis, the study combines quantitative and qualitative methods. Quantitative analysis includes a range of statistical techniques, such as t -tests, one-way and multifactorial ANOVA, mixed-design ANOVA, and non-parametric tests (e.g., Wilcoxon signed-rank test, Mann–Whitney U test), to compare differences across conditions. Effect size measures (Cohen’s d , η^2 , partial η^2) are used to assess the magnitude of EMS effects. In longitudinal experiments, repeated measures and post-hoc comparisons are applied to evaluate retention and learning trajectories. Qualitative analysis is conducted through questionnaires and semi-structured interviews to capture subjective experiences of EMS use, with responses coded and categorized using content analysis. Additionally, multimodal data integration is employed by comparing behavioral performance data (e.g., task outcomes), physiological signals (e.g., heart rate, EMG), and subjective reports, enabling a comprehensive understanding of EMS effects.

In summary, this methodological framework integrates four complementary dimensions: experimental design, system implementation, interdisciplinary theoretical grounding, and multimodal data analysis. It not only ensures the technical feasibility and scientific rigor of the research, but also provides a systematic foundation for exploring the augmentation potential of EMS within an interdisciplinary context. This framework establishes the methodological basis for the empirical studies presented in subsequent chapters.

3.4 Research Questions Revisited

In Chapter 1, this dissertation introduced several core research questions aimed at exploring the potential of EMS in Augmented HCI. Building on the research scope, conceptual framework, and methodological approach outlined in this chapter, these questions are revisited and further refined to provide a clear roadmap for the subsequent empirical studies.

RQ1 Can EMS effectively enhance skill acquisition efficiency through direct muscular stimulation, and can such effects be retained over time?

This question addresses the *sensorimotor dimension*, focusing on how EMS may accelerate the acquisition of motor skills and support retention beyond immediate training.

RQ2 Can EMS facilitate coordination in complex multi-limb and perceptual-motor tasks?

This question concerns the *coordination dimension*, examining whether EMS can help users establish more efficient mappings across multiple actions or modalities, thereby improving overall coordination.

RQ3 Can EMS, in combination with physiological signals, contribute to the regulation of emotional and physiological states, thereby improving performance under demanding conditions?

This question pertains to the *affective and physiological dimension*, exploring whether EMS can act as an intervention mechanism to stabilize user performance under stress or high workload.

RQ4 How can EMS systems balance augmentation benefits with user agency, safety, and ethical considerations?

This cross-cutting question applies across all dimensions, addressing the boundaries of EMS use in practice. It focuses on issues such as autonomy, personalization of stimulation parameters, long-term usability, and the broader ethical responsibilities of applying augmentation technologies.

In summary, these four research questions correspond to the three augmentation dimensions identified in this study, together with an overarching inquiry into ethical and practical constraints. They form the guiding structure for the empirical investigations that follow, ensuring that the dissertation systematically addresses both the possibilities and limitations of EMS in Augmented HCI.

3.5 Chapter Summary

This chapter has systematically elaborated on the scope of the study, the conceptual framework, the methodological foundation, and the core research questions. First, in the section on research scope and positioning, the dissertation clarified its focus on the application of non-invasive EMS, emphasizing its potential in skill acquisition, coordination enhancement, and affective regulation, while delineating its boundaries from clinical rehabilitation research. Second, in the conceptual framework, the dissertation proposed a three-dimensional model of EMS-based Augmented HCI—namely sensorimotor augmentation, coordination augmentation, and affective and physiological state augmentation—and further established a three-layer structure comprising the technical layer, the task layer, and the ability layer, to systematically explain how EMS can operate across different levels. Third, in the methodological section, the dissertation outlined the experimental research approach, system development strategies, interdisciplinary theoretical grounding, and multimodal data analysis techniques, ensuring that the study is both technically feasible and theoretically anchored in behavioral science, medicine, and engineering. Finally, this chapter revisited the four core research questions, addressing EMS in terms of skill acquisition efficiency and retention, coordination enhancement, affective and physiological regulation, as well as challenges concerning agency, safety, and ethics. These questions not only provide the logical backbone for the subsequent experimental designs but also establish the foundation for the integrated discussion of results.

Overall, this chapter has completed the transition from research background to research objectives and methodology, constructing the theoretical framework that underpins the entire dissertation. The following Chapter 4 will delve further into the technical details and methodological underpinnings of EMS, discussing its hardware systems, signal regulation mechanisms, efficiency modeling methods, and integration with interactive systems, thereby providing the technical foundation for the empirical studies that follow.

Chapter 4

Technical Foundations of the EMS-Based Interaction Platform

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4.1 Principles and Theoretical Foundations of EMS

EMS is a technique that induces muscle contraction by applying low-intensity pulsed currents to the skin surface. Its fundamental mechanism lies in activating motor nerves through external current, thereby eliciting action potentials and driving the corresponding muscles to contract [70]. Unlike voluntary movements, in which commands originate in the cerebral cortex and are transmitted via the spinal cord to peripheral nerves, EMS bypasses parts of the central nervous system and directly excites peripheral nerve endings, thus artificially controlling or assisting muscle activity. This externally driven mechanism makes EMS both a form of physiological intervention and a mode of interaction control.

At the neurophysiological level, the principle of EMS can be summarized as “membrane depolarization—action potential generation—muscle fiber contraction” [71]. When electrodes on the skin surface deliver a pulsed current of sufficient amplitude, the cur-

rent passes through skin, electrolytes, and tissue to reach motor nerve fibers, causing local membrane potential changes. Once this change exceeds the threshold, an action potential is generated and propagates along the axon to the neuromuscular junction, releasing acetylcholine to trigger muscle fiber contraction. Unlike the selective activation of motor units in voluntary movement, EMS relies on current diffusion in tissue and often activates a range of fibers in a relatively “synchronous” manner [72]. This leads to contraction dynamics that differ from voluntary contractions and can provide stronger, more immediate control in certain tasks.

Related technologies include Transcutaneous Electrical Nerve Stimulation (TENS) [73], Neuromuscular Electrical Stimulation (NMES) [74], Functional Electrical Stimulation (FES) [46], and Transcranial Direct Current Stimulation (tDCS) [75]. TENS is primarily used for pain relief by stimulating sensory nerves to block nociceptive transmission [76]; NMES emphasizes inducing muscle contractions for strength training or maintaining muscular function [77, 78]; FES is commonly applied in rehabilitation medicine, aiming to reproduce functional movements in daily activities [79, 80]; and tDCS applies low-intensity direct current to the scalp to modulate cortical excitability, thereby influencing cognition, emotion, and motor learning [81, 82]. By contrast, EMS is relatively easy to wear and operate, as it can be applied to limbs without the complex electrode arrangements required for head-mounted systems. At the same time, it acts directly on muscles and produces visible motor effects in a more intuitive manner. For this reason, the uniqueness of EMS in Augmented HCI lies not only in rehabilitation or simple muscle training, but in serving as an interaction medium that directly drives muscles to assist task execution, accelerate skill acquisition, or regulate physiological states.

From a signal perspective, EMS typically uses pulsed rather than continuous current to avoid tissue damage. Common parameters include current intensity, pulse width, pulse frequency, and waveform types. These parameters jointly determine the sensation, comfort, and effectiveness of stimulation, and are therefore central to system design. Rather than elaborating on specific ranges here, this dissertation provides a detailed discussion of parameter modulation mechanisms in Section 4.3.

Within the context of interactive systems, the theoretical foundation of EMS can be regarded as a “body-level interaction channel” [83]. Traditional HCI typically influences

user cognition and decision-making through visual or auditory cues, with the user then performing the action voluntarily. By contrast, EMS intervenes directly at the muscular level, providing immediate prompts or driving movement, thereby shortening the pathway from perception to execution. This characteristic gives EMS two distinct potentials: on one hand, it can serve as an assistive tool to accelerate skill learning and coordination pattern formation; on the other hand, it can act as an intervention mechanism to regulate user states when combined with physiological signals. In other words, EMS is not merely a physiological stimulation technique but an interaction mechanism that transforms technological signals into bodily actions.

In summary, the principles and theoretical foundations of EMS are built upon the neurophysiological mechanisms of action potentials while also relying on electrical engineering for signal parameterization and hardware design. Its uniqueness lies in bridging physiology and technology by directly acting on human muscles, making it a key enabler of Augmented HCI. The following sections examine the architecture of EMS systems, methods of signal regulation, and efficiency modeling, providing the technical foundation for subsequent empirical studies.

4.2 System Architecture of EMS

To apply EMS in the context of Augmented HCI, it is essential to construct a system architecture that is safe, controllable, and adaptable to multi-task scenarios. The core of an EMS system lies in transmitting external electrical signals stably to the target muscles, thereby enabling precise action cues or motor induction. Building on the physiological principles outlined above, this dissertation adopts a modular architecture consisting of four main components: the power supply and signal generation module, the control unit, the electrodes and connection structures, and safety and adaptation mechanisms (Fig. 4.1).

The power supply and signal generation module provides stable current output for the entire system. Common commercial EMS devices include products designed for medical rehabilitation (for example, Omron’s low-frequency therapy series [84], widely used for pain relief and post-surgical rehabilitation) as well as those for sports and

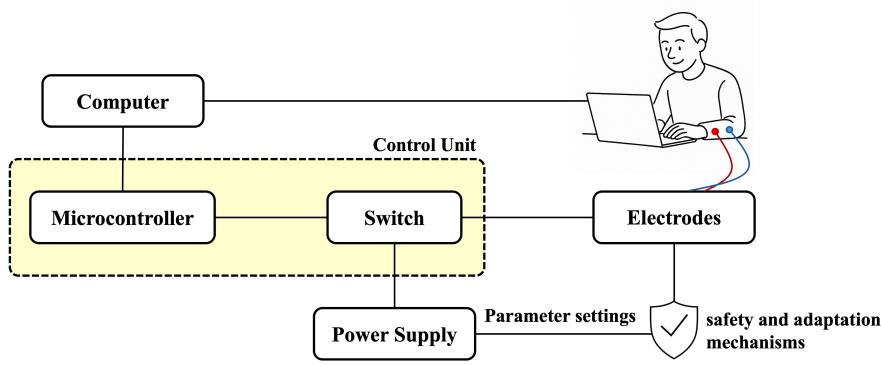


Figure 4.1: System architecture of the EMS system for Augmented HCI, consisting of a power module, control unit, electrodes, and safety mechanisms, ensuring stable signal transmission and adaptive stimulation control.

fitness (for example, the PowerDot series [85], targeted at athletes and fitness users for muscle stimulation and recovery training). These devices deliver low-intensity pulsed signals, often with multi-channel configurations that are suitable for research requiring independent stimulation of both hands or multiple fingers. In research-oriented systems, voltage-controlled pulse generation circuits are typically employed, with parameters such as pulse width, frequency, and current intensity adjustable to achieve precise control over stimulation strength and sensory levels. To avoid tissue damage, symmetric biphasic rectangular waveforms are commonly used to ensure charge balance.

The control unit manages the timing and programmable execution of stimulation signals. Microcontrollers such as Arduino UNO [86], ESP32 [87], and M5Stack [88] are used to control relays or electronic switches through digital signals and to interface with higher-level interactive systems via serial connections or wireless communication. This enables real-time data exchange with applications such as game programs or sensor platforms (e.g., eye tracking, heart rate monitoring), forming the basis for event-driven control strategies that are further detailed in Section 4.5.

The electrodes and connection structures represent the interface between the EMS system and the user's body. Surface electrodes are typically made of conductive gel or conductive fabric, attached to the skin to reduce contact resistance and ensure effective current delivery to target muscle groups. For hand-related tasks, common electrode placement includes the flexor digitorum profundus, flexor digitorum superficialis, and

forearm extensors, which are directly responsible for finger flexion, extension, and hand movements. The size and placement of electrodes significantly affect stimulation outcomes: larger electrodes cover broader muscle areas but reduce precision, while smaller electrodes allow more localized control but require careful adjustment of current intensity and placement accuracy. To accommodate diverse experimental needs, this research also explored wearable textile-based electrodes made of conductive fibers, enabling more convenient use of EMS in long-duration or multi-user contexts.

The safety and adaptation mechanisms are indispensable components of the EMS system. Since individuals vary in skin impedance, muscle sensitivity, and current tolerance, the system must support personalized parameter adjustment. In practice, a threshold test is conducted prior to experiments to determine the lowest intensity that induces clear muscle contraction without discomfort, which is then used as a reference for training parameters. Furthermore, the system includes automatic shutdown and protection features, such as interrupting output in the event of electrode detachment or abnormal current, to prevent unintended stimulation. These hardware-level safety measures are complemented by interaction-level mechanisms discussed in Section 4.5.

In summary, the design goals of an EMS system architecture extend beyond electrical signal generation and transmission to ensuring stimulation safety, controllability, and adaptability. Through the stable output of the power and signal generation module, the programmable flexibility of the control unit, the rational design of electrode structures, and the implementation of multi-layered safety mechanisms, EMS systems can support a wide range of applications, from skill learning to emotional regulation. This architecture establishes the technical foundation for subsequent research on signal regulation mechanisms, stimulation efficiency modeling, and integration with interactive systems.

4.3 EMS Signals and Parameter Modulation

EMS performance depends not only on system hardware and electrode placement, but also critically on the parameter settings of the stimulation signals. Variations in current intensity, pulse width, frequency, and waveform directly affect the recruitment of nerve fibers, muscle contraction characteristics, and user perception (Table 4.1). Therefore, the

scientific adjustment of EMS signal parameters is key to achieving effective, comfortable, and safe stimulation. This section systematically explains the major parameters and their modulation mechanisms.

Table 4.1: Major EMS signal parameters and their modulation characteristics (minimal version)

Parameter	Typical Range	Main Effects
Current	1–10 mA	Activation depth
Voltage	0–20 V	Output regulation
Pulse Width	50–500 μ s	Fiber recruitment
Frequency	1–100 Hz (20–40 Hz typ.)	Contraction rhythm
Waveform	Monophasic / Sym. Bi / Asym. Bi	Comfort balance

Current Intensity. Current intensity determines the number and depth of nerve fibers activated by stimulation. In general, low-intensity currents (1–3 mA) only induce mild sensations or superficial muscle contractions, while higher currents (5–10 mA or above) can recruit larger ranges of muscle fibers, producing more pronounced motor output. Because skin and tissue resistance varies significantly between individuals, commercial EMS devices typically provide an output voltage range of 0–20 V, with current intensity adjusted to accommodate different user needs. In experimental settings, a threshold test is performed to determine the lowest current capable of eliciting clear muscle contraction without discomfort, and this value is then used as the basis for subsequent training.

Pulse Width. Pulse width typically ranges from 50–500 μ s and directly influences the spatial recruitment of nerve fibers and the perceived stimulation intensity. Shorter pulse widths ($\leq 100 \mu$ s) primarily stimulate large-diameter fibers, often producing sharper sensations with limited contraction, while longer pulse widths (200–400 μ s) can activate a broader range of fibers, resulting in stronger contractions. Excessively long pulse widths may cause unnecessary pain or fatigue, thus requiring adjustment according to task demands. For fine motor training (e.g., finger control), moderate pulse widths (around 200 μ s) are commonly adopted to provide stable cues while maintaining comfort; for larger motor tasks or strength training, longer pulse widths may be used to enhance contraction effects.

Stimulation Frequency. Frequency determines the temporal characteristics of muscle contraction. At low frequencies (1–10 Hz), muscles exhibit discrete twitches, suitable for rhythmic training or light cues. At mid-range frequencies (20–40 Hz), contractions begin to fuse into sustained tension (tetanic contraction), appropriate for posture holding and functional training. At higher frequencies (≥ 50 Hz), contractions become stronger and smoother, but the risk of muscle fatigue and discomfort also increases. Thus, in skill training and interactive applications, mid-range frequencies of 20–40 Hz are typically chosen as a compromise, allowing effective cues under relatively comfortable conditions.

Waveform Type. Waveform characteristics also significantly influence user experience. Common EMS waveforms include monophasic rectangular pulses, symmetric biphasic pulses, and asymmetric biphasic pulses. Among these, symmetric biphasic waveforms achieve charge balance within each cycle, reducing skin irritation and electrochemical reactions, and are therefore most commonly used in research and practice. Asymmetric biphasic waveforms allow different charge distributions in each phase, enabling more fine-grained control of fiber recruitment. In augmented interaction applications, biphasic rectangular waveforms are generally adopted as a standard setting to balance effectiveness and safety.

In practical use, parameter adjustment must also account for individual differences and task requirements. Due to variability in skin impedance, muscle thickness, and sensitivity, fixed parameters cannot ensure universal applicability. This study adopts an “individualized threshold calibration” approach, in which the minimal perceptual threshold and the minimal contraction threshold are identified for each participant prior to experiments, and training parameters are then set relative to these values. With respect to task requirements, fine motor control demands lighter stimulation to avoid interfering with voluntary actions, whereas rhythm or reaction training can employ stronger stimulation to provide clear motor guidance.

In summary, the modulation of EMS signal parameters is central to its function in Augmented HCI. By appropriately configuring current intensity, pulse width, frequency, and waveform, and combining these with individualized calibration and task adaptation, EMS can achieve multi-level augmentation effects while ensuring safety and comfort. This provides the foundation for subsequent modeling of stimulation efficiency

and integration with interactive systems.

4.4 Modeling and Computation of Stimulation Efficiency

In applications of Augmented HCI, the effectiveness of EMS depends not only on electrode placement and signal parameters, but also on current conduction efficiency, tissue resistance properties, and electrode–skin interface conditions. To better understand and optimize the role of EMS in different tasks, this study proposes a modeling framework for stimulation efficiency (Stimulation Efficiency, ε).

From a physical perspective, the process of EMS can be simplified as “current flows from the electrode, passes through skin and tissue, and ultimately acts on target nerves and muscle fibers.” In this process, stimulation efficiency ε can be defined as the proportion of input electrical power that is effectively absorbed by biological tissue and induces neuromuscular responses. Its basic expression is:

$$\varepsilon = \frac{P_{\text{eff}}}{P_{\text{in}}} \quad (4.1)$$

where P_{in} denotes the electrical power output from the device, and P_{eff} represents the portion effectively utilized by the neuromuscular system. Expanding this definition gives:

$$\varepsilon = f(I, V, T_p, f_r, A, \eta_c, H) \quad (4.2)$$

where the parameters are defined as shown in Table 4.2.

Table 4.2: Parameters and Symbols in EMS Output Model

Symbol	Description
I	Output current (mA)
V	Output voltage (V)
T_p	Pulse width (μs)
f_r	Pulse frequency (Hz)
A	Electrode–skin contact area (cm^2)
η_c	Electrode material efficiency (dimensionless, $0 \leq \eta_c \leq 1$)
H	Skin humidity factor (dimensionless, $0 \leq H \leq 1$)

Here, η_c and H are introduced as dimensionless empirical scaling factors to capture the effects of electrode material properties and skin conditions, rather than as strictly measured physical quantities.

The input energy per pulse E_p can be expressed as:

$$E_p = V \cdot I \cdot T_p \quad (4.3)$$

At a stimulation frequency of f_r , the input power per unit time is:

$$P_{\text{in}} = E_p \cdot f_r = V \cdot I \cdot T_p \cdot f_r \quad (4.4)$$

Considering electrode contact efficiency and skin conduction properties, the effective power can be approximated using a simplified multiplicative model as:

$$P_{\text{eff}} = P_{\text{in}} \cdot \frac{A}{A + R_s} \cdot \eta_c \cdot H \quad (4.5)$$

where R_s denotes an equivalent area constant related to skin impedance. Finally, stimulation efficiency can be written as:

$$\varepsilon = \frac{P_{\text{eff}}}{P_{\text{in}}} = \frac{A}{A + R_s} \cdot \eta_c \cdot H \quad (4.6)$$

This formula indicates that, under identical settings of current, pulse width, and frequency, EMS efficiency is primarily influenced by electrode contact area, electrode material, and skin humidity (Fig. 4.2). The larger the contact area, the higher the conductivity, and the more hydrated the skin, the greater the efficiency. This result aligns with empirical observations: when electrodes are loose, poorly attached, or the skin is dry, identical output parameters often fail to induce effective muscle contraction.

Although the above model is simplified, it highlights the multi-factor coupling characteristics of EMS effects. Based on this model, the present study adjusts stimulation parameters such as current intensity, pulse width, and frequency according to these physical relationships, and further evaluates and validates their effects through subsequent empirical experiments.

In summary, the modeling of EMS stimulation efficiency provides a theoretical foun-

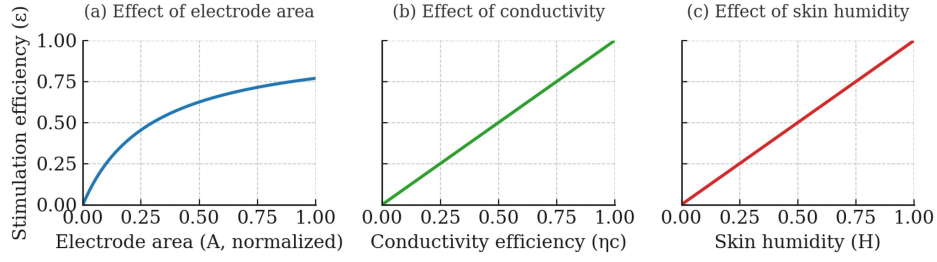


Figure 4.2: Effects of electrode area, conductivity, and skin humidity on stimulation efficiency. (a) When other conditions are constant, increasing the electrode area (A) enhances stimulation efficiency, but the improvement gradually saturates as the area becomes larger, due to the asymptotic behavior introduced by the skin impedance term R_s . (b) When other conditions are constant, higher electrode conductivity (η_c) results in greater stimulation efficiency, showing an approximately linear relationship that follows directly from the definition of η_c as a normalized conductivity scaling factor in the model. (c) When other conditions are constant, higher skin humidity (H) leads to higher stimulation efficiency under the assumed linear scaling of H , indicating that hydrated skin facilitates current conduction.

dation for understanding current conduction processes and guiding parameter optimization. This framework serves not only as a conceptual basis for the physical modeling of EMS but also as a reference for experimental parameter tuning in the later studies discussed in this dissertation.

4.5 Integration of EMS with Interactive Systems

The application of EMS in Augmented HCI depends not only on the hardware devices themselves but also on effective integration with interactive systems. EMS can fully realize its augmentation potential only when it is tightly coupled with task contexts, sensor inputs, and real-time feedback mechanisms. In this research, integration methods for EMS and interactive systems were designed across multiple experimental scenarios, focusing on four main aspects: interface design, real-time control, cross-modal integration, and safety and ethical mechanisms.

In terms of interface design, EMS devices must achieve low-latency communication with interactive systems. Building on the microcontroller-based architecture described in Section 4.2, Arduino, ESP32, and M5Stack boards were employed as intermediate control

units, establishing communication with higher-level software (e.g., Python programs, game engines) via serial, Bluetooth, or Wi-Fi connections. In this way, critical events in interactive tasks (such as target appearance, keypress signals, or changes in heart rate) can trigger EMS output within milliseconds using an event-driven protocol. For instance, in a shooting task, when a target appears, the system immediately sends a trigger signal to the microcontroller, which then applies a short pulse to the relevant finger, forming an action cue.

In terms of real-time control, EMS must remain synchronized with the user’s motor intentions; otherwise, it may cause dissonance or interfere with the interaction experience. To address this, event synchronization and latency calibration were implemented. Before the start of an experiment, the input–output delay of the system (e.g., the time gap between target display and EMS trigger) was measured and calibrated to ensure that stimulation occurred within the task-appropriate temporal window. For tasks requiring multiple sequential stimulations (e.g., rhythm training), stimulation sequences were pre-computed according to task frequencies, thereby avoiding runtime communication jitter that could lead to timing shifts.

In terms of cross-modal integration, EMS often needs to work in coordination with other sensors and feedback channels. For example, in stress regulation experiments, heart rate sensors were used to monitor the user’s physiological state in real time; when an elevated heart rate was detected, EMS was applied to respiratory muscles to help restore stability. In hand–eye coordination experiments, eye tracking was used to determine the distribution of visual attention, while EMS provided bodily guidance when attention shifts were required. In this manner, EMS functioned not as an isolated stimulation device, but as a component of a multimodal interactive system operating alongside visual, auditory, and haptic feedback.

In terms of safety and ethical mechanisms, EMS integration must carefully balance user experience with risk management. In addition to the hardware-level protections described in Section 4.2, interaction-level measures were incorporated, including providing an emergency stop button to allow users to interrupt stimulation at any time and gradually adjusting parameters during long-term use to prevent fatigue or discomfort. Furthermore, during system design, the principle of “augmentation rather than

replacement” was followed, whereby EMS served only as an assistive cue or guidance mechanism rather than fully replacing voluntary user actions, thereby ensuring user agency and sense of control.

In summary, the integration of EMS with interactive systems goes beyond technical interfacing, encompassing task design, real-time synchronization, cross-modal collaboration, and the balance of safety and ethics. Through these integration methods, this research demonstrated the application of EMS in diverse interactive contexts such as game training, musical instrument learning, and emotion regulation, providing a transferable framework and practical insights for the design of future Augmented HCI systems.

Chapter 5

Sensorimotor Augmentation

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5.1 Overview of Sensorimotor Augmentation

Within the research framework of Augmented HCI, the enhancement of sensorimotor abilities represents the most fundamental and critical dimension. To accomplish any

interactive task, humans must rapidly and accurately map perceptual information from the external environment to bodily actions. From simple clicking and keypress operations to the mastery of complex professional skills, the efficiency of sensorimotor coordination directly determines user performance. However, traditional skill training often relies on extensive repetition and long-term accumulation. Such processes are inefficient and prone to the development of erroneous movement patterns during the early stages of learning, thereby increasing the difficulty of skill acquisition.

EMS, by directly acting on human muscles, can provide immediate action cues or actuation at the millisecond level. This unique characteristic makes it highly suitable for improving two key aspects of sensorimotor coordination: the timing of actions and the precise control of finger movements. First, EMS can guide users to perform the appropriate action at the exact moment a target appears, thereby helping them form correct response patterns in a shorter period of time. Second, EMS can stimulate hand or finger muscles to assist users in executing fine and rapid movements, thus improving both precision and speed. These mechanisms establish the theoretical basis for EMS applications in the enhancement of sensorimotor abilities.

This chapter validates the effects of EMS on sensorimotor enhancement through two empirical studies. The first study examines the role of EMS in action timing training, focusing on whether it enables users to more quickly acquire timing skills in a shooting game context. The second study investigates finger control, testing whether EMS can improve speed and accuracy in fine motor tasks while also evaluating the retention of training effects. Together, these studies aim to address the following questions: Can EMS significantly improve user performance at the sensorimotor level, and can such improvements be maintained in both the short and long term?

5.2 EMS-Based Training for Timing Control

Based on “Method of Electrical Muscle Stimulation for Training FPS Game Players in the Timing of Shots.” – Zhou and Segawa, Proc. ACM Hum.-Comput. Interact. (CHI PLAY 2023)

In first-person shooter (FPS) games, accurate shot timing is a critical skill, yet casual players often require extensive training to master it. Traditional practice methods are time-consuming and limited by experience and equipment. EMS can directly stimulate the relevant muscles, providing immediate cues at the motor level and accelerating the formation of correct response patterns. This section introduces an EMS-based training method for shot timing and evaluates its effectiveness through empirical study.

5.2.1 Introduction

With the advancements in computer hardware, entertainment computing has grown rapidly and has become a large-scale industry and a research field [89]. Games are an important part of this industry. In recent years, an increasing number of players have participated in e-sports entertainment events and competitions. Although the e-sports category is not considered a sport in the traditional sense, it has a large user base and business value [90, 91]. As a part of e-sports, FPS games are extremely competitive and playable, and many players devote their time and energy to them. For players, control and experience in the game are important, as these elements directly affect their score in the game. The following factors can affect their gaming experience: the frame rate and resolution [92, 93, 94], the delay and instability caused by the network environment [95], and using a head-up display for the game interface [96]. A study [97] showed that bullet magnetism and area cursors can assist players in FPS games and optimize their gaming experience. Players’ emotions in FPS games tend to change with the situation, and for these changes, bio-information can be obtained and analyzed using sensors [98, 99]. Several studies have shown that using this bio-information can also optimize the gaming experience to some extent [100, 101]. In FPS games, there may be considerable difference in skill levels between hobby and professional players, which also affects their gaming experience. Average or novice players often do not enjoy their gaming experience because

of a lack of skills [102]. To enhance the in-game control and compensate for the lack of experience, players often need to spend time improving their game skills [103]. According to [104], game control can be enhanced by developing a flexible mindset that enables players to react quickly and effectively during a game.

The current mainstream approach is to improve the player’s control and optimize the gaming experience by using professional gaming devices (such as gaming mice, keyboards, and displays). When correctly configured, these devices can compensate to some extent for a player’s lack of gaming skills and optimize the control of the game. Various training software for FPS games [105] have powerful features for situational simulation and customization, and players can improve their gaming skills by training repeatedly using such software. However, the following problems still need to be solved: (1) Improving shooting skills in FPS games through repeated training takes a long time. (2) Although training software exists, it is difficult for players to understand the training method and summarize the experience gained during the training, and strengthen their skills without a coach.

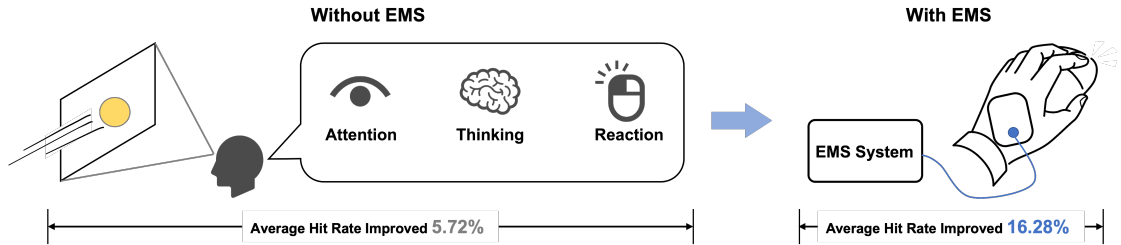


Figure 5.1: Quick and effective EMS training method to improve hit rates on moving targets in FPS games. To shoot at a moving target in first-person shooter (FPS) games, the brain usually needs to perform a series of information-processing tasks and provide feedback to drive the muscles to perform the action. The process is as follows: (1) Identifying the target. (2) Calculating the best time to shoot. (3) Determining and reacting to the shot. In this study, we constructed a system that uses EMS to drive finger movements as a proxy for this process. We believe that using this EMS system for shooting timing training can quickly improve the hit rate.

Here, we propose a new method of training players for FPS games. We constructed an EMS-based shooting system (Fig. 5.1) to automatically calculate the timing of a shot when the player encounters a moving target. When the system determines that the target can be hit, it stimulates the player’s hand muscles to respond using EMS to shoot

the target. The training method repeats the process under certain rules to strengthen the player's muscle memory. Hence, the players can gradually master the timing of shooting the moving targets and enhance their control skills for FPS games.

Our goal is to train players for FPS games using an EMS-based system that can improve their game control and gaming experiences. It is noteworthy that the proposed method is not intended to replace other training methods. A training method using EMS should be used as a complementary method to FPS training.

5.2.2 Related Work

Our approach is based on understanding the human perception of motion. To explain our training method, we examine several aspects of motion perception, the definition of training, and the use of EMS.

Sensorimotor

Human motion perception is based on a complex sensorimotor system [106]. Johansson et al. analyzed hand-eye coordination by asking participants to reach for and move a bar to press a target switch [107]. When people interact with an object, they support hand movements by visually marking key locations of the object and then invoking parts such as fingers to point to these marked locations for movement. Hand-eye coordination requires adequate support in motion perception. Similarly, the process of grasping objects based on haptic feedback also relies on motion perception [108]. The sensorimotor system plays an important role in human interactions with target objects through visual, tactile, and auditory feedback, and we seamlessly acquire information and adjust our physical movement and body posture accordingly in both ordinary and trained or skilled movements. Based on this sensorimotor system, we can respond correctly to relatively complex motor environments.

Definition of training

Training is the act of accumulating experience through practice to achieve a certain goal. Lachman [109] defined this process as one in which learning is a relatively stable modification of the stimulus-response relationship as a result of functional environmental

interactions through the senses. Krakauer and Mazzoni [110] showed that human senses can be trained and that through learning, we can reduce the false predictions of our senses. The human primary motor cortex (M1) displays mirror activity in response to movement observation, is capable of forming motor memories, and is involved in motor learning [111]. We can train the movement by repeating the same process, and when the training is over, an after-effect is created, which retains the effect of our training [106]. FPS games are highly competitive e-sports and require coordination of physical functions, sensory awareness, and other aspects to control and win the game. Nagorsky and Wiemeyer demonstrated the importance of coordination training in e-sports, which is highly correlated with players' motion perception and plays an important role in the ability to control one's body and limbs well and to predict and complete movements during a game [112]. Ersin et al. [113] showed that the player perception and reaction speed in the visual and auditory senses are highly correlated with time spent on the game. Therefore, it is indispensable for players to train their senses. Proper training enables them to accumulate more sensory experience and have a better perception of the game for a better gaming experience [114]. [115] showed that the use of tDCS (transcranial direct current stimulation) could improve the player's judgement of head fakes in basketball in order to improve the player's perception of the action during the game. This further demonstrates the possibility of using external stimulation to train the player's in-game motion perception.

Advantages of EMS

Compared to the traditional actuation of robot arms [116] or exoskeletons [117], EMS devices tend to be more convenient to wear and smaller and easier to use. At first, EMS was commonly used as a treatment for the rehabilitation of patients with motor disabilities or to support patients with physical deficits [118]. With the expansion of EMS-related research, recent studies focused on the use of EMS for interaction and expansion of body functions. Takahashi et al. [119] achieved more flexible finger movements through EMS by configuring electrodes on the hand. Nishida et al. [120] demonstrated that EMS could enable people to have faster reaction times by driving muscles. Kasahara et al. [34] used EMS to drive the hand and developed an EMS-based system based to improve

the reaction speed. When the EMS device was removed after training, the effect of the training was maintained. Therefore, EMS can be used as a training tool for improving physical performance.

Timing perception in the game

In an FPS game, the players must always concentrate, obtain information about the game scenario through our senses, and make quick and accurate judgments [121, 122]. Typically, the enemies in a game are in a moving state. It often takes a certain time interval between the bullet flying out of the gun chamber and hitting the target after firing and the moving enemy itself is in motion. Therefore, we need to estimate the best firing time quickly to ensure that our bullets can accurately hit the moving target. It is difficult to grasp the timing. If we shoot too early, the bullet will pass before the target moves to its intended position, and if we shoot too late, the bullet will miss the target. Therefore, shooting at a moving target is not simply a matter of quick reaction, but of calculating the accurate timing of the shot based on the predicted movement of the target. Importantly, this process of modifying shot control based on the judgment of timing corresponds to the definition of motion perception in [106], which means that timing is also a form of motion perception. Previous studies have shown that judgment- and prediction-based motion perception can be trained [123, 106].

Kasahara et al. [34] provided us with a way to use EMS to enhance the responses. Because responsiveness is also a part of motion perception, we recognized the possibility of using the EMS to enhance human motion perception combining studies [34] with [106]. Therefore, we propose a new hypothesis: it is possible to build a system that uses an EMS to control an FPS game, in which the system automatically determines the best time to shoot and uses it to drive the player's hand to shoot and hit the target. We believe that using EMS for training FPS games can quickly improve a player's shooting skills.

Of note, we consider a different situation in this study compared to that investigated in Kasahara and Nishida's works [120, 34], which focused on improving reaction times through training. In contrast, the proposed approach is designed to train players to improve the timing of their shots in a game. Although they also considered training

involving motion perception, the timing of shots in FPS games is a more complex skill that primarily depends on calculating or judging a shot, predicting a target's movements, and adjusting one's hand motions accordingly rather than purely relying on fast reflexes alone.

5.2.3 System Composition

Here, we built a system that uses an EMS to drive the player's hand, and we connected the system to an FPS game (Fig. 5.2).

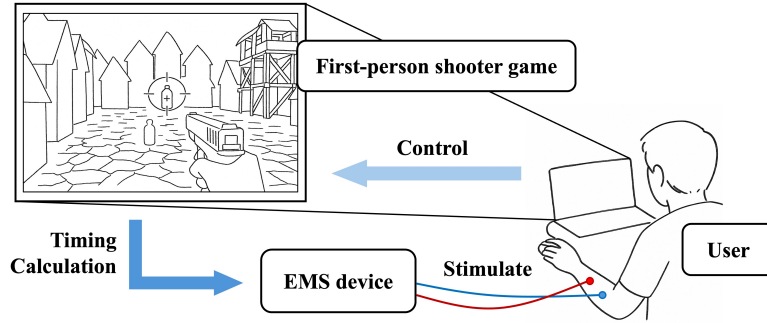


Figure 5.2: EMS-based FPS training system. The EMS device connects to a first-person shooter game, where the system determines the optimal shooting moment and triggers muscle stimulation to assist the user's mouse click.

In the game, when the player tries to shoot a moving target, the system will automatically start at the best time to shoot and use it to drive the player's hand to click the mouse to hit the target. Our aim is to train the shot timing using this set of FPS game control systems based on the EMS drive. When an EMS is used to train players for FPS games, the players do not need complex configurations, specialized gaming devices, or professional training software, allowing for relatively low-cost, efficient training.

Configuration of EMS

Our EMS system (Fig. 5.3) is a set of a switch control, power supply, and electrodes. By wearing this EMS device, participants can use the EMS to drive their fingers to shoot in the game.

Switch: We used ESP32 [87] and PETTOYA 554 relays [124] (Fig. 5.3(a)) as controllers to control the switching of EMS devices through programs written in Arduino,

which allows us to activate and output the electric current required to control finger movements as needed. When the switch is turned on, the EMS device outputs a $50\ \mu\text{s}$ pulse to stimulate the hand muscles to trigger a mouse click, after which it turns off automatically.

Power supply: Here, we chose the macros' MEF-38 [125] (Fig. 5.3(b)) as a power supply for the EMS device. The MEF-38 is an electrical stimulation massager for muscle exercise that provides stable stimulation output according to the manufacturer's specifications. Because our system requires only electrical stimulation capable of driving finger movements, we used this existing massage device to minimize the burden of the EMS on the muscles and to ensure the safety of the participants.

Electrodes: We use the approach from [34]: electrodes are placed on the finger deep flexors of the participant's arm, which allows the device to actuate only finger clicks on the mouse without interfering with the normal activity of other hand muscles when the EMS device is activated (Fig. 5.3(c)).



Figure 5.3: EMS device: (a) ESP32 and PETTOYA 554. (b) MEF-38 for power supply. (c) Electrode configuration.

FPS game

To connect EMS devices to an FPS game and provide a mode for shooting training, we created an FPS game (see Appendix A.1) using Python and the Ursina Engine (Fig. 5.4). The Ursina engine [126] is open-source and provides many templates for creating 3D games, which allows us to make simple FPS games and configure our shooting training mode using Python. We connected the game with the EMS device (Fig. 5.4(c)).

In the game, participants used a standard mouse to control the crosshair and aim at moving targets. The task was implemented in Ursina using a first-person view and was

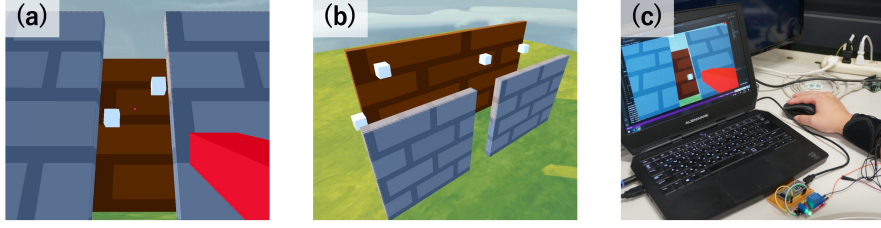


Figure 5.4: FPS game made with Ursina engine. (a) The game is played in first-person view, and the player needs to control the mouse to point the aimer at the target and then shoot. (b) A top-angle view of the game’s scene. The target’s movement is covered partly by walls. This helps to simulate the scene in a real game. (c) Connecting the game to the EMS device.

displayed at a resolution of 1920×1080 pixels with a refresh rate of 60 Hz. Targets were rendered as cube objects with a fixed on-screen hitbox (BoxCollider) and a uniform scale of 1.39 (world units). A hit was registered only when the target was under the cursor at the moment of clicking, corresponding to an instantaneous ray-based selection via the engine’s hovered state, and the target was removed immediately upon a valid hit.

To constrain visual exposure and simulate timing-critical shots in FPS games, two vertical wall objects were placed in front of the player to form a narrow visible region, such that targets were only observable within the opening while moving along a fixed straight-line path. Each target spawned at $z = -2$ (world units) with its initial x position uniformly sampled from $[-20, -8]$ and then moved along the positive x -axis by 30 world units using a constant-speed animation with a duration randomly sampled from 3.5 to 4.0 s, yielding a nominal speed of approximately 7.5–8.6 world units/s. The player’s initial position was fixed at $(x, z) = (-4, -30)$. The number of concurrently presented targets was fixed to five in the current configuration.

The system defined the ideal firing timing as the moment when the crosshair intersected the target within the visible opening. In the EMS condition, the system triggered the EMS device by sending a serial command (“1”) when the cursor first entered a target (on-mouse-enter event), which physically induced an index-finger click to fire and hit the target (Fig. 5.5). Participants were seated at a fixed viewing distance from the display, which was kept constant across all experimental conditions.

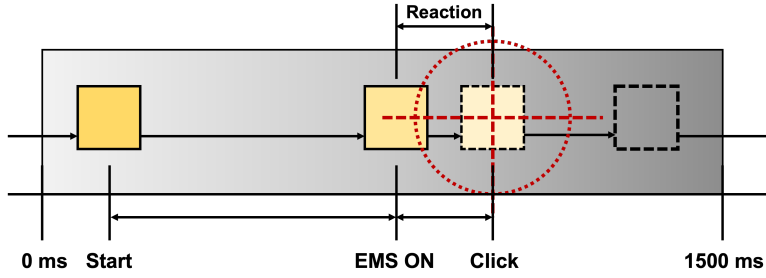


Figure 5.5: When the system detects that the aim is at the best time to shoot, the EMS device will be activated and drive the player’s finger to click the mouse.

IRB Process

This study was reviewed and approved by the local ethics committee of Kyoto Sangyo University (Approval No.: KSU Ethics 0168-1; Study title: “Game Control Systems Using Electrical Muscle Stimulation”). All experiments were conducted with the informed consent of the participants, who were fully informed of the study’s purpose, procedures, and potential risks prior to participation.

5.2.4 Experiment 1: Reaction Test

We used an EMS system to replace the typical FPS game control. Because we use the EMS devices for FPS game control; the reaction speed could not be lower than the player’s reaction speed in the original general control. Therefore, we needed to test the reaction speed before and after using the EMS device and confirm that the system does not have a negative effect on the player’s reaction speed and control of the game (Fig. 5.6). As described in the subsection FPS Game (Section 5.2.3), the Ursina engine [126] was used to simulate the test environment.

Experimental Approach

Considering that our test should simulate an FPS game situation as accurately as possible, we used a visual stimulus for the test. In the test, we set up an enemy (the target). When the participants noticed that the target appeared, they would click the mouse as quickly as possible. Our program automatically recorded the time when the target appeared and the time when the participant pressed the mouse, and then calculated the

reaction time.

When the EMS device is used for testing, the device automatically starts when the target appears, which signals to the participant to click on the mouse. The participants did not need to actively click on the mouse when using the EMS device. At the end of each test, the program automatically calculated the reaction time from the time the target appeared to the time the EMS drove the finger to click on the mouse.

To test the effect of using EMS to control the game on participants' reaction times, we first tested their reaction times with normal control without the EMS device (Fig. 5.6(a)). We then allowed the participants to wear the EMS device for the test and recorded their reaction times when driven by the EMS device (Fig. 5.6(b)).

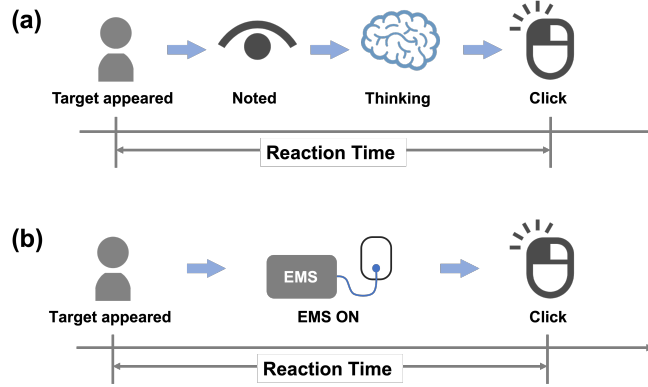


Figure 5.6: Reaction test. (a) In general (without EMS), participants need to pay attention, judge, and act from the moment they see the target appeared until they click the mouse. (b) When testing with EMS devices, the participant's attention, thinking, and driving processes are replaced by the EMS system.

Device Configuration

As described in the subsection Configuration of EMS (Section 5.2.3), our EMS setup followed the configuration used in previous studies [119, 34]. Because participants were required to rapidly actuate finger movements via EMS to trigger mouse clicks, the stimulation needed to produce clean and crisp finger responses while avoiding unintended muscle activation that could interfere with mouse control. Accordingly, the stimulation intensity was adjusted based on prior work and individual comfort levels, and the pulse width was set to 50 μ s. The electrodes were applied to the participant's wrist and

secured with a wristband to prevent displacement during movement. With the appropriate configuration, the participant's finger reliably clicked the mouse once upon EMS activation without interfering with normal mouse operation.

Participants

Ten participants (age: 18–29 years, 9 males and 1 female) performed the response test in this experiment, and each was tested using the approach described in the subsection Experimental Approach (Section 5.2.4). Each participant first performed 10 reaction tests without the EMS device and then another 10 reaction tests with the EMS device.

Results

We tested the reaction speed of 10 participants in an FPS game with and without the EMS device. We recorded the reaction times of the 10 participants for each test and calculated the average reaction times of the participants after 10 tests with and without EMS devices. Subsequently, we compared the average reaction time of the participants before and after using the EMS device: the shorter the reaction time, the faster the reaction speed (Fig. 5.7). According to the results, all 10 participants showed some improvement in their reaction speed when using the EMS device.

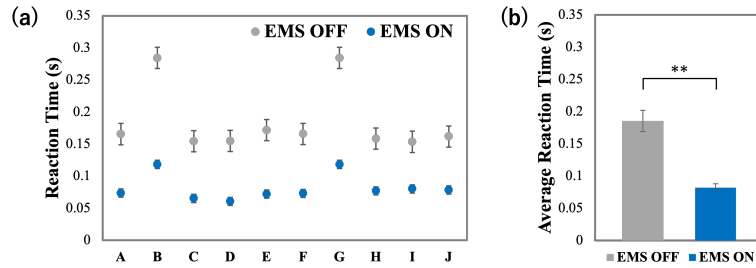


Figure 5.7: Reaction test results. (a) There was an increase in each participant's reaction speed with the use of the EMS device compared to the reaction speed without the use of the EMS device. (b) The average reaction time of the participants without the EMS device was 0.1855 s, and the average reaction time with the EMS device was reduced to 0.0817 s.

The mann-whitney u test was used to examine the two sets of data without and with the EMS device. The significance level was set at 1% (a two-tailed test). According to the

statistical analysis, the u-value was 100.0 and, the p-value was 0.00018. The test results confirmed that at the 1% level, participants responded significantly faster with the EMS device than without it. Therefore, when using the EMS device, the participant's reaction speed was not slower than in normal conditions (without the EMS device), and it was even faster. In other words, when the participants play the game with EMS devices, these devices do not negatively affect the participants' control, and they enhance the participants' reaction speed and control in the game to a certain extent.

5.2.5 Experiment 2: FPS Game Training

Our aim was to train participants on shooting timing with a moving target in an FPS game using a system built with the EMS. Therefore, we need to conduct a controlled experiment to ensure that the training approach using the EMS is more effective and efficient than the approach without the EMS. As in Section 5.2.4 (Experiment 1: Reaction Test), the Ursina engine [126] was used to simulate an FPS game.

Experimental Approach

Using the FPS game setup described in Section 5.2.3, we set up five moving targets in each game. To simulate a realistic FPS game scenario, walls were placed to conceal part of each target's movement, making it more difficult for participants to calculate the optimal shooting timing based solely on their own perception (Fig. 5.4(b)). Different movement speeds were assigned to each target, and the interval during which each target appeared and disappeared from behind the wall was approximately 1–1.5 s.

At the beginning of each game, the conditions were kept as similar as possible, except for the randomly generated movement speed of the targets. After the game started, participants were required to control the mouse to click and hit five fast-moving targets within a time limit of two minutes. If a mouse click successfully hit a target, the target disappeared and was counted as a hit. If the mouse was clicked but failed to hit the target, it was counted as an off-target hit. After all five targets were hit or the two-minute limit was reached, the system calculated the participant's hit rate for the current game.

Device Configuration

The EMS configuration used in the FPS game training was identical to that described in the subsection Device Configuration (Section 5.2.4). During the FPS game task, the stimulation intensity was adjusted based on participant feedback to ensure effective finger actuation without causing discomfort. The pulse width of the electrical stimulation was set to 50 μ s. To minimize the physical burden associated with repeated mouse control during the experiments, we used a Logitech G603 gaming mouse [127]. Owing to its ergonomic design and relatively light weight, this mouse allowed participants to perform the task in a more comfortable manner and reduced the likelihood of muscle fatigue.

Training Method

For the experiments, we used three training methods (Fig. 5.8).

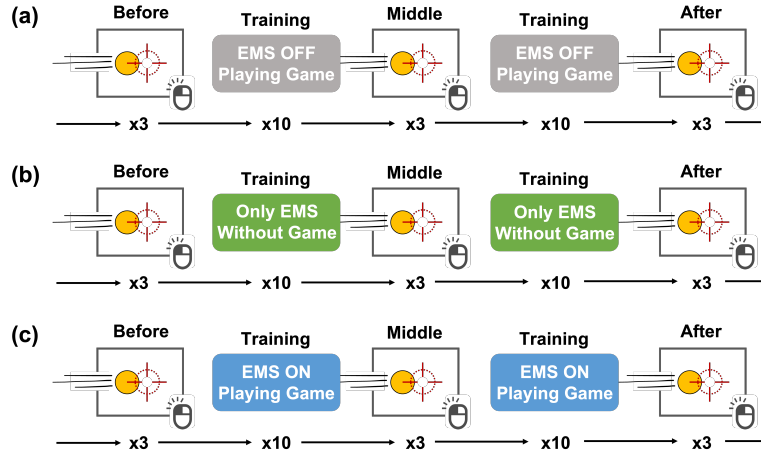


Figure 5.8: Three training methods. (a) Without the EMS device. (b) Without FPS games, only with the EMS device for electrical stimulation. (c) Wearing the EMS device to play the FPS game.

non-EMS: Participants practiced without EMS devices and repeated the game (Fig. 5.8(a)). With this method, participants did not receive any outside hints and only relied on their own senses to master the timing of the shot.

Only EMS: To exclude the possibility that the participants' reaction speed becomes faster and thus the hit rate in the game improves by simply using electrical stimulation of the muscles, we set up a series of training sessions using only electrical stimulation

(Fig. 5.8(b)). The participants wore EMS devices for this training. During the training, they did not play any game, but the wrist was continuously electrically stimulated, and the hand muscles were driven to click the mouse. The single electrical stimulation setup was the same as in the subsection Device Configuration (Section 5.2.4), and each session consisted of 10 electrical stimulations at 5 s intervals.

With the EMS: In this training, participants wore the EMS devices to play FPS games (Fig. 5.8(c)). During training, the participants were required to control the mouse to aim at a target. The EMS device drove the participant to click on the mouse to shoot at the target when it was the best time to shoot. The player perceived the best shooting timing through electrical stimulation from the outside, and reinforced the timing of the shoot through this process. Importantly, our aim was not simply to require participants to achieve a perfect hit rate with the EMS device but to learn and master the best shooting timing through the stimulation from the EMS device.

Participants

Thirty participants (age: 18–29 years, 27 males and 3 females) were recruited and tested using the approach described in the subsection Experimental Approach (Section 5.2.5). All participants reported having no prior experience with FPS games or only minimal exposure insufficient for proficient gameplay.

Before the start of the training, each participant played the game three times without using any EMS device to calculate their average hit rate as a baseline. Participants then completed ten training sessions, with a 10 s interval between consecutive sessions. After the first round of training, participants played the game three times, and the number of hits was recorded. Following the second round of training, participants again played the game three times, and the hits were recorded in the same manner. In total, all 30 participants were tested under identical conditions, and hit data were collected for each trial.

30 participants were trained using each of the three methods described in the subsection Training Method (Section 5.2.5).

First, considering the ability of the EMS to enhance human reaction speed, as mentioned in [34], it was necessary to confirm whether the increase in the participants' hit

rate was solely due to the increase in reaction speed after EMS training. Therefore, we compared the average hit rate of 10 participants before and after training with only EMS training (no games) to verify that participants' hit rates did not improve after training with only EMS devices but no games. As we described in the subsection Timing Perception in the Game (Section 5.2.2), participants were able to reach the target not because of a faster reaction rate, but because their mastery of shot timing was enhanced by using EMS in the FPS game.

We then need to compare the average hit rate of 10 participants before and after training with the EMS to confirm that the method of training with the EMS in a custom FPS game is effective.

Finally, we need to compare the results of 30 participants trained with each of the three methods to confirm that the method of training with the EMS in a custom FPS game is more efficient than the other two methods.

Training with electrical stimulation only

10 participants were trained using only electrical stimulation after wearing the EMS device. We recorded the hit rate of each participant in an FPS game before and after the training with only the electrical stimulation. The results show no change in hit rate before and after training (Fig. 5.9).

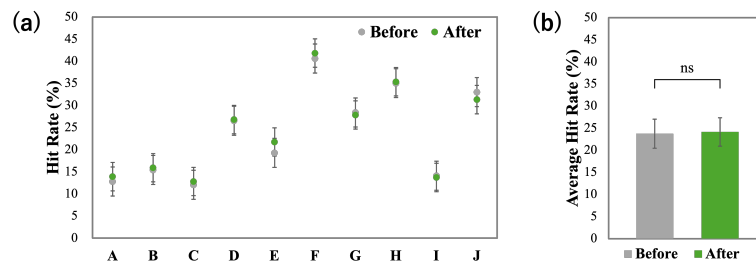


Figure 5.9: Average hit rate changes in 10 participants before and after training with only the electrical stimulation. (a) There was no significant change in the average hit rate of the 10 participants before and after training with the Only EMS method. (b) The average hit rate of 10 participants before and after training. The average hit rate before training was 23.74% and the average hit rate after training was 24.14%.

After the calculation, the average hit rate of the 10 participants improved by only

0.40% after training with only the electrical stimulation. We concluded that training without gameplay did not improve the participants' hit rate in the FPS game.

We used a mann-whitney u test to examine the two datasets before and after training with only the electrical stimulation. The significance level was set at 5% (a two-tailed test). According to the statistical analysis, the u-value was 47.5, and the p-value was 0.8798. The results of the test confirmed no significant difference in the hit rate of the participants before and after the training with only the electrical stimulation. Therefore, the training with only the electrical stimulation did not improve the participants' hit rate in the FPS game.

Feasibility of the EMS method

Before comparing the results of the three methods, we need to confirm that the method of training a custom FPS game using EMS can improve shooting skills. We recorded the hit rate of 10 participants before and after training with the EMS (Fig. 5.10). A mann-whitney u test was used to test the validity of the training using the EMS method. The significance level was set at 1% (a two-tailed test). According to the statistical analysis, the u-value was 15.0, and the p-value was 0.0091. The test results confirmed that the participants' hit rate improved significantly after training with the EMS compared to before. It shows that training with the EMS can quickly improve a player's mastery of shooting timing in the game.

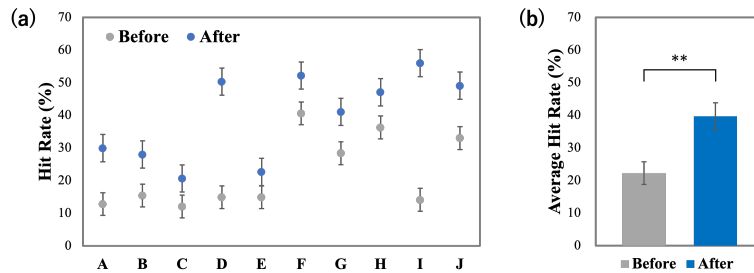


Figure 5.10: Average hit rate changes in 10 participants before and after training with the EMS. (a) There was a significant change in the average hit rate of the 10 participants before and after training with the EMS method. (b) The average hit rate of 10 participants before and after training. The average hit rate before training was 22.26% and the average hit rate after training was 39.71%.

Comparison of the three methods

In order to prove that the method of training a custom FPS game using EMS is more effective, we divided 30 participants into three groups and trained them using the non-EMS method, the EMS-only method and the EMS method, respectively. We compared the results of the three training methods to confirm that the method using EMS is more effective than the other two. We recorded the average hit rate of each participant before the start of the training, after the first training, and after the second training. Fig. 5.11 (a)(b)(c) shows the change in the average hit rate in the FPS game before, during, and after training for the three groups.

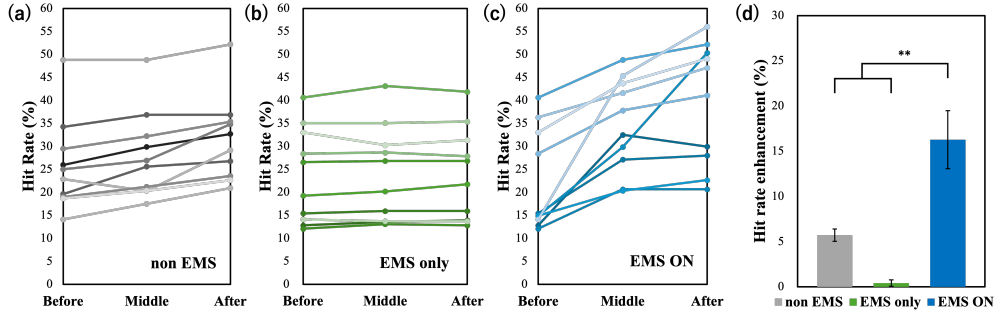


Figure 5.11: Comparison of the three methods. (a) The average change in hit rate before, during, and after the FPS training for 10 participants using the non-EMS method. (b) The average change in hit rate before, during, and after the FPS training for 10 participants using the EMS-only method. (c) The average change in hit rate before, during, and after the FPS training for 10 participants using the EMS method. (d) Changes in participants' average hit rate in FPS games after training in the three methods.

We found that participants' hit rates after training were higher than those before training, regardless of whether they were trained using the non-EMS method or the EMS method, except for the EMS-only method. We hypothesized that shooting timing training in a custom FPS game using the EMS device is more efficient than the other two. Because the training time was the same for all three groups, we needed to prove that after the same training time, the improvement in hit rate was higher with the EMS method than with the other two methods. We subtracted the hit rates of the three groups before and after the training to calculate the average hit rate increase for each participant (Fig. 5.11 (d)). This allows us to see more visually which improves the hit

rate after the training.

The 10 participants who trained using the method without EMS had a 5.72% increase in the average hit rate after the training, the 10 participants who trained using the EMS-only method had a 0.40% increase in the average hit rate after the training, and the 10 participants who trained using the EMS device had a 16.28% increase in the average hit rate after the training.

The ANOVA analysis was used to confirm whether there was a significant difference between the results of the three training methods. The significance level was set at 1%. According to the statistical analysis, the F-value was 18.0366 and the p-value was 1.0605×10^{-5} . The test results confirmed that there was a significant difference between the results of the three training methods at the 1% level.

A further Tukey HSD test was used to confirm that the results of training with EMS were significantly different from the results of the other two methods. The significance level was set at 1% (two-tailed test).

The following are the results of the test (Table. 5.1).

Table 5.1: Multiple Comparison of Means - Tukey HSD

Group 1	Group 2	Mean Difference	p-value	Lower	Upper	Significant difference
with EMS	non-EMS	10.562	0.0015	2.008	19.116	True
with EMS	EMS only	-15.8783	0.0	-24.4324	-7.3243	True
non-EMS	EMS only	-5.3163	0.1377	-13.8704	3.2377	False

The results showed that participants trained with the EMS had a more significant increase in average hit rate, both compared to participants trained without the EMS and compared to participants trained with the EMS only.

5.2.6 Discussion

Our study demonstrated that the use of EMS in our custom FPS game can help players to master the timing of shots and quickly improve their shooting skills. We will discuss the results of this study for future studies and future work.

Limitation

It must be acknowledged that there are limitations to our research at this point.

First, we did not investigate whether the effects would diminish over time. In this study, we verified that players could quickly improve their skill at the game and did not test whether this improvement was retained over a period of weeks or months. We plan to investigate the persistence of these effects in future work to further explore the feasibility of using an EMS system to train players to play FPS games.

Second, we only experimented with a simple custom game rather than using any existing FPS games. In the subsection Experiment 2: FPS Game Training (Section 5.2.5), we set up a small number of targets (five in total), which moved in a single pattern—random-speed motion in the horizontal direction only. In a real FPS game, players are faced with a more complex environment where enemy actions may be unpredictable. Nonetheless, we believe this study demonstrates the potential for using EMS to train players’ perception of movement in FPS games, which is the value of the present study. Our study provided a novel approach to FPS game training for those who require it. Future studies will involve setting up more complex experimental projects in actual FPS game battles in order to further validate the feasibility of using EMS to train players in different FPS game skills.

Third, we only conducted a quantitative analysis of the players’ hit rates in the game. In future research, we plan to conduct a qualitative analysis by asking participants to respond to a questionnaire with items reflecting their experiences playing a game as well as their levels of fatigue, comfort, and so forth.

Fatigue of training

When training for the FPS games using the method without and with EMS devices, we found that the training with EMS devices seemed less likely to reach fatigue. Training for FPS games is very energy-intensive, and shooting at moving targets requires the use of motor senses for timing [106]. Normal training methods are mainly designed to allow players to master the timing on their own through repetitive training. As there are no hints, the player needs to maintain a high level of concentration during the entire training process, which can easily cause mental fatigue. When the EMS is used for training, the system provides electrical stimulation from the outside at the best possible time; therefore, players do not need to maintain a high level of concentration as in the

traditional way, which makes players less likely to be fatigued in the EMS training mode.

Fig. 5.12 shows the change in the average hit rate during the first and second training sessions in both training modes.

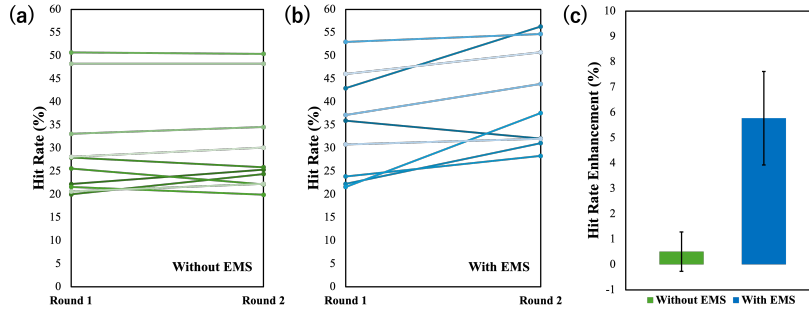


Figure 5.12: Change in the average hit rate of participants in the first and second training sessions when training using the method without and with the EMS device. (a) Participants had an average hit rate of 29.82% for the first session and 30.33% for the second session when trained using the non-EMS mode. (b) Participants had an average hit rate of 35.97% for the first session and 41.74% for the second session when trained using the EMS device. (c) Comparison of the increase in average hit rate after the first round of training to the second round of training for participants trained with and without the EMS.

The average hit rate in the second training session with the non-EMS training mode tended to decrease slightly compared to the first training session. By contrast, the hit rate continued to increase during the second training session when the EMS mode was used. It was calculated that the average hit rate in the second training session was only 0.51% higher than that in the first session in the non-EMS mode, while the average hit rate in the second training session was 5.77% higher than that in the first session in the EMS mode. We presume that this is because EMS training is less likely to cause mental fatigue in players, which results in continued improvement in the second round. This is the subject of future research.

Effects of EMS on different body types

Here, we found that muscle actuation by EMS devices is susceptible to the effects of obesity. At the same voltage strength, people with obese body types had more difficulty driving through the EMS device than people with standard body types. For example,

when the electrical stimulation intensity was set to 1.5-2V, most participants reported that it was just fine. In this setup, moderately sized participants are able to fire with an accurate mouse click with good control of hand muscles via EMS, and electrical stimulation at this intensity produces no discomfort for the participant. However, the intensity of this stimulation appeared to be too low for the more obese participants, who found it difficult to respond to electrical stimulation of this intensity in the hand muscles. Thus, for participants with relatively obese body types, we needed to tune the electrical stimulation to a 2-3V range in order to ensure that their muscles could be driven by EMS.

We speculated that this was because the muscles of obese individuals were covered with fat, and it was difficult for electrical stimulation to drive the muscles through fat. Here, we solved this problem by increasing the output voltage. Considering the generalizability of the training methods using the EMS, it is necessary to investigate individual differences caused by the body size in future studies.

5.2.7 Applications of this study

In this study, we only verified the use of EMS in a custom game to quickly improve the player's shooting skills. Whether EMS devices could be effective for training players to play conventional FPS games remains a topic for future research. However, we will list some application scenarios for training with the EMS when future studies are completed.

Hobby players training

Most people who play FPS games do so only as a hobby or recreationally, and only a very small minority play professionally. Because training with an EMS could be simpler than conventional professional training comprising practicing with a team, coaching, studying post-game replays, and so forth, such training could be considered as well-suited for hobby players. Many hobby players spend relatively little time playing games and want to enjoy playing without putting a great deal of effort into training or practice. These players make up a large percentage of total game sales and might be expended to consider purchasing EMS devices. By using EMS for FPS training, hobby players can quickly improve their shooting ability in FPS games, which may greatly improve their

experience in the game.

E-sports training

Our training method is not only suitable for hobby players, but it can also be applied to professional e-sports training. Unlike hobby players, professional players who often participate in e-sports competitions undergo more difficult and extended training. High-intensity training and a long time required to maintain a sitting position may cause an accumulation of fatigue for professional players [128, 129]. The EMS training method can greatly improve the efficiency of e-sports training, which reduces fatigue and minimizes health consequences.

Training for traditional sports

In addition to e-sports, our training method is also applicable to traditional sports (such as, shooting and archery). It is well known that training a professional athlete is costly and time-consuming. Long hours of training are often physically and mentally stressful for athletes, which may affect their health in the long term [130, 131]. When athletes use the EMS for training, it can improve the training effect and reduce the training time without causing an additional physical burden to the athletes to minimize the consequences for the athletes' health.

5.2.8 Conclusion and Future Work

In this study, we developed a new EMS-based training method for FPS games. Players can use EMS devices to train the timing of shooting in FPS games. We have experimentally confirmed that participants were able to quickly improve their skills at a custom FPS game by using an EMS device. Using EMS for FPS game training has the following advantages: (1) It can quickly improve the player's ability to master the shooting timing in a short time, so they can quickly improve their game skills. (2) By enhancing motion perception with external stimulation, players can themselves predict the timing of shots and can adjust the stimulation according to their individual differences. (3) The EMS is noninvasive and easy to implement; therefore, players can train with a simple configuration.

In conclusion, we only verified the use of EMS in a custom game to quickly improve the player's shooting skills. Whether EMS devices could be effective for training players to play conventional FPS games remains a topic for future research. This method may be more suitable for recreational or hobby players who wish to quickly improve their gaming skills without putting in the time and effort that might otherwise be required. EMS training techniques may also be applied to other games and sports when future studies are completed. The findings of this study can be applied to scenarios similar to mastering the timing of shots. As with shooting in FPS games, sports such as fishing or baseball also require hand-eye coordination and prediction of timing [132]. This study could provide a reference for such investigations.

As for future work, we will further validate the feasibility of using EMS to train FPS game skills. We will conduct experiments on the retention effects after training with EMS to further validate the feasibility of the method. And, considering that we only used a custom FPS game for training in this study, in future work, we will use different FPS games for training to verify the generalizability of the method. Moreover, not only be limited to quantitative analysis, but we will also conduct qualitative analysis to verify the feasibility of using EMS for FPS game training.

5.3 EMS-Based Training for Finger Control

Based on “Augmenting Finger Control with EMS: Toward Speed, Precision, and Embodied Interaction in Games.” – Zhou and Segawa (under review)

Finger control is a core aspect of human–computer interaction, underlying tasks from everyday input with keyboards and touchscreens to rapid actions in gaming contexts. However, developing speed and precision in finger movements usually demands prolonged practice, making it difficult for users to improve quickly. EMS provides a way to directly influence finger muscles, offering immediate assistance in fine motor control and potentially accelerating skill acquisition. In this section, we introduce an EMS-based training method for finger control, and evaluate its effects on speed, accuracy, and retention through empirical study.

5.3.1 Introduction

Hand control, especially precise finger movements, is a core skill in video games. Most games rely on finger input through buttons, mouse, joystick, or touchpad. Some games require frequent and precise finger control. For example, in shooting games, players may need to click rapidly while maintaining accuracy, depending on the type of weapon. In multiplayer online battle arena (MOBA) and real-time strategy (RTS) games, faster and more efficient finger control is often the key to winning battles. Highly challenging rhythm games require players to move their fingers quickly while maintaining consistent timing and speed. However, improving finger speed and accuracy is not easy. It typically requires extensive training and can be difficult to master. Many players struggle to improve their finger control through self-training, making this skill gap a major barrier between beginners and experienced players.

Finger control can be improved through specific training. Pascual [133] found that consistent practice on a musical instrument can lead to neuroplasticity in the human brain, improving hand-muscle coordination and finger control accuracy. Professional pianists tend to show greater confidence in strength, coordination, and rhythmic control after long-term and repetitive training [134]. Sailer et al. [135] found that adjusting vi-

sual and tactile feedback can optimize hand-eye coordination and improve finger control over angle and force. Griffith et al. [136] found that video game players often develop superior hand-eye coordination and more precise hand control than non-players after targeted skill training. In addition, some studies have explored using assistive devices to improve finger control. Seim et al. [137] developed a passive tactile training method that significantly improved users' typing speed. Furuya et al. [138] used exoskeletons to improve finger control and help pianists overcome performance plateaus. Batmaz et al. [139] compared AR and VR-based assistive systems in improving hand-eye coordination and strengthening hand control, offering new possibilities for hand-control training.

Although these studies suggest that hand and finger control can be improved through skill-based training or assistive devices, prolonged, high-intensity and repetitive training has its limitations. Extended gaming sessions may increase mental fatigue, while intensive finger training can lead to muscle fatigue due to overuse [140]. Players who rely on continuous finger movements often experience inevitable fatigue [101]. As training duration and intensity increase, these effects become more pronounced, eventually leading to diminishing returns. Therefore, achieving effective training and rapidly improving hand and finger control within a short period remains a significant challenge.

EMS is a technique that uses low-intensity electrical currents to directly stimulate target muscles, enabling or assisting limb movement. Initially, EMS was primarily used in medical rehabilitation, but in recent years, its potential for enhancing individual abilities and skills has gained increasing attention. Studies have shown that EMS can effectively improve motor performance and facilitate skill learning. For example, Kasahara et al. [54] reported that EMS can enhance user reaction speed, while Zhou and Segawa demonstrated that EMS can significantly improve both motor and perceptual abilities in a short period, highlighting its feasibility for accelerating game-skill training [141]. They further proposed an EMS-based hand-eye coordination training method, confirming its short-term effectiveness and applicability in real gaming environments [142]. Beyond perceptual-motor training, EMS has also been applied in closed-loop behavior correction systems. Kattoju et al. [143] showed that EMS can be used to guide posture adjustment based on real-time sensing, illustrating the broader potential of EMS as an interactive modality for shaping human movement and skill acquisition.

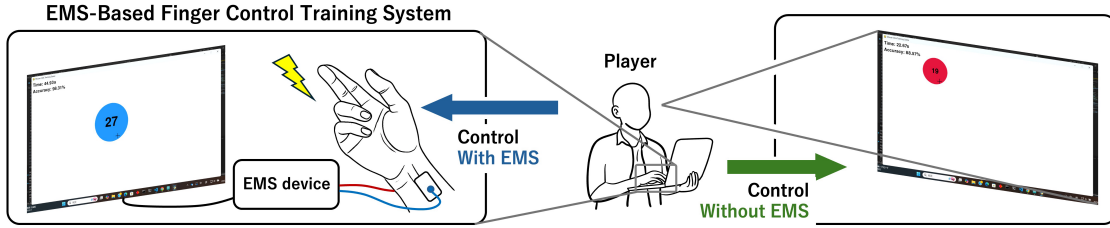


Figure 5.13: This study developed an EMS-based finger training system that allowed participants to rapidly improve finger speed and precision. Through this training, participants can improve their finger control in games, enhancing game performance.

Compared to other assistive technologies, EMS has the unique advantage of directly stimulating muscles, actively participating in limb movement, and accelerating the formation of muscle memory. This characteristic gives EMS significant potential in motor skill learning and improvement. Based on this, we propose a new research hypothesis: EMS also provides a notable advantage in improving finger-related skills in gaming, particularly in increasing finger speed and precision.

This study introduces an EMS-based finger training system designed to improve gaming skills (Fig. 5.13). The system stimulates hand muscles to help players rapidly improve finger speed and accuracy, thereby optimizing game control. The primary objective is to evaluate the practical potential of EMS training for skill improvement, specifically by examining changes in player performance after EMS training. This research not only offers a new approach to gaming skill training that improves the player experience but also provides valuable insights for the application of EMS in professional skill training and future research.

In contrast to prior EMS studies that primarily supported perceptual timing or hand-eye coordination during game interactions [141, 142], the present work focuses on improving the execution component of finger control itself. Our study demonstrates that EMS-based training can strengthen two fundamental aspects of finger performance—speed and precision—and that these improvements persist beyond the training session. Unlike earlier work that centered on perceptual or coordination gains, our results show that EMS can directly enhance the motor capabilities required for rapid, repeated clicking, addressing a bottleneck that often limits players even when their perceptual judgments are accurate.

Furthermore, by evaluating performance across both an FPS aiming task and a rhythm-based game, we examine whether execution-level improvements generalize across different interaction contexts. The use of a larger participant sample ($n = 30$) and more demanding multi-click tasks provides additional empirical support for EMS as a practical method for finger-level motor augmentation.

Overall, this work contributes a systematic investigation of EMS for enhancing fine-motor execution, expanding the scope of EMS-based training beyond perceptual or coordination tasks and demonstrating that EMS-induced gains in finger speed and precision can be retained and transferred across game scenarios.

5.3.2 Related Work

Our method is based on using EMS to train finger control to improve gaming skills. To explain our training approach, we will provide a detailed discussion of several key aspects, including finger control in gaming, skill acquisition and development, and the application of electrical muscle stimulation.

Finger Control and Gaming Skills

Finger movement is coordinated by bones, joints, muscles, tendons, and the nervous system. The muscles in the hand control the flexion and extension of the fingers, while fine motor skills rely on the integrated function of the brain and nervous system. Finger control is fundamental to hand movement and overall limb coordination, and plays a critical role in both daily activities and specialized skills. Jeannerod [144] found that hand control, particularly grip regulation, is closely related to the precise adjustment of finger speed. Duncan et al [145] described the mechanical characteristics of finger movements in grasping and other basic actions and analyzed how the fingers work together in these tasks. Valero [146] investigated the role of muscles and the nervous system in finger movement, emphasizing the importance of muscle strength and precision in finger control. Hu and Ren [147] used 3D motion analysis and a biomechanical tendon network model to further investigate the role of muscles in the finger control mechanism.

In many video games, skill improvement is closely linked to finger control ability. Forman [148] noted that many games and esports require players to exert high levels of

finger control during gameplay. Whether using a keyboard, mouse, controller, or touch screen, players must precisely adjust finger force and speed [149]. Different game genres have different finger control requirements. In shooting games, players must precisely control their fingers to fire weapons, and with certain semi-automatic weapons, rapid clicking speed is often the key to victory [150]. In MOBA and RTS games, precise finger control is essential for deploying units and performing skills [151] [152] [153]. In rhythm games, players with faster finger speed typically have a significant advantage [154]. In these games that rely heavily on finger control, factors such as finger speed and accuracy serve as critical indicators of gaming skill.

Skill Learning and Development

Finger control is a complex cognitive and motor process that relies on continuous feedback to regulate precise finger movements. From a neuroscience perspective, this process involves the perception and integration of visual and tactile information, followed by the generation of refined motor output. Desmurget et al. [155] noted that the human central nervous system uses online visual–tactile feedback to plan and adjust motor tasks in real time. Johansson et al. [107] further demonstrated, through fingertip manipulation experiments, that fine motor control emerges from a tightly coupled interaction between sensory inputs and motor commands. These findings highlight the neural mechanisms underlying finger control and provide a basis for understanding how such skills are learned and refined.

From a skill acquisition perspective, finger control follows the core principles of sensorimotor learning. Learning can be viewed as a process of establishing stable stimulus–response relationships through repeated exposure and correction [109]. During this process, the sensory system interacts with the environment to minimize perceptual and motor prediction errors [110]. Modern computational theories of motor learning suggest that the brain maintains internal forward models that generate predictions of expected sensory consequences. These predictions, formulated through efference copies of motor commands, are compared with incoming sensory feedback to compute error signals that guide adaptation [106].

At the neural level, sensorimotor learning is associated with mechanisms such as Heb-

bian plasticity and spike-timing-dependent plasticity (STDP) [156], where the temporal alignment of sensory and motor signals contributes to the strengthening of synaptic connections. Through these timing-sensitive mechanisms, repeated pairing of intention, movement, and feedback can accelerate the formation of stable motor representations. Sailer et al. [135] demonstrated that hand control depends on recurrent sensorimotor loops in which external feedback refines movement execution. Such feedback-driven learning accumulates over time and can lead to long-term retention of improved motor performance [106].

Together, these studies show that improvements in finger control arise from the interaction of predictive motor processes, error correction, and repetition. This framework provides a theoretical foundation for understanding how external interventions—such as EMS—may accelerate the acquisition and consolidation of fine finger control skills by supplying consistent proprioceptive events that align with voluntary action.

Skill Training Using EMS

EMS is a limb activation technique that induces muscle contractions through low-intensity electrical stimulation. Compared to traditional assistive devices such as robotic arms [116] and exoskeletons [117], EMS offers high responsiveness, minimal physical bulk, and easy integration into interactive systems. While early EMS research largely focused on rehabilitation and motor-function recovery for individuals with movement impairments [118], recent advances have expanded its use to HCI and interactive augmentation [120].

A substantial body of work has examined EMS as both an actuation mechanism and a feedback modality within interactive systems. One influential line of research originated from Rekimoto and colleagues, whose PossessedHand system [54] showed that EMS can reliably actuate finger flexion and extension while preserving users' sense of agency, establishing EMS as a promising interface for fine-motor interaction. In parallel, Lopes and collaborators have investigated EMS as a medium for interactive augmentation. Through systems such as Muscle-Plotter [56], EMS-based force feedback [157], and Impacto [158], they demonstrated that EMS can serve not only as a source of movement actuation but also as a precise proprioceptive cue that facilitates fine motor

learning. Their work on stimulation timing further revealed how temporal characteristics of EMS modulate kinesthetic perception, reaction speed, and voluntary motor control [34]. Collectively, these studies provide a comprehensive understanding of how EMS can shape both movement execution and sensorimotor adaptation.

In gaming contexts, EMS has been explored as a means to enhance perceptual–motor skills. Zhou and Segawa [141, 159, 142] demonstrated that EMS can accelerate learning in FPS reaction-time tasks and hand–eye coordination scenarios, offering evidence that EMS can support rapid skill acquisition when performance depends on perceptual timing or visuomotor alignment. However, these prior studies primarily addressed perceptual or coordination processes rather than the fine-grained execution of finger movements.

More recent work has increasingly focused on EMS for dexterous finger actuation. Takahashi et al. [119] investigated electrode placements that produce controlled flexion and extension of individual fingers through stimulation applied to the back of the hand, providing important insights into finger-level EMS control. EMS has also been applied in skill-specific domains, such as musical instrument training. Niijima et al. [12, 160] used EMS to support piano performance by reinforcing correct finger posture and timing, while Zhou et al. [161] demonstrated that EMS can facilitate rhythm acquisition in percussion-based tasks by guiding consistent finger and wrist movements.

Compared to soft exoskeleton gloves and other mechanical assistive devices, EMS enables unobtrusive, low-latency muscle activation without constraining hand posture or movement. This makes it particularly suitable for gaming scenarios that require rapid, precise, and repetitive finger actions.

Building on these findings, our study focuses specifically on EMS-based training for fine finger control. We target the flexor digitorum superficialis and flexor digitorum profundus for finger flexion and the extensor digitorum for finger extension. Whereas prior EMS research has emphasized improvements in perceptual timing or visuomotor coordination, our work instead examines enhancements in motor execution at the finger level. This distinction is important because players may correctly perceive an action yet fail to execute it due to limitations in finger speed or precision. By strengthening the execution component of motor performance, EMS-based finger training has the potential to accelerate gaming skill acquisition and improve consistency in high-frequency clicking

tasks.

5.3.3 EMS-Based Training System

To facilitate training, this study developed an EMS-based finger training system (Fig. 5.14). The system integrates an EMS device with a customized training program, optimizing electrode placement and electrical stimulation parameters to achieve precise control over participants' finger movements. During training, the EMS device drives finger movements through real-time feedback from the customized program, improving hand muscle control. Through targeted finger training, participants can improve fine motor control of their hand muscles, resulting in better gaming performance.

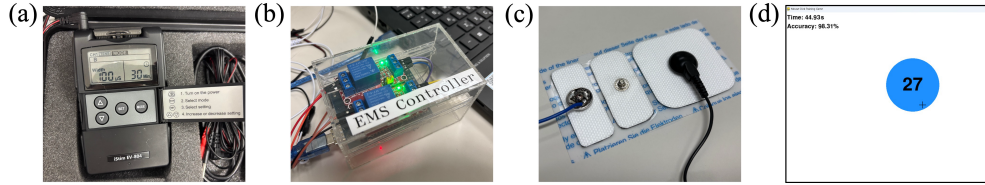


Figure 5.14: Configuration of EMS-based training system. (a) Power supply (EV-804). (b) Switch control. (c) Electrode configuration. (d) Finger-training game.

EMS Configuration

In this study, an EMS device consisting of a power supply, switch control, and electrodes was used to drive the participants' hand muscles during training, allowing for precise finger control.

The system used the iStim EV-804 [162], a commercial dual-channel EMS device commonly employed for muscle training and rehabilitation (Fig. 5.14(a)). The device generates biphasic, current-limited stimulation pulses with adjustable intensity, pulse width, and frequency, and internally regulates the output amplitude to remain within safe limits. Because the present study requires only mild stimulation to activate the finger flexor and extensor muscles without inducing excessive force or discomfort, the EV-804 was selected as it provides stable, low-intensity stimulation suitable for fine-motor experiments while ensuring participant safety.

The EMS system was controlled by an Arduino UNO [86] and a TONGLING relay

[124], with activation and deactivation of the device managed by an Arduino program (Fig. 5.14(b)). The system delivers pulse stimulation from 50 μ s to 100 μ s on demand, targeting the participant's hand muscles, and automatically turns off after stimulation. To account for individual differences due to age or physical condition, the system allows fine-tuning of pulse duration to ensure effective stimulation while avoiding discomfort.

Electrode placement was determined based on previous research [119], with electrodes placed on the extensor digitorum, flexor digitorum superficialis, and flexor digitorum profundus (Fig. 5.15). This configuration ensures that EMS effectively stimulates the targeted hand muscles to drive finger movement while minimizing interference with normal hand activity. This design increases participant comfort during the experiment and improves the usability of EMS for finger training.

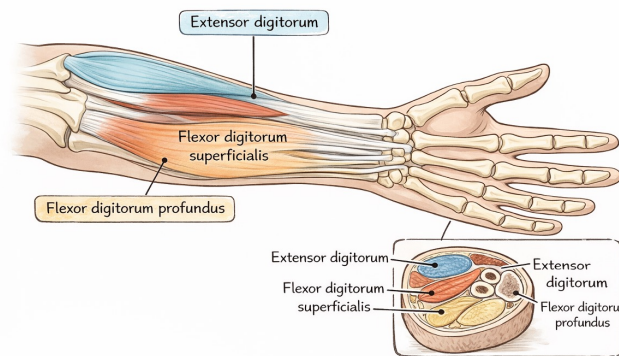


Figure 5.15: Illustrative overview of the forearm muscle groups involved in finger movement. The figure highlights the approximate regions of the extensor digitorum, flexor digitorum superficialis, and flexor digitorum profundus, which were targeted for EMS placement in this study. The diagram is intended as a conceptual reference to support electrode placement strategy rather than a precise anatomical representation.

Finger Activation

This study focuses on finger training, which requires adjustments to the EMS system to achieve more precise finger activation.

In click-based game control, finger movement primarily consists of two basic actions: flexion and extension. The extensor digitorum is responsible for finger extension, while the flexor digitorum superficialis and flexor digitorum profundus control finger flexion [163, 164, 165]. These muscles are distributed throughout the palm, wrist, and forearm

and collectively contribute to finger movement [166]. However, individual finger flexion relies primarily on tendon function [167].

Based on these physiological characteristics, we implemented a longitudinal electrode array to achieve precise finger control. Specifically, electrodes approximately 1 cm wide were placed on the tendons where the flexor digitorum superficialis branches to each finger, allowing for controlled flexion (Fig. 5.16). In addition, to prevent unintended movement of non-target fingers, additional electrodes were placed on the extensor digitorum to counteract involuntary flexion caused by electrical stimulation.

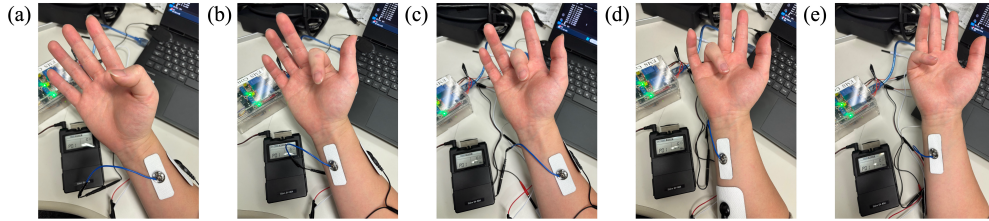


Figure 5.16: Use electrode placement to precisely control individual finger movements. (a) Bending the right thumb. (b) Right index finger flexed. (c) Right middle finger flexed. (d) Right ring finger flexed. (e) Right little finger flexed.

This electrode configuration allows for independent activation of individual fingers, allowing the EMS system to more precisely control finger movements during training, thereby improving game performance.

Calibration Procedure

Before the training session began, a calibration procedure was conducted to identify a safe and effective stimulation level for each participant. Calibration began by gradually increasing the pulse width (starting from 50 μs in 5 μs increments) until a visible but mild finger flexion was observed, which was defined as the activation threshold. Participants then reported any discomfort, and the stimulation intensity was adjusted slightly downward to ensure that the sensation remained comfortable, repeatable, and free from strain or strong tingling. The final training level was set at approximately 10–20% above the activation threshold while remaining below any level that could cause discomfort; at this level, EMS reliably produced a rapid flexion without excessive force or noticeable co-activation of adjacent fingers. In addition, the calibration process confirmed that the

EMS-induced flexion generated a stable downward motion sufficient to actuate a standard mechanical gaming mouse, ensuring that the induced movement was both strong enough to trigger a click and consistent across repeated stimulations. If unintended finger movements occurred, electrode positions were adjusted along the tendon lines or the pulse width was reduced to refine selectivity. This calibration process typically required two to four iterations and was repeated whenever participants reported changes in sensation.

Finger Training

We developed a mouse-click finger-training game (see Appendix A.2) in Python using Pygame (Fig. 5.14(d)). The game was presented at a resolution of 1366×768 pixels, and the system cursor was hidden and replaced with a crosshair to mimic aiming in FPS-like interaction. In each round, participants completed a sequence of five targets (`NUM_TARGETS = 5`). Each target was displayed as a blue circle with a radius of 120 pixels, and a number shown at its center indicated the required number of valid clicks to clear that target (i.e., participants must click inside the circle exactly that many times). The required click count for each target was randomly sampled from $\{5, 10, 15, 20, 25, 30\}$, and target locations were also randomly generated within the screen bounds. When a target's remaining count reached zero, it disappeared and the next target immediately spawned at a new random location until all five targets were cleared.

A click was counted as effective only if it occurred within the target area; otherwise, it was treated as an off-target click. The game recorded the completion time and an accuracy measure defined as the ratio of effective clicks to total clicks. Thus, participants were encouraged to repeatedly produce rapid and controlled clicks while maintaining cursor stability, resembling common gameplay demands such as repeatedly firing at a target (e.g., semi-automatic firing or burst-like actions) while keeping the aim on the target.

Importantly, EMS only assists the clicking action by providing a rapid and well-timed flexion at target onset; all cursor movements between targets must still be performed voluntarily by the participant, ensuring that spatial aiming and mouse navigation remain entirely under the user's control.

As discussed in Section 5.3.2, skill acquisition relies on repeated training to establish stable stimulus-response relationships. In this study, participants undergo finger training through repeated gameplay to improve relevant gaming skills.

To increase engagement and challenge, we introduced a reward-punishment mechanism to increase participants' focus and encourage more deliberate task performance. In the game, shorter completion times indicate better finger control. Any mistake, such as an incorrect number of clicks, results in an increase in total time. This design is intended to make participants more cautious in their actions, reduce accidental or random clicking, and ensure effective training. Similar reward-punishment systems are widely used in game design and have been shown to improve player focus and motivation [168].

This study uses this training method to improve participants' finger control in games and further explores the potential applications and benefits of EMS in gaming skill training.

EMS Actuation Timing and Trigger Logic

To clarify how EMS interacted with the training task, we describe here the timing and control logic governing stimulation during finger-training sessions. EMS was not delivered continuously; instead, a pulse was triggered only at the onset of each target to assist rapid and consistent finger flexion. When a new target appeared, the program issued a digital command to the Arduino-controlled relay, activating the EMS channel associated with the flexor digitorum and producing a brief downward finger movement to facilitate the initial click. Any subsequent clicks within the same target were performed entirely voluntarily, as EMS was never used to generate repeated activations. Each EMS pulse had a duration between 50–100 μs based on the participant's calibrated threshold, after which the system entered a short refractory window of 150 ms to prevent overstimulation and avoid involuntary double activations. The stimulation ceased immediately after this single pulse, ensuring that no prolonged contraction occurred and that participants retained full voluntary control once the finger returned to its resting position. In this configuration, EMS functioned strictly as a brief assistive cue at target onset rather than an automated clicking mechanism.

Evaluating Finger Control

In this study, finger control is assessed based on two key factors: speed and accuracy. These metrics are widely regarded as crucial indicators of gaming performance, especially in games that require precise finger control, such as shooting and rhythm-based games.

Clicks Per Second (CPS) is a commonly used metric for evaluating finger speed in gaming. CPS refers to the number of clicks performed per second and reflects a player's clicking speed in a given time frame. CPS is especially important in games that require quick clicks. A higher CPS indicates faster execution, which can improve a player's chances of success and overall efficiency in completing in-game tasks. Many games have built-in CPS tracking features to help players analyze their performance. CPS training typically involves repetitive clicking exercises; however, excessive clicking can lead to muscle fatigue or even hand injury. Therefore, it is important to manage training intensity and duration appropriately.

Accuracy refers to a player's ability to click precisely on targets, a critical factor in games requiring precise control, such as FPS, MOBA, and RTS games. Higher accuracy indicates more stable finger control and fewer mistakes, providing players with a competitive edge in gameplay. Many games offer dedicated training modes focused on accuracy, allowing players to refine their finger control through repetitive practice. Additionally, specialized training programs such as Aimlabs and KovaaK's provide structured exercises designed to improve aiming precision and operational accuracy. Similar to speed training, accuracy training relies on extensive repetition, and excessive training can lead to fatigue. To ensure long-term effectiveness, training intensity should be managed to prevent fatigue and maintain performance improvement.

5.3.4 Evaluation of finger training

To evaluate the effects of EMS-based finger training on participants, we conducted a series of experiments.

IRB Process

This study was reviewed and approved by the local ethics committee of Kyoto Sangyo University (Approval No.: KSU Ethics 0168-1; Study title: “Game Control Systems Using Electrical Muscle Stimulation”). All experiments were conducted with the informed consent of the participants, who were fully informed of the study’s purpose, procedures, and potential risks prior to participation.

Participants

We recruited Thirty participants (21 males and 9 females) aged 19 to 31. The participants had diverse backgrounds in physical ability, occupation, and gaming experience, with selection conducted randomly. All participants were in good health and had no physiological or cognitive impairments that could affect the experiment. Additionally, none of the participants had previously experienced professional or targeted finger training. These selection criteria ensured an objective evaluation of the effectiveness of EMS-based finger training.

It is worth noting that while this study did not impose strict age restrictions, the optimal age range for competitive gaming is generally considered to be between 16 and 25 years [169, 170]. Players in this age group typically demonstrate superior reaction speed, hand-eye coordination, cognitive processing, learning ability, physical endurance, and gaming experience. The age distribution of our participants aligns closely with this range, enhancing the study’s relevance for real gaming populations.

To conduct a controlled experiment, participants were randomly assigned to one of two groups: the experimental group (with EMS) and the control group (without EMS), with fifteen participants in each. Apart from the presence or absence of EMS, all experimental conditions were kept consistent between the two groups, including the game task, training procedure, number of trials, task duration, visual display settings, input device, and performance evaluation metrics. All experimental data were systematically recorded. This design ensured that any observed differences between the two groups could be attributed primarily to the EMS intervention while minimizing the influence of external variables.

Training Process

Both groups followed the designated training protocol (Fig. 5.17 within the game environment constructed in Section 5.3.3. Since the games in this study primarily relied on right-hand index and middle finger mouse clicks, training was specifically designed for these two fingers. Each finger underwent five training rounds (i.e., five full playthroughs), with each round consisting of five games. The total number of required clicks per game remained consistent, and participants were instructed to complete the task as quickly as possible. To minimize the effect of fatigue on the experimental results, all participants were given a one-minute break between training rounds.

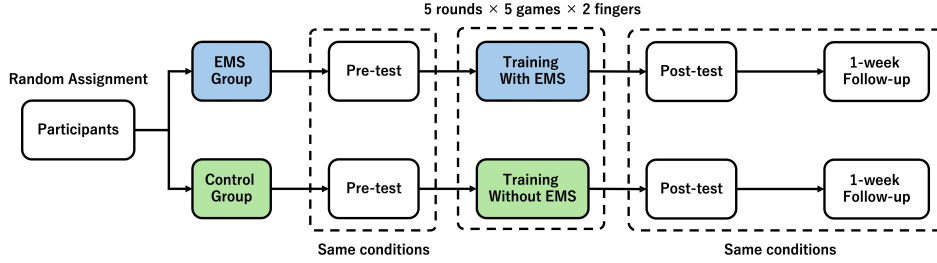


Figure 5.17: Participants in the two groups completed the tests and training following the same procedure, with or without EMS.

All participants completed three pre-training evaluations: a CPS finger speed assessment, an FPS aiming task, and a rhythm-based music game test. The evaluation order (CPS → FPS game → rhythm game) was fixed and remained identical across the Pre-training, Post-training, and Follow-up assessments. To assess the effects of training on finger control and gaming performance, we measured participants' finger speed and in-game performance before and after training to determine any improvements. In addition, to assess the retention of training effects, all participants were instructed not to engage in any games or activities similar to the training for the following one week. A follow-up test was administered after one week to determine whether the training effects had been maintained. All test data were systematically recorded throughout the experiment.

It is important to note that the fifteen participants in the EMS group wore the EMS device during all five rounds of training for both the index and middle fingers

(totaling 50 games). However, in all other aspects, their experimental procedures were identical to those of the control group, ensuring comparability of experimental conditions. Additionally, efforts were made to maintain consistency in the experimental environment before and after training, minimizing external interference and ensuring the validity and reliability of the study. During both the Post-training and Follow-up evaluations, all EMS devices were removed from the participants' hands, and no stimulation was delivered. All performance measurements in these sessions were purely voluntary.

Control Condition

The Control condition matched the EMS condition in every aspect except for the electrical stimulation itself. Both groups played the same training game with identical timing, target distribution, difficulty, and instructions, and no additional visual or auditory cues were provided exclusively to the EMS group. The Control group also did not receive any substitute timing cues such as vibration or sound; all actions relied solely on voluntary perception and movement. The number of training rounds, required clicks, break intervals, and task objectives were identical between the two groups, with the only difference being the brief EMS-induced finger flexion at target onset in the EMS group. Because the EMS pulse inherently provides a momentary proprioceptive sensation, the EMS condition may have benefited from both a physical initiation movement and a timing cue. This potential confound is discussed in the Discussion section, and future work will include a feedback-only condition to further isolate these effects.

CPS Evaluation

Thirty participants (EMS: $n = 15$, Control: $n = 15$) completed the training with or without EMS. We evaluated finger speed using CPS at three time points (pre-, post-, and one week post-training), as described in Section 5.3.3. Each CPS score is the average of three trials to ensure reliability.

For the index finger (Fig. 5.18(a)), the EMS group improved from 6.26 (pre) to 7.30 (post) and 7.17 (follow-up), i.e., mean gains of +1.04 and +0.91. The Control group changed from 6.45 (pre) to 6.72 (post) and 6.63 (follow-up), i.e., +0.27 and +0.18. For the middle finger (Fig. 5.18(b)), the EMS group improved from 5.97 (pre) to 7.09 (post)

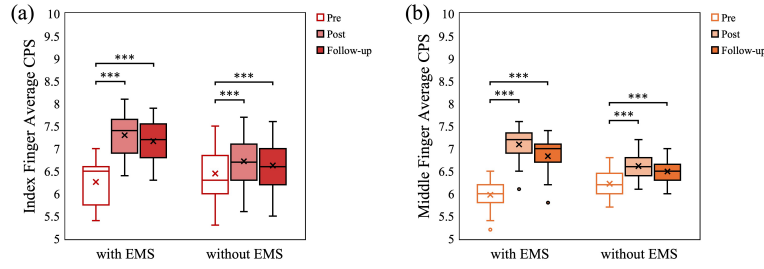


Figure 5.18: CPS (index and middle finger) for EMS and Control at pre-, post-, and 1-week follow-up. (a) Index finger average CPS. (b) Middle finger average CPS.

and 6.83 (follow-up), i.e., +1.12 and +0.86. The Control group changed from 6.22 (pre) to 6.61 (post) and 6.49 (follow-up), i.e., +0.39 and +0.27.

We conducted 2 (group: EMS vs. Control; between) $\times$ 3 (time: pre, post, follow-up; within) mixed-design ANOVAs separately for index and middle fingers. For the index finger, there was a robust main effect of time, $F(2, 56) = 720.96$, $p < .001$ (Greenhouse–Geisser $\epsilon = 0.508$, sphericity violated), and a strong group $\times$ time interaction, $F(2, 56) = 272.44$, $p < .001$ (Table 5.2). The main effect of group did not reach significance, $F(1, 28) = 2.13$, $p = .156$. For the middle finger, we again observed a strong main effect of time, $F(2, 56) = 953.98$, $p < .001$ (Greenhouse–Geisser $\epsilon = 0.520$, sphericity violated), and a significant group $\times$ time interaction, $F(2, 56) = 228.77$, $p < .001$ (Table 5.4). The main effect of group was not significant, $F(1, 28) = 2.11$, $p = .157$.

Bonferroni-corrected post-hoc comparisons showed that CPS increased from pre to post and remained above baseline at follow-up for both fingers (all $p_{\text{corr}} < .001$). For both fingers, follow-up was *lower* than post (index: $p_{\text{corr}} < .001$; middle: $p_{\text{corr}} < .001$), indicating some decay after one week but still clear retention relative to pre (Tables 5.3, 5.5). Between-group contrasts revealed no baseline differences. For the index finger, EMS outperformed Control at both post and follow-up after correction ($p_{\text{corr}} = .031$ and $.044$, respectively). For the middle finger, EMS was superior at post ($p_{\text{corr}} = .004$) but not at follow-up ($p_{\text{corr}} = .061$).

In summary, CPS improved markedly over time in both groups, with substantially larger immediate gains under EMS and partial retention at one week. Although there was some decline from post to follow-up, EMS participants still maintained higher CPS than baseline, and (for the index finger) remained significantly ahead of Control at

follow-up. The significant interactions indicate that EMS accelerated learning relative to repetitive practice alone.

Table 5.2: Mixed-design ANOVA for CPS (Index Finger)

Source	SS	df ₁	df ₂	MS	<i>F</i>	<i>p</i>	Sig.
Group	2.178	1	28	2.178	2.125	.156	False
Time	7.393	2	56	3.696	720.957	< .001	True
Group×Time	2.794	2	56	1.397	272.437	< .001	True

Table 5.3: Post-hoc comparisons for CPS (Index Finger)

Contrast	A	B	<i>t</i>	df	<i>p_{unc}</i>	<i>p_{corr}</i>	Sig.
Time (all)	post	pre	8.865	29	< .001	< .001	True
Time (all)	follow-up	pre	7.628	29	< .001	< .001	True
Time (all)	follow-up	post	-14.297	29	< .001	< .001	True
Group @ pre	EMS	Control	0.833	28	.412	1.000	False
Group @ post	EMS	Control	-2.747	28	.010	.031	True
Group @ follow-up	EMS	Control	-2.599	28	.015	.044	True

Table 5.4: Mixed-design ANOVA for CPS (Middle Finger)

Source	SS	df ₁	df ₂	MS	<i>F</i>	<i>p</i>	Sig.
Group	0.822	1	28	0.822	2.113	.157	False
Time	9.298	2	56	4.649	953.984	< .001	True
Group×Time	2.230	2	56	1.115	228.765	< .001	True

5.3.5 Evaluation of Finger Control in Gaming

To further assess the impact of finger training on participants' gaming skills, we conducted evaluations in a shooting game and a rhythm-based music game.

In the Shooter Game: Aimlabs [171] is a training platform designed to improve first-person shooter (FPS) game skills, with approximately 40 million users. Aimlabs allows for custom training (Fig. 5.19) to simulate the gameplay and mechanics of popular FPS games such as Counter-Strike, Rainbow Six, and Call of Duty. Many players, both casual and professional, use Aimlabs for skill training in shooting games. Therefore, this

Table 5.5: Post-hoc comparisons for CPS (Middle Finger)

Contrast	A	B	t	df	p_{unc}	p_{corr}	Sig.
Time (all)	post	pre	10.746	29	< .001	< .001	True
Time (all)	follow-up	pre	9.704	29	< .001	< .001	True
Time (all)	follow-up	post	-11.763	29	< .001	< .001	True
Group @ pre	EMS	Control	1.970	28	.059	.176	False
Group @ post	EMS	Control	-3.537	28	.001	.004	True
Group @ follow-up	EMS	Control	-2.463	28	.020	.061	False

study utilizes Aimlabs to evaluate participants' actual performance in shooting games after finger training.

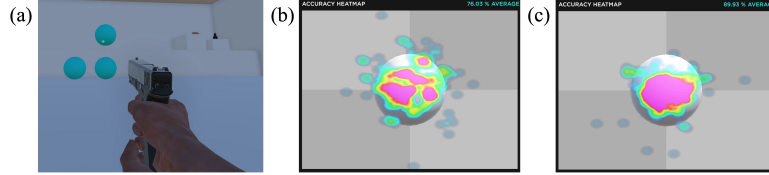


Figure 5.19: Game control in Aimlabs. (a) Customized shooting tasks are created using the shooting skill assessment editor. (b) Performance of a player with lower shooting skills, showing a more scattered shot distribution. (c) Performance of a player with higher shooting skills, showing a more concentrated shot distribution.

We created a custom training scenario, similar to Counter-Strike, where participants must precisely control the mouse to quickly eliminate targets. Each training session lasts 30 seconds, and at the end of the test, the system automatically calculates the participant's accuracy rate and average time to eliminate a single target. As described in Section 5.3.3, accuracy rate and average time per kill are key indicators for assessing finger control precision. We collected data from both groups pre-, post-, and one week post-training to evaluate whether their finger precision improved. Each participant's performance in the game was measured as the average of three tests to ensure reliability.

For hit accuracy (Fig. 5.20(a)), the EMS group increased from 80.44% (pre) to 85.03% (post) and 84.41% (follow-up), i.e., gains of +4.59 and +3.97 percentage points. The Control group changed from 79.65% (pre) to 83.58% (post) and 82.81% (follow-up), i.e., +3.93 and +3.16 points. For average time per kill (Fig. 5.20(b)), the EMS group decreased from 0.359 s (pre) to 0.246 s (post) and 0.241 s (follow-up), i.e., improvements

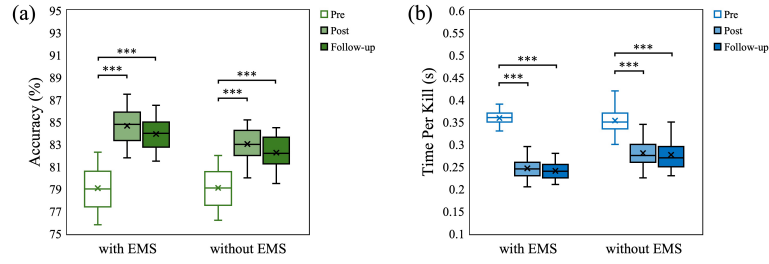


Figure 5.20: Comparison of in-game test results at pre-, post-, and 1-week follow-up for both groups. (a) Hit accuracy (%). (b) Average time per kill (s).

of -0.113 s and -0.118 s. The Control group decreased from 0.353 s (pre) to 0.280 s (post) and 0.277 s (follow-up), i.e., -0.073 s and -0.077 s.

We conducted 2 (group: EMS vs. Control; between) $\times 3$ (time: pre, post, follow-up; within) mixed-design ANOVAs for accuracy and time per kill. For accuracy, there was a strong main effect of time ($p < .001$) and a significant group $\times$ time interaction ($p < .001$), while the main effect of group was not significant ($p = .092$) (Table 5.6). For time per kill, we again observed a strong main effect of time ($p < .001$) and a significant group $\times$ time interaction ($p < .001$), with a non-significant main effect of group trending toward significance ($p = .054$) (Table 5.8).

Bonferroni-corrected post-hoc comparisons showed that, for accuracy, both groups improved from pre to post and remained higher than pre at follow-up (both $p_{\text{corr}} < .001$), whereas post $>$ follow-up (i.e., a small drop) was also significant ($p_{\text{corr}} < .001$) (Table 5.7). Between-group contrasts indicated no baseline difference ($p_{\text{corr}} = 1.000$); EMS outperformed Control at post and follow-up ($p_{\text{corr}} = .035$ and $.018$). For time per kill, pre $\rightarrow$ post and pre $\rightarrow$ follow-up were significant (both $p_{\text{corr}} < .001$), and follow-up was slightly faster than post ($p_{\text{corr}} < .001$) (Table 5.9). Between-group contrasts again showed no baseline difference ($p_{\text{corr}} = 1.000$), while EMS was faster than Control at post and follow-up ($p_{\text{corr}} = .014$ and $.009$).

Overall, EMS yielded larger gains than Control on both accuracy and kill time specifically at post/follow-up (interaction pattern), even though the overall group main effects were not significant. This indicates that EMS accelerated improvement during training and supported short-term retention, leading to superior FPS task performance relative to repetitive practice alone.

Table 5.6: Mixed-design ANOVA for Aimlabs Accuracy

Source	SS	df ₁	df ₂	MS	<i>F</i>	<i>p</i>	Sig.
Group	27.005	1	28	27.005	3.050	.092	False
Time	392.785	2	56	196.392	2053.564	< .001	True
Group×Time	14.006	2	56	7.003	73.228	< .001	True

Table 5.7: Post-hoc comparisons for Aimlabs Accuracy. Bonferroni-corrected *p* reported where applicable.

Contrast	A	B	<i>t</i>	df	<i>p_{unc}</i>	<i>p_{corr}</i>	Sig.
Time (all)	post	pre	27.115	29	< .001	< .001	True
Time (all)	follow-up	pre	21.527	29	< .001	< .001	True
Time (all)	follow-up	post	-20.860	29	< .001	< .001	True
Group @ pre	EMS	Control	0.028	28	.978	1.000	False
Group @ post	EMS	Control	-2.690	28	.012	.036	True
Group @ follow-up	EMS	Control	-2.965	28	.006	.018	True

In the Rhythm Game: In addition to the shooting game, we also conducted an evaluation of a rhythm-based music game. Since this study was specifically designed to train the right index and middle fingers, we chose MuseDash [172], a rhythm game that can be played with only two types of keys.

MuseDash is simple and easy to learn and is well received by rhythm game players. In this game, players press the appropriate keys in synchrony with the musical rhythm. In this study, we selected tracks with a moderate difficulty level in MuseDash, which typically correspond to tempos in the range of approximately 120–180 BPM. Under these conditions, players are required to produce sustained rhythmic inputs at a rate of several keystrokes per second during continuous sections. Since there are only two types of input (up and down), the challenge does not lie in multi-finger coordination, but rather in finger speed and rhythmic accuracy. This control method makes MuseDash suitable for evaluating the effectiveness of the finger training used in this study.

To evaluate participants’ finger speed and precision under fast-paced rhythmic conditions, we measured their completion rate in the game. All participants completed the same rhythm test, and upon completion, the system automatically calculated their completion rate. As in previous evaluations, we collected data pre-, post-, and one week

Table 5.8: Mixed-design ANOVA for Aimlabs Time per Kill

Source	SS	df ₁	df ₂	MS	<i>F</i>	<i>p</i>	Sig.
Group	0.010	1	28	0.010	4.050	.054	False
Time	0.181	2	56	0.091	2689.886	< .001	True
Group×Time	0.008	2	56	0.004	122.796	< .001	True

Table 5.9: Post-hoc comparisons for Aimlabs Time per Kill. Bonferroni-corrected *p* reported where applicable.

Contrast	A	B	<i>t</i>	df	<i>p_{unc}</i>	<i>p_{corr}</i>	Sig.
Time (all)	post	pre	-22.991	29	< .001	< .001	True
Time (all)	follow-up	pre	-23.146	29	< .001	< .001	True
Time (all)	follow-up	post	-4.597	29	< .001	< .001	True
Group @ pre	EMS	Control	-0.551	28	.586	1.000	False
Group @ post	EMS	Control	3.071	28	.005	.014	True
Group @ follow-up	EMS	Control	3.272	28	.003	.009	True

post-training to determine whether training resulted in improvements in finger control. Each participant's performance was recorded as an average of three tests to ensure accuracy and reliability.

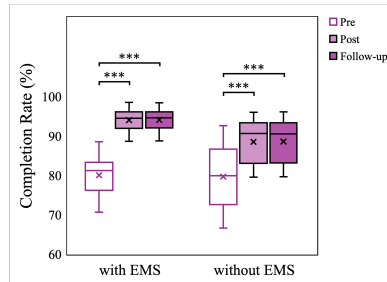


Figure 5.21: Comparison of rhythm game (MuseDash) completion rates at pre-, post-, and 1-week follow-up for both groups.

For completion rate (Fig. 5.21), the EMS group improved from 80.1% (pre) to 93.7% (post) and 93.8% (follow-up), yielding gains of about +13.6 and +13.7 percentage points. The Control group changed from 79.4% (pre) to 88.8% (post) and 88.9% (follow-up), i.e., gains of +9.4 and +9.5 points. Thus, EMS produced larger improvements, though both groups showed practice-related gains.

We conducted a 2 (group: EMS vs. Control; between) $\times$ 3 (time: pre, post, follow-

up; within) mixed-design ANOVA for completion rate. Results showed a strong main effect of time ($p < .001$), a significant group $\times$ time interaction ($p < .001$), but the overall main effect of group was not significant ($p = .056$) (Table 5.10).

Bonferroni-corrected post-hoc comparisons showed that completion rate improved from pre to post and was retained at the 1-week follow-up (both $p_{\text{corr}} < .001$). Post vs. follow-up comparisons indicated a very small additional increase ($p_{\text{corr}} < .01$), though practically negligible. Between-group contrasts indicated no baseline differences, while EMS outperformed Control at post and follow-up ($p_{\text{corr}} < .01$), consistent with the interaction effect (Table 5.11).

In summary, the rhythm game results show that EMS training led to significantly greater improvements in completion rate compared to repetitive practice. Although both groups improved, EMS gains were consistently larger and well retained at the 1-week follow-up. These findings confirm that EMS not only enhances finger speed and precision under rhythmic conditions but also supports the transfer of training effects to actual gameplay in music games.

Table 5.10: Mixed-design ANOVA for MuseDash Completion Rate

Source	SS	df ₁	df ₂	MS	F	p	Sig.
Group	324.140	1	28	324.140	3.989	.056	False
Time	2624.401	2	56	1312.200	387.771	$< .001$	True
Group $\times$ Time	132.271	2	56	66.135	19.544	$< .001$	True

Table 5.11: Post-hoc comparisons for MuseDash Completion Rate. Bonferroni-corrected p reported where applicable.

Contrast	A	B	t	df	p_{unc}	p_{corr}	Sig.
Time (all)	post	pre	15.373	29	$< .001$	$< .001$	True
Time (all)	follow-up	pre	15.390	29	$< .001$	$< .001$	True
Time (all)	follow-up	post	3.597	29	.001	.004	True
Group @ pre	EMS	Control	-0.150	28	.882	1.000	False
Group @ post	EMS	Control	-3.234	28	.003	.009	True
Group @ follow-up	EMS	Control	-3.245	28	.003	.009	True

5.3.6 User Survey

As mentioned in Section 5.3.3, training-induced fatigue and stress should be minimized. Therefore, we conducted a user survey to assess the level of fatigue caused by the training.

We collected fatigue ratings from 30 participants (15 EMS, 15 Control) after training, using a scale from 0 (no fatigue) to 5 (severe fatigue). In the Control group (without EMS), 3 participants reported mild fatigue (level 1), 6 participants reported moderate fatigue (level 3) with muscle soreness in their fingers and wrists, and 3 participants reported severe fatigue (level 4), requiring extended rest for recovery. In contrast, in the EMS group, only 3 participants reported mild fatigue (level 1). Another participant noted slight discomfort from using EMS but did not experience fatigue or difficulty completing training. The remaining 11 participants reported no fatigue or discomfort.

To examine group differences statistically, we compared fatigue ratings using a non-parametric Mann–Whitney U test, as the ratings were ordinal. The analysis showed that EMS participants reported significantly lower fatigue scores than the Control group ($U = 42.0, p < .001$). This confirms that EMS training not only improved finger performance but also effectively reduced subjective fatigue compared to repetitive practice alone.

These results indicate that participants who used EMS experienced markedly less finger and hand muscle fatigue during training, while those without EMS were more likely to report moderate to severe fatigue.

5.3.7 Discussion

This study proposes a method using EMS to enhance finger control, which helps participants improve their gaming skills. Our research shows that EMS can effectively increase participants' finger speed (CPS) and rapidly improve their performance in a shooting game and a rhythm game. Furthermore, our experiments confirmed that the skill improvements gained from finger training were retained even after one week. We will discuss the results of this study to support future research and work.

Contributions and Distinction from Prior EMS-Based Training

Our findings extend the existing literature on EMS-enabled skill augmentation in several ways. Previous studies by Zhou and Segawa [141, 142] demonstrated that EMS can

improve timing-related control and hand–eye coordination in gaming contexts. These tasks primarily involve perceptual alignment, decision timing, and visuomotor mapping. In contrast, the present study focuses on a different and more fundamental aspect of game interaction: fine-grained finger execution. Finger speed and precision rely on rapid muscle activation, consistent force generation, and high-frequency repetition, which differ substantially from timing or aiming tasks. To our knowledge, this work is the first to investigate how EMS can directly support the acquisition of finger-level motor skills in high-frequency clicking tasks.

A second distinction lies in task generalization. While prior studies concentrated on improvements within a single task domain, our results demonstrate cross-task transfer. Participants trained on a custom finger-clicking task showed performance improvements not only in the trained task, but also in two distinct game genres: an FPS scenario requiring rapid target engagement and a rhythm game requiring precise tempo execution. This cross-genre generalization suggests that EMS supports improvements in underlying finger control mechanisms rather than task-specific strategies.

Third, the present study uses a larger and more statistically reliable sample size ($n=30$), compared to the smaller-scale cohorts in earlier work. The training task also involved more complex sequences, requiring repeated multi-click operations under variable target conditions. These enhancements strengthen the robustness and generalizability of our findings.

Taken together, this work complements and advances prior EMS research by shifting the focus from perceptual or coordination augmentation toward direct motor execution enhancement at the finger level, and by demonstrating that EMS-induced improvements can transfer across multiple real-game contexts.

Why EMS Improves Finger Control

The results of this study show that EMS training led to larger improvements in finger speed, precision, and in-game performance compared to voluntary practice alone. Several mechanisms may account for these differences.

Proprioceptive feedback. Each EMS pulse produces a brief but mechanically consistent finger flexion. This stimulation acts as a proprioceptive event that aligns

voluntary intention with a reliable sensory consequence. Such proprioceptive inputs contribute to the refinement of internal motor models by reducing variability in movement execution. In contrast, voluntary practice alone produces more variable movement trajectories, which may slow the formation of stable sensorimotor associations.

Reduction of training-induced fatigue. Our fatigue analysis showed that participants in the Control group reported significantly higher levels of physical fatigue. Fatigue has been shown to impair motor learning and disrupt consolidation of new skills [173, 174]. By providing partial actuation at the onset of each movement, EMS reduced the physical load on the flexor muscles, allowing participants to sustain consistent performance throughout the training. Lower fatigue likely enabled more effective practice and contributed to the larger learning gains observed in the EMS group.

Consistency of movement patterns. Because EMS generated a rapid and repeatable initiation of finger flexion, participants in the EMS condition experienced more uniform movement patterns across repetitions. Consistency is an important factor in motor memory formation, as repeated exposure to stable movement trajectories facilitates the extraction of motor primitives and the strengthening of associated neural pathways [175, 176]. In contrast, variability in voluntary movement may introduce noise into the learning process, leading to slower improvement.

Motor learning mechanisms. The combination of proprioceptive input, reduced fatigue, and consistent actuation may interact with established mechanisms of sensorimotor learning, such as Hebbian plasticity and spike-timing-dependent plasticity [156]. EMS provides temporally aligned sensory and motor events that may accelerate the refinement of internal forward models and strengthen the coupling between intention and execution. This alignment may explain why improvements in the EMS group persisted at the one-week follow-up despite the absence of further stimulation.

Role of timing cues. Although EMS actuation coincided with the appearance of each target and may have served as a timing cue, timing information alone cannot fully explain the observed results. Improvements were retained during follow-up sessions with no stimulation, and the EMS group outperformed the Control group even in the rhythm game, where precise timing cues were already present within the gameplay. These findings suggest that the benefits of EMS stem from improved motor execution

rather than exclusively from additional timing information.

Taken together, the evidence suggests that EMS enhances finger control through a multifaceted combination of proprioceptive reinforcement, reduced fatigue, stable movement initiation, and biologically plausible motor learning processes. These mechanisms likely work in concert to accelerate the acquisition and consolidation of fine motor skills.

Limitation

While this study provides a new approach and reference for using EMS to enhance gaming skills, we must also acknowledge its limitations.

First, our experiment involved a shooting game (Aimlabs) and a rhythm game (MuseDash). The control methods in these games represent only a subset of the diverse control schemes in video games. In Aimlabs, the customized gameplay focused on rapid clicking with a fixed task structure and limited interaction variations. Similarly, MuseDash requires players to press two types of buttons in response to rhythmic cues, simplifying finger coordination compared to other rhythm games. Many games involve more complex control schemes, including multi-button combinations, dynamic target tracking, and adaptive actions (e.g., OSU). Future research should extend the evaluation to a wider range of games with different control mechanisms to further assess the generalizability of EMS training in gaming environments.

Second, we assessed skill retention only one week after training. Although the results suggest that improvements from EMS training persist for at least one week, we have yet to examine its long-term effects over longer periods (e.g., weeks or months). Finger training in gaming, like other motor skill training, follows basic principles of skill acquisition. Typically, skills or abilities that are improved through training form memory traces in the brain, known as retention effects. Training can be thought of as a process of acquiring new information, while memory determines the degree of retention. Bailey and Bartsch suggest that training-induced memory can be divided into short-term memory (lasting minutes or hours) and long-term memory (lasting weeks, months, or even permanently) [177]. Long-term memory can sometimes be established in a single training session and retain its effects over an extended period. Compared to short-term memory, long-term memory not only has a longer retention period but also plays a

more significant role in storage capacity [178]. Given that the effects of gaming skills training may diminish over time, long-term evaluations are needed to determine whether EMS training leads to lasting improvements. Future research should further investigate the retention of EMS-induced improvements over longer periods to assess its long-term impact on gaming performance.

Third, our study involved 30 participants (15 with EMS, 15 without EMS), which provides a stronger basis for statistical analysis compared to smaller-scale studies. Nevertheless, the sample size is still relatively limited, and individual differences in baseline skills and adaptability may have influenced the results. To further improve generalizability and reliability, future research should include larger and more diverse participant groups. In addition, more comprehensive qualitative analyses, such as broader user surveys and interviews, could provide deeper insights into subjective factors such as fatigue, comfort, and perceived improvements in the gaming experience.

Fourth, the assessment of fatigue relied mainly on self-reported ratings. While these results provide valuable subjective insights, they may be influenced by individual perception biases. Objective physiological measures such as electromyography (EMG), heart rate variability (HRV), or muscle oxygenation could complement self-reports and provide more robust evidence on how fatigue interacts with motor learning and training outcomes. Future studies should incorporate such multimodal measures to better capture the relationship between training load, fatigue, and performance.

Finally, our study focused exclusively on non-professional players and did not examine the effects of EMS training on professional players. Given the diversity of the gaming population, future research should include professional players as a control group to determine if EMS training offers advantages over traditional training methods. Including professional players in the evaluation of training effectiveness would further enhance the applicability and professionalism of EMS as a gaming training tool.

Potential Feedback-Related Confound

A potential confound in our study concerns the fact that EMS actuation at the onset of each target may also have served as a timing cue. Because the Control condition received no comparable cue, one may argue that the EMS group's advantage could stem from the

additional temporal signal rather than the muscle actuation itself. We acknowledge this possibility and discuss here why the observed improvements cannot be fully explained by timing cues alone.

Differences between timing cues and muscle actuation. A timing cue provides information about when to initiate an action, whereas EMS-induced actuation also generates a proprioceptive and kinesthetic signal that reflects how the action is performed. The stimulation produces a brief, mechanically consistent flexion, allowing participants to internalize a stable action template. Such proprioceptive input is known to contribute to sensorimotor learning and is qualitatively different from receiving a passive cue [175].

Evidence beyond timing cues. Several observations from our data suggest that the advantage of EMS cannot be attributed solely to timing information. First, improvements were retained at the 1-week follow-up, despite the absence of EMS or any cues during the retention tests. If training benefits were based solely on external cues, we would expect the performance gap between groups to narrow substantially at follow-up. Instead, EMS participants maintained higher CPS and superior in-game performance, demonstrating consolidation of motor patterns rather than reliance on momentary temporal signals.

Second, the EMS group displayed larger improvements not only in tasks where timing cues could be helpful (CPS, Aimlab), but also in the rhythm game, where stimulus timing is already provided by the game itself. Since MuseDash inherently offers precise rhythmic cues, the presence of an additional onset cue from EMS would have contributed minimally. The consistent advantage across tasks suggests that EMS facilitated improvements in motor execution rather than merely providing extra timing information.

Third, subjective fatigue ratings showed that the EMS group experienced significantly less physical fatigue during training. Reduced fatigue is known to preserve movement consistency and enhance motor learning efficiency. This effect is independent of timing cues and likely contributed to the larger training gains in the EMS group [179].

Future control conditions. While these findings suggest that timing cues do not fully account for the observed improvements, we agree that separating the influence of cues and actuation is important. As future work, we plan to introduce an additional “feedback-only” condition in which participants receive a vibrotactile or auditory sig-

nal at target onset without any muscle actuation. This will allow direct comparison between (1) cue-only learning, (2) actuation-based learning, and (3) voluntary practice, helping to isolate the specific contribution of EMS-driven muscle activation in finger-skill acquisition.

Overall, although EMS actuation may have provided a momentary temporal cue, multiple lines of evidence indicate that the benefits observed in this study stem from more than timing assistance alone. The results are better explained by a combination of motor execution support, proprioceptive feedback, reduced fatigue, and improved movement consistency, which together facilitate the acquisition and retention of fine finger-control skills.

Why was APM not Evaluated

Actions Per Minute (APM) refers to the total number of actions performed per minute, including clicks, keystrokes, skill activations, and movement commands. It is commonly used as a performance metric in RTS games such as StarCraft and MOBA games such as Dota 2 and League of Legends, where it is often associated with a player’s overall efficiency and multitasking ability [180].

However, APM does not necessarily correlate directly with actual player performance in all gaming contexts. Higher APM does not always translate into better gameplay outcomes. Skilled players often exhibit optimized APM, meaning that they focus on performing meaningful and efficient actions rather than frequent, low-efficiency checks [181] [182]. For example, in RTS games, expert players tend to have lower APM during strategic decision-making phases and higher APM during intense micro-control situations. Similarly, in MOBA games, APM is only one of many factors influencing success, along with map awareness, decision-making, and teamwork coordination [183] [184].

In this study, we focused primarily on finger speed and accuracy rather than overall action frequency. Given that excessive or unnecessary actions do not always contribute to improved performance, and that different games require different levels of APM, we did not include APM as a core evaluation metric. Instead, we prioritized CPS and in-game accuracy as these metrics are more directly related to the effectiveness of EMS training on participants’ finger control.

The Role of Fatigue in Training Outcomes

Although both the EMS and Control groups showed significant improvements after training, the EMS group consistently demonstrated larger gains in CPS and in-game tasks. We interpret this difference as being strongly influenced by training-induced fatigue.

Our user survey indicated that participants without EMS reported notably higher levels of fatigue, often moderate to severe, whereas EMS participants reported little to no fatigue. Prior studies have shown that fatigue can reduce motor learning efficiency and hinder consolidation of new skills [185, 186]. In our study, Control participants did improve, but the short-term high-intensity training likely induced fatigue that limited their overall training effects. Thus, their gains, though significant, were smaller and less sustained than those of the EMS group.

In contrast, EMS training generated muscle contractions with less voluntary effort, enabling participants to maintain attention and coordination with reduced fatigue. This lower physical load likely contributed to the larger and more stable improvements observed in the EMS group, consistent with previous findings that EMS can facilitate motor adaptation while reducing training burden [141].

Overall, these results suggest that one of the key advantages of EMS training lies not only in direct muscle activation but also in mitigating fatigue during intensive practice. Future research should include more comprehensive evaluations across longer training periods, varied tasks, and diverse participant groups to further validate the mechanisms and generalizability of EMS-based training.

Applications

Although the effectiveness of EMS in hand-eye coordination training for other games or sports requires further research, the results of this study suggest that EMS training has potential applications. The following are potential application scenarios.

Professional Skill Training: In this study, participants had no extensive experience in shooting or rhythm games before the experiment, yet their skills improved significantly after EMS training. Finger control plays a crucial role in mastering these motor skills, indicating that the proposed method may apply to broader professional skill training.

Many industries rely on precise finger control, such as musical instrument performance, surgical procedures, and competitive sports, where training often requires substantial time and cost [187, 188]. Patel et al. highlighted that scientifically effective training methods are essential for skill acquisition and performance enhancement [189]. Given the specialized nature and importance of these skills, professionals in relevant fields may consider integrating EMS training into their training systems to accelerate skill acquisition and reduce training costs. By enhancing finger control and coordination through EMS, professionals can improve training efficiency and master complex skills more quickly.

Reducing Training Load in Competitive Sports and E-sports: In both competitive sports and e-sports, athletes undergo long hours of high-intensity training to maintain their competitive level. Unlike amateur players, professional athletes must engage in prolonged, high-level training, which can lead to sports-related injuries over time [114, 149]. Studies have shown that accumulated training load is a major contributing factor to injuries in both traditional sports and e-sports [130, 190]. Since finger control plays a critical role in competitive training, EMS training could serve as an effective and safe training tool. By improving finger control with EMS, athletes can increase training efficiency, reduce training time, and decrease the risk of overuse injuries. Incorporating EMS into training programs can help professional players maintain peak performance while minimizing the long-term physical stress caused by extended training sessions.

5.3.8 Conclusion and Future Work

This study proposes an EMS-based finger training method aimed at improving players' finger control in games. Through a series of experiments, we demonstrated that EMS training effectively improved participants' finger speed and accuracy, leading to better performance in shooting and rhythm games. Furthermore, the experimental results showed that the training effects were retained even one week after the training session, indicating that EMS not only provides short-term skill improvement but also has a certain retention effect.

EMS-based finger training offers several advantages. (1) It can rapidly improve finger speed and accuracy within a short period, helping players improve their gaming

performance more efficiently. (2) Improved finger control facilitates quicker adaptation to unfamiliar game mechanics, thus reducing the learning curve. (3) EMS provides a relatively low-fatigue training method that is easy to implement, allowing players to engage in training with minimal preparation. However, further research is needed to determine whether EMS can provide similar benefits in a wider range of games or physical training contexts. This method may be particularly beneficial for amateur players seeking rapid skill improvement. Additionally, given the importance of precise finger control in competitive sports and e-sports, future research could explore the potential applications of EMS in professional training. The findings of this study serve as a preliminary reference for related research.

In future studies, we plan to further investigate the broader applications of EMS training in finger control. This will include increasing the sample size to improve the reliability and applicability of the data, as well as testing the effectiveness of EMS training across different game genres to assess its generalizability. In addition, we will conduct long-term experiments to examine the retention of training effects over time. Moreover, alongside quantitative analysis, we will gather subjective feedback from participants regarding their training experience, comfort, and learning efficiency for qualitative evaluation. Through these investigations, we aim to gain a more comprehensive understanding of the potential of EMS training and explore its applicability in various domains.

5.4 Chapter Summary

This chapter focused on sensorimotor augmentation, examining the applications and effects of EMS in timing control and fine finger movement. Two empirical studies validated the potential of EMS from different perspectives. First, in timing control training, the results demonstrated that EMS could help users quickly establish correct response patterns, thereby significantly improving the accuracy and speed of their actions. Second, in finger control training, EMS not only enhanced participants' fine motor performance but also showed partial long-term effects in retention tests conducted after the training. These findings indicate that EMS can exert a direct augmentative effect on the sensorimotor level, functioning both as an immediate cue to enhance short-term performance and, through its integration with voluntary motor intentions, as a facilitator of skill learning and retention.

Overall, the results of this chapter confirm the feasibility and effectiveness of EMS in sensorimotor coordination, providing a foundation for its application in more complex augmentation tasks. The outcomes suggest that EMS can improve basic motor execution and, to some extent, shape the learning process itself. Building on this foundation, the next chapter expands the scope of investigation to explore EMS in higher-level coordination augmentation, particularly through hand-eye coordination training and musical instrument learning tasks, to validate its potential in multi-limb collaboration and complex skill acquisition.

Chapter 6

Coordination Augmentation

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6.1 Overview of Coordination Augmentation

Within the research framework of Augmented HCI, the enhancement of coordination represents a more complex dimension than basic sensorimotor control. Many real-world

tasks do not rely solely on the accuracy of single actions but instead require users to integrate multiple motor signals across time and space to achieve multi-limb collaboration. Examples include bimanual input in games, interaction control in virtual environments, and musical instrument performance, all of which demand synchronization between vision and hand movements as well as coordination between both hands. Compared with traditional training methods, EMS can provide external guidance at critical moments, helping users to rapidly establish correct coordination patterns, thereby reducing learning costs and accelerating the process of skill acquisition.

This chapter presents two studies to examine the role of EMS in coordination augmentation. The first study focuses on hand-eye coordination training, investigating whether EMS can improve users' bimanual performance and visual attention switching in dynamic tasks, thereby enhancing overall task outcomes. The second study addresses musical instrument learning, testing whether EMS can provide guidance in matching musical rhythms with hand movements and assist learners in acquiring complex bimanual playing patterns within a short period of time. Through these empirical studies, this chapter seeks to answer the following question: Can EMS significantly enhance user performance in multi-limb coordination and complex skill learning, and does it show potential in terms of retention and transferability?

6.2 EMS-Based Training for Hand–Eye Coordination

Based on “Method of Electrical Muscle Stimulation to Improve Hand-eye Coordination Training in Gaming.” – Zhou and Segawa, Proc. ACM Hum.-Comput. Interact. (CHI PLAY 2024)

Hand–eye coordination is a fundamental ability for effective interaction, requiring the integration of visual perception with bimanual movements. While essential in gaming and other interactive tasks, acquiring this ability within a short time can be challenging, especially for unfamiliar activities. EMS offers a way to directly guide hand movements while supporting attention distribution across both hands, making it a promising method for accelerating the acquisition of hand–eye coordination. In this section, we introduce an EMS-based training approach and evaluate its effectiveness through controlled experiments in both customized and real gaming contexts.

6.2.1 Introduction

Precise coordination between the hands is crucial for complex tasks such as playing musical instruments, playing games, or performing surgery, where the hands operate at different frequencies, amplitudes, directions, and forces [191]. This specific coordination, which relies on hand-eye coordination, integrates visual information to guide hand movements [107]. When tasks require both hands, attention isn’t fixed on one hand but is distributed according to the demands of the task. Appropriate allocation of attention improves hand-eye coordination and supports complex bilateral movements [192]. As skills develop, individuals may rely less on vision and more on tactile feedback for precision tasks. However, this level of coordination typically depends on extensive, repetitive training. When people are faced with an unfamiliar sport, it is difficult to develop coordination between the hands in a short period. Hand-eye coordination plays a very important role in the early stages of training for these hand-coordination exercises. Through hand-eye coordination training, people can visually acquire information that can be used to modify and guide the coordination of the hands, thus mastering unskilled movements in a continuous process of modification [135].

Video games are often competitive and challenging, and in many game genres, coordi-

nation between perception and action plays an important role. In action-oriented games such as first-person shooters, players must continuously integrate visual information with hand movements to aim and shoot accurately [136]. Similarly, in MOBA (multiplayer online battle arena) games, players rely on both mouse and keyboard inputs to navigate, target opponents, and execute skills under time pressure. In rhythm-based games, player performance is influenced by multiple factors, including auditory timing, predictive processing, and motor execution. While experienced players often rely on learned patterns and temporal prediction, especially at higher difficulty levels, visual cues and hand-eye coordination remain important, particularly for novice players and in reaction-driven segments where targets must be tracked or aligned in real time (e.g., games that combine rhythm input with cursor or pointer control such as *osu!*). Beyond action and rhythm games, hand-eye coordination is also required in non-action contexts, such as Quick Time Events (QTEs), where players must respond to visual prompts within limited time windows to maintain immersion or progress in the game. Overall, although the relative contribution of visual, auditory, and predictive processes varies across genres and skill levels, proficient hand-eye coordination remains a fundamental component of interactive gameplay and contributes significantly to player experience [193]. Therefore, training hand-eye coordination is an important aspect of improving game-related motor skills.

Previously, hand-eye coordination training has been performed by touching a physical object or a 2D screen [194]. Wang et al. proposed a learnable action space, the Hand-Eye Action Network (HAN), which learns coordinated hand-eye movements from human remote control demonstrations [195]. There have also been several virtual reality-based studies of hand-eye coordination [196, 197]. Batmaz et al. compared hand-eye coordination training in three approaches: augmented reality, virtual reality, and traditional physical touch [139]. However, there are no studies on hand-eye coordination training using electrical muscle stimulation.

Previous research suggests the potential of EMS to train human motor perception [141]. The mechanism of hand-eye coordination closely mirrors that of motion perception, with both relying fundamentally on sensory input to control the body. Drawing on this parallel, this study presents a method of training hand-eye coordination using EMS

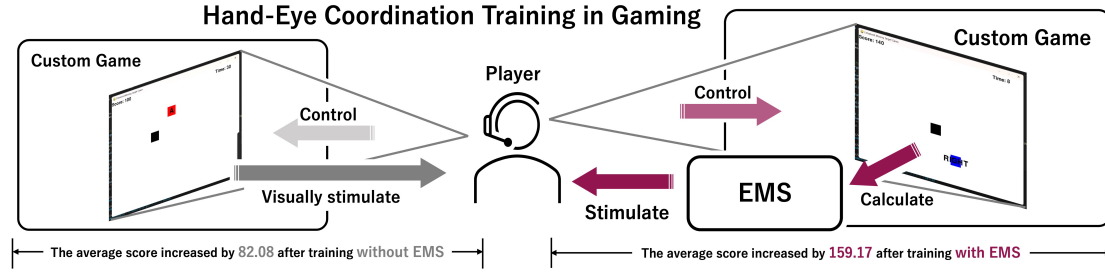


Figure 6.1: To facilitate hand coordination training in gaming, this study developed a customized training system based on EMS. Participants can switch their attention with the help of EMS to improve the efficiency of hand-eye coordination training.

(Fig. 6.1). By using EMS, it's possible to improve the distribution of attention during hand activities and improve hand-eye coordination. This approach may allow for more efficient training of hand coordination skills in a shorter period.

6.2.2 Related Work

Our approach is primarily based on the human learning process of hand-eye coordination. To explain our training method, we examine several key aspects of the principles of hand-eye coordination, the learning process, and the use of electrical muscle stimulation.

Hand-Eye Coordination

Hand-eye coordination is commonly defined as the control of hand movements using visual feedback. During movement, our eyes direct our attention to stimuli and help the brain to understand the spatial position of the body. By allocating attention appropriately, we can support bilateral hand movements with visual information received through the eyes, thereby distributing tasks efficiently. Research by Michel et al. shows that the human central nervous system can plan tasks involving hand movements based on visual feedback [155]. Roland and colleagues investigated the coordination between vision and touch in object manipulation by analyzing fingertip movements [107]. These studies suggest that proper allocation of attention is crucial for mastering hand-eye coordination in activities that require its use.

The learning process of hand-eye coordination

Training is the act of accumulating experience through practice to achieve a certain goal. Lachman [109] defined this process as one in which learning is a relatively stable modification of the stimulus-response relationship as a result of functional environmental interactions through the senses. Krakauer and Mazzoni [110] showed that human senses can be trained and that through learning, we can reduce the false predictions of our senses. The human primary motor cortex (M1) displays mirror activity in response to movement observation, is capable of forming motor memories, and is involved in motor learning [111]. We can train the movement by repeating the same process, and when the training is over, an after-effect is created, which retains the effect of our training [106].

Human learning of motor skills relies on the motion perception system. When attempting to learn new movements, we first gather information through senses such as vision and hearing to make judgments and decisions. We then adjust our limb movements and control intensity based on predictions made from this information [106]. Based on this motion perception system, when faced with unfamiliar motor tasks, we can gradually master them through repeated practice and feedback. The principles of hand-eye coordination are similar to those of motor perception, as both are controlled by sensory information. Research by Sailer and others shows that learning hand-eye coordination also involves using visual information, correcting decisions through feedback from hand movements, and improving control of hand activities through repeated practice [135].

Hand-eye coordination in games

Similar to more physical sports, some games, such as action or competitive games, require the player to coordinate vision, touch, and body functions to control the game well and win [136]. In shooter games, players need to visually observe the enemy's position and control the mouse (or controller) to aim and shoot. Since enemies in shooter games are often on the move, players need to predict the movement trajectory using visual information and modify the mouse (or controller) control to shoot accurately [198]. In MOBA games, players must constantly use the mouse to control their characters to move and attack. Due to the highly competitive nature of MOBA games, the player's

viewpoint must constantly switch between multiple targets on the enemy and own side for proper judgment and control [151]. In addition to shooter and MOBA games, many other types of games rely on the feedback and coordination of visual and hand control. In these games, player control is highly dependent on hand-eye coordination.

A study [112] mentioned that training in coordination is very important in eSports, which is highly related to the player's motion perception, and plays an important role in whether the player can control the arm or body parts well to predict and complete the movement in the game. Therefore, the training of hand-eye coordination is indispensable for players, and good training can enable players to accumulate more sensory experience, so that they can have better control in the game to obtain a better gaming experience [114]. A study [115] showed that the use of tDCS (transcranial direct current stimulation) can enhance the players' judgment of fakes in basketball to improve the players' perception of movements in the game. This shows us the possibility of training players' skills in the game using external stimulation.

EMS for Hand–Eye Coordination Training

Initially, EMS was mainly employed in rehabilitation contexts, where it was used to support patients with motor disabilities or physical impairments [118]. With the expansion of EMS-related research, its applications have gradually extended to interaction and the augmentation of bodily functions. For example, Takahashi et al. [119] achieved more flexible finger movements by configuring electrodes on the hand, Nishida et al. [120] demonstrated that EMS could accelerate reaction times by directly driving muscles, and Kasahara et al. [34] developed an EMS-based system to improve reaction speed, with training effects persisting even after the device was removed. These studies highlight the potential of EMS not only as a medical tool but also as a training method for enhancing physical performance.

Building on this foundation, Zhou and Segawa explored the potential of EMS in first-person shooter (FPS) game training, demonstrating its feasibility in motor perception tasks [141]. More recently, Zhou et al. also investigated the use of EMS in hand–eye coordination training [159]. As discussed in Section 6.2.2, we propose a new hypothesis based on the similarity between motor perception and hand–eye coordination learning

mechanisms: EMS has the potential to play a significant role in supporting hand–eye coordination training. Previous approaches to hand–eye coordination training have relied on physical touch or immersive AR/VR systems [139], in which participants depend on their own sensory feedback and judgments, making predictions and correcting errors through repeated practice. By contrast, EMS enables the system itself to generate precise predictions and directly stimulate the user to act, thereby bypassing some of the inefficiencies of self-guided trial-and-error learning. In this way, EMS may reduce mispredictions, improve training efficiency, and provide a novel pathway for augmenting hand–eye coordination in interactive systems.

6.2.3 System Composition

In this study, an EMS-based customized training system was constructed to deliver hand–eye coordination training. The system has four main components: the EMS device, eye-tracking, attention allocation assessment, and a custom training game. In the training game, the visual feedback received by the participant was mainly classified into two types, and the participant had to use the left and right hand to control according to the feedback. At the start of training, the participant’s attention was required to switch between the left or right hand depending on the type of feedback and to make the correct movements according to the cues. During this process, the electrical stimulation device will automatically calculate the correct stimulation timing and stimulate the participant’s left or right hand at the appropriate time to help the participant switch attentional areas and make the correct inputs. The eye-tracking device will record the participant’s pupil movement during the process to analyze the participant’s attentional allocation. Through this system, the participant will be able to improve their attention allocation and hand–eye coordination during the game through targeted training with the help of the EMS.

Configuration of EMS

Our EMS device consists of a set of power supplies, switch controls and electrodes. By wearing the EMS device, participants can use the EMS to receive cues during training to assist in the proper allocation of attention.

Power supply: We chose the EV-804 [162] from iStim as the power supply for our EMS device. The EV-804 is a two-channel muscle stimulation massager that provides a stable power output. As our system only requires a mild electrical stimulation of the participant's hand muscles to change attention, we used this existing massage device to minimize the strain of the EMS on the muscles, ensuring the effectiveness of the EMS device and the safety of the participant.

Switch: We used Arduino UNO [86] (Fig. 6.2(a)) and PETTOYA 554 relays [124] (Fig. 6.2(b)) as controllers to control the switch of the EMS device through a program written in Arduino, which allowed us to activate it when needed and output the required current as a cue to stimulate the participants' hand muscles. When the switch is turned on, the EMS device outputs a 50–100 μ s pulse to stimulate the hand muscles and then turns off automatically. Taking into account individual differences in participants' age and bodily functions, we adjusted the pulse length according to the actual situation to ensure that the point stimulation could effectively prompt participants to switch their attention without causing discomfort.

Electrodes: We refer to the study [141] where electrodes were placed on the finger deep flexors of the participant's arm, which allowed the device to effectively stimulate the participant's hand muscles when the EMS device was activated (Fig. 6.2(d)). With this configuration, the EMS device can ensure that the participant effectively switches attentional areas without interfering with the normal activity of the hand muscles.

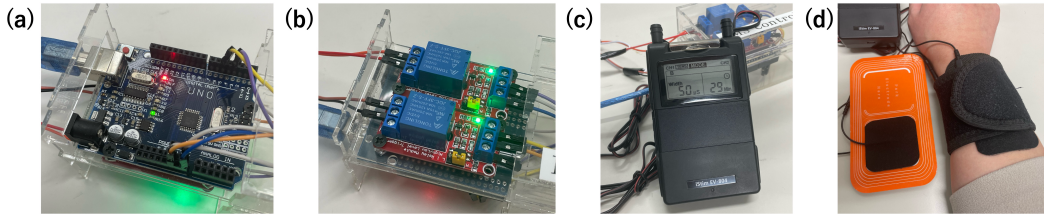


Figure 6.2: Configuration of EMS device. (a) Arduino. (b) PETTOYA 554 relays. (c) Power supply (EV-804). (d) Electrode configuration.

Eye tracking

This study uses the webcam that comes with the computer (Macbook Pro M1) to track the user's gaze during the game. Using a program written in Python and OpenCV

(see Appendix B.1.1), the system can track the user's pupil movement in real time and use it to analyze the user's attentional allocation (Fig. 6.3). When the participant's attention is focused on the center of the screen, the system displays "Center". When the participant's attention shifts to the left and right (left and right hand), the system displays "Left" and "Right" respectively. The system is programmed to calculate the time spent by the participant in shifting attention.

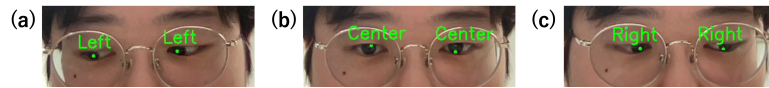


Figure 6.3: Eye tracking. (a) Attention to the left. (b) Attention to the center. (c) Attention to the right.

Assessment of attention allocation

To assess participants' attention allocation, we set up an attention allocation assessment test. During the test participants are required to allocate their attention between two visual fields on cue and to make correct inputs on controllers with their left or right hands to complete the test successfully. To facilitate the targeted test in attentional allocation, a custom training program was developed using Python. The test system consists of a monitor and two keyboards. The monitor is placed in the center of the participant's view, while the keyboards are placed in the left or right visual fields, respectively. When the test starts, the participant must press the letters on the keyboard in the correct visual field based on the letters and colors displayed on the monitor. If the letter is red, the participant must press on the left keyboard with the left hand; if the letter is blue, the participant must press on the right keyboard with the right hand. During the test, the EMS device provides stimulation cues to the left or right hands based on the corresponding letters, thus encouraging the participant to shift focus between the visual fields. At the same time, an eye-tracking device records the participant's attention in real time, which allows analysis of the test results.

Customized training game

To train hand–eye coordination, we created a custom training game (see Appendix B.1.2) using Python (Fig. 6.4). The EMS device was connected to the game so that participants could receive appropriate stimulation cues during training. The game setup consisted of a monitor, a keyboard, and a mouse. During gameplay, participants were required to coordinate keyboard and mouse inputs to aim at and touch a moving target.

Two types of targets were presented. When the target was red, participants were required to press a corresponding letter key displayed on the target (randomly selected from a fixed set of commonly used keys: `qw easd zxc`) while moving the mouse to touch the target. When the target was blue, participants were required to press and hold either the left or right mouse button, as indicated by on-screen cues, while moving the mouse to touch the target. Target types were randomly assigned with equal probability.

Target positions were randomly generated within the screen area (800×600 pixels), with the constraint that the entire target block (50×50 pixels) remained visible on the screen. Target movement was randomized within predefined bounds: the horizontal and vertical velocities were independently sampled from the set $\{-1, 0, 1\}$ pixels per frame, resulting in slow and unpredictable motion while avoiding abrupt or excessively fast movement. These random parameters were re-sampled immediately after a target was successfully cleared, requiring participants to continuously adapt their control strategies to changing task conditions.

If a participant pressed or held the correct input while touching the target, the target was defeated and 10 points were awarded. Conversely, if the participant pressed an incorrect key or failed to press the required input when touching the target, 20 points were deducted. Through this design, the game simulated typical video game actions that require continuous correction and control based on visual feedback, thereby training hand–eye coordination in a dynamic yet controlled environment. Similar hand–eye coordination tasks combining visual and haptic feedback have been reported in previous studies [139], supporting the representativeness of the proposed training task.

When the participant plays the game using the EMS, the system cues the participant with electrical stimulation based on the type of target on the monitor. By using the

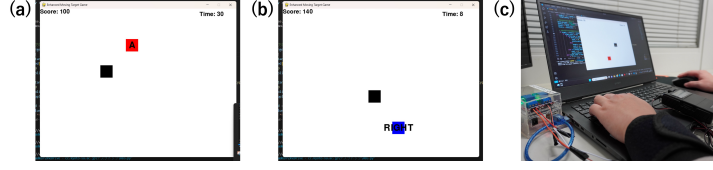


Figure 6.4: Customized training game. (a) Red targets use left hand input. (b) Blue targets use right hand input. (c) When using EMS, the system automatically prompts participants to use their left or right hand for input.

EMS, the participant’s attention can be quickly switched between left and right hand control and the correct control can be performed to complete the game.

6.2.4 Experimentation Overview

In this study, participants will perform hand-eye coordination training with and without the EMS. To validate the effectiveness and feasibility of the proposed training method, a series of experiments will be conducted.

Initially, when participants train while wearing EMS devices, the method of allocating attention will change from self-evaluation (based on the brain’s analysis of visual information) to external cues. Theoretically, with EMS, this feedback is almost reflexive due to the direct muscular stimulation. A study [34] has shown that participants achieve faster reaction times when using EMS. However, given that reaction speed and attentional allocation are not entirely the same in our study, it is necessary to test whether participants’ attentional allocation improves by using EMS before experimenting with the effectiveness of the training method. Better allocation of attention can effectively promote hand-eye coordination training, and this experiment allows an assessment of participants’ allocation of attention when using EMS.

Subsequently, a controlled experiment will be conducted to confirm the effectiveness of our proposed training method. Participants will perform hand-eye coordination training using the customized training game. In the experiment, participants will be divided into two groups: those training without EMS and those training with EMS. We will compare and evaluate the participants’ pre- and post-training scores and analyze both groups to confirm that the EMS-based training approach proposed in this study improves the efficiency of hand-eye coordination training in the customized training game. This

experiment is designed to evaluate the effectiveness of hand-eye coordination training using EMS.

Afterward, the training effect will be evaluated in a real game. Theoretically, participants' hand-eye coordination will be improved after hand-eye coordination training in a custom game. To further verify the participants' effect after training, it is necessary to experiment with a real game. Given that the custom game constructed for this study was mainly played by tracking the target with the keyboard and mouse, we will evaluate it in a game with very similar controls. The OSU [199] (Fig. 6.5) is a very representative music game whose gameplay consists of tracking a moving target with the mouse to the rhythm of the music and pressing the keyboard or mouse keys to hit it. In the game, the player has to track the target using visual feedback and control and correct the hand activity based on real-time feedback, which is typical of hand-eye coordination. We will record the accuracy in the OSU before and after customized hand-eye coordination training for participants with and without EMS. By comparing participants' accuracy in the OSU before and after training, we can evaluate whether the hand-eye coordination training proposed in this study has the potential to be applied to real games. Furthermore, by comparing the participants' accuracy improvement in the OSU after training with and without EMS, we can also further verify whether the use of EMS helps to improve the effectiveness of hand-eye coordination training. This experiment was used to preliminarily verify whether the hand-eye coordination training method using EMS has the potential to be applied to other real games.



Figure 6.5: Controls in the OSU.

Finally, the retention effect will be verified for participants after performing hand-eye coordination. As mentioned in Section 6.2.2, when the participants complete the training, there is an aftereffect that allows for the retention of the training effect over the following time. Therefore, in this study, we will verify whether the participants'

hand-eye coordination can retain the improvement effect over the following time after training with the customized game. Confirmation of the retention effect will help to support the effectiveness of the training method in the long term.

This study was reviewed and approved by the local ethics committee of Kyoto Sangyo University (Approval No.: KSU Ethics 0168-1; Study title: “Game Control Systems Using Electrical Muscle Stimulation”). All experiments were conducted with the informed consent of the participants, who were fully informed of the study’s purpose, procedures, and potential risks prior to participation.

6.2.5 Experiment 1: Improvements in attention allocation

In this study, participants used EMS to replace their own attentional allocation during training sessions. To ensure that the use of EMS did not adversely affect their attention allocation due to unfamiliarity with the system, it was necessary to conduct an experiment. In this experiment, we verified that the participants’ attentional allocation was not negatively affected by the use of EMS. We also assessed the improvement in participants’ attentional allocation when using EMS.

Experimental Approach

Considering the operation of hand-eye coordination, we conducted experiments using the attention allocation assessment system constructed in Section 6.2.3. In the experiment, participants had to make decisions based on the text displayed on the screen and allocate their attention to the correct area. At the beginning of each test, participants’ attention was first directed to the central area (screen). Then, when red letters appeared on the screen, participants had to shift their attention to the left visual field and enter the correct letters using the keyboard on the left. When blue letters appeared, they had to shift their attention to the right visual field and enter the correct letters using the right side keyboard. During this process, the system automatically analyzed the participants’ gaze movements and calculated the time taken for the eyes to move from the central area to the left or right area (attention allocation) after the letters appeared. We used time as a parameter because it was more convenient to compare how fast or slow the process was from the appearance of the visual information to the feedback given by the

participants when making autonomous judgments or using the EMS device, to facilitate the assessment of whether the participants' attentional allocation was improved.

Ten participants (19-30 years old, 9 males and 1 female) performed the tests. Each participant first performed 10 tests without the EMS and then another 10 tests with the EMS device.

Results

Ten participants completed the test with and without the EMS device. We recorded the time taken by the 10 participants to switch attention each time, and calculated the average time taken by the participants for each of the 10 attention-switching tests with and without the EMS device. The following is a comparison of the time taken to switch attention before and after using the EMS device, where a shorter time means a more rapid switch of attention (Fig. 6.6). It is observed that the speed of attentional switching increased for all 10 participants when using the EMS device.

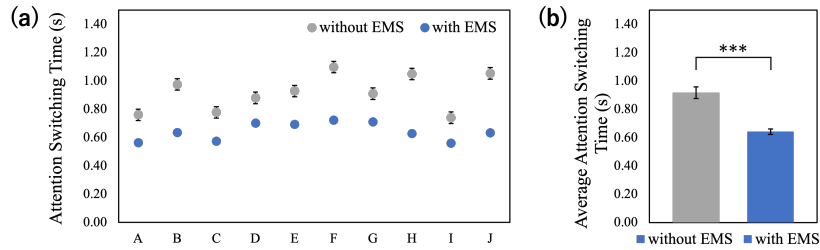


Figure 6.6: Attention switching test results. (a) Attention-switching duration with and without EMS for ten participants. (b) The average time of the participants without EMS was 0.92 s, and the average time with EMS was reduced to 0.64 s.

The mann-whitney u test was used to examine the two sets of data without and with the EMS device. The significance level was set at 0.1 % (a two-tailed test). According to the statistical analysis, the u-value was 100.0 and, the p-value was 0.00018. Test results confirmed that at the 0.1 % level, participants switched attention significantly faster with the EMS device than without it. Therefore, the participants' attentional switching was not negatively affected and was even significantly improved when using the EMS device.

6.2.6 Experiment 2: Hand-eye coordination training in a custom game

Our aim was to improve the effectiveness of hand-eye coordination training using EMS in a customized training game, enabling players to master hand-eye coordination in an unfamiliar sport in a short time, improve their game skills and enhance their game experience. Therefore, it was necessary to conduct a controlled experiment to evaluate the effectiveness of using EMS for hand-eye coordination training in a customized game compared to the method without EMS (simple repetitive training).

Experimental Approach

The experiment was conducted using the customized training game constructed in Section 6.2.3. In the experiment, participants had to complete the test as quickly as possible, making sure to use the correct controls. Participants were asked to use their left or right hand controller (mouse or keyboard) depending on the color of the displayed target. The time limit for each test was 1 minute. At the end of the test, the system calculated the participant's score for the test. Higher scores meant that participants made fewer mistakes and performed more accurate and faster controls in a customized game that required visual and tactile coordination, reflecting improved skills. Therefore, we used game scores as an important parameter for assessing hand-eye coordination skills in our experiment.

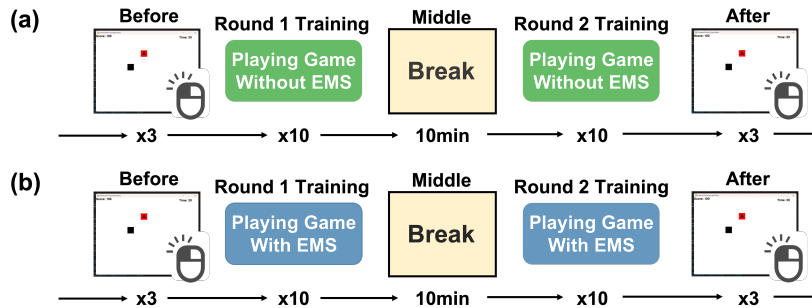


Figure 6.7: The training process. (a) The training process for participants without EMS. (b) The training process for participants with EMS.

Sixteen participants (19-30 years old, 15 males and 1 female) performed the experiment. All participants followed the process for training (Fig. 6.7). Each participant was

first tested three times before training began. The sixteen participants were then divided into two groups (eight per group) with and without EMS training for two rounds of training (repeated runs). The participants had to complete the game 10 times (1 minute each) during each round of training. Considering the fatigue that may result from long-term training, participants were asked to take a 10-minute break after each round of training. At the end of the training, each participant was tested again three times. The results of each test were recorded for all participants. It should be noted that the eight participants who trained with EMS only wore the EMS device for two rounds of training (20 times in total), and the rest of the procedure was the same as for the eight participants without EMS.

Evaluation of effectiveness

Sixteen participants were trained with and without EMS. Before comparing the results of the two groups of participants, we needed to compare the scores on the test before and after training separately for each group to assess whether both training methods were effective. We recorded each participant's score on the pass test before and after training and calculated the average score before and after training for each of the two groups of participants. The following is a comparison between the two groups of participants before and after training (Fig. 6.8). It can be seen that both the non-EMS group and the EMS group showed some improvement in their scores after training.

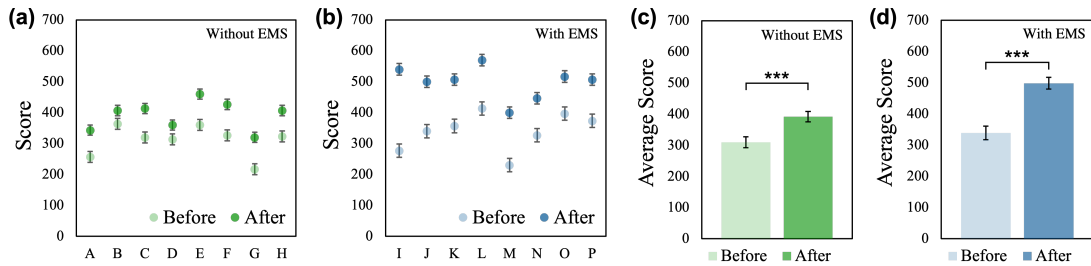


Figure 6.8: Comparison of game scores before and after training with and without EMS. (a) Comparison of game scores of eight participants before and after training without EMS. (b) Comparison of game scores of eight participants before and after training with EMS. (c) The average score improvement of participants trained without EMS. (d) The average score improvement of participants trained with EMS.

The paired samples t-test was used to examine the pre- and post-training data for the two groups of participants trained without and with EMS. We first analyzed the results of the group that did not train with EMS. According to the statistical analysis, the t-value was -9.7152 and, the p-value was 2.5874×10^{-5} . Subsequently, we also analyzed the results of the group that trained with EMS. According to the statistical analysis, the t-value was -9.7930 and, the p-value was 2.4554×10^{-5} . The results of the test confirmed that there was a significant difference between the pre- and post-training performance of the participants who trained without the EMS device at the 0.1 % level. And at the 0.1 % level, there was also a significant difference between the pre- and post-training performance of the participants who trained with the EMS device. Therefore, both participants with and without the EMS device had improved hand-eye coordination skills after training.

Comparison of the two methods

To verify whether the EMS-based training method proposed in this study was more effective than training without EMS (repetition only), we compared the change in average game scores before and after training between the two participant groups. Importantly, the game settings, scoring rules, task duration, and difficulty parameters were identical for both groups throughout the experiment, ensuring that any observed score differences were not attributable to differences in game configuration.

Under these controlled conditions, participants in the non-EMS group showed an average score increase of 82.08 after training, whereas participants in the EMS group exhibited a larger average increase of 159.17 (Fig. 6.9). Because the analysis focused on within-group score improvements under identical scoring mechanisms, the observed differences reflect relative changes in task performance rather than absolute score values

determ

The mann-whitney u test was used to examine the two sets of data without and with the EMS device. According to the statistical analysis, the u-value was 0.0 and, the p-value was 0.0009. The test results confirmed that, at the 0.1 % level, the improvement in game score after training was more significant for participants with the EMS device than for those without. Therefore, training with the EMS is more effective than training

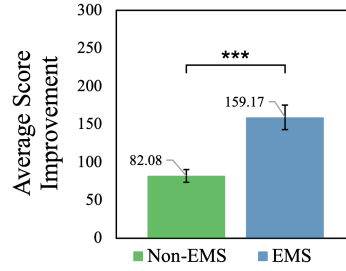


Figure 6.9: Comparison of training results between two groups of participants with and without EMS.

without the EMS in customized hand-eye coordination training.

6.2.7 Experiment 3: Real music game testing

To verify whether the method proposed in this study for training hand-eye coordination in custom games using EMS can be applied to real games, it is necessary to conduct further experiments. As described in Section 6.2.4, the experiment was conducted in a music game called OSU. In Experiment 2, we confirmed that the use of EMS could rapidly improve participants' hand-eye coordination in a custom game. To further confirm that this effect was equally effective in the real game, we collected participants' results in OSU for evaluation. We also compared the OSU results between two groups of participants who trained with and without EMS.

Experimental Approach

Considering the custom game controls constructed in this study, we asked participants to use similar controls in OSU. We selected a section of about 1 minute of rhythm in OSU for the experiment. All participants were tested on a segment of the same rhythm. During the test, participants were required to control the mouse to track a target that followed the rhythm and to press a key on the keyboard at the appropriate time. If the participant failed to control the mouse to track the target correctly, or pressed the keys at the wrong time, this would result in a miss. Each mistake made by the participant resulted in a decrease in the accuracy of the test. At the end of the test, we recorded the average accuracy of the participants in this test. In OSU, high accuracy is a reflection of good visual and tactile collaboration, which represents more precise

control by participants. Therefore, we used the accuracy rate as an indicator to assess participants' hand-eye coordination in OSU.

Sixteen participants (19-30 years old, 15 males and 1 female) performed the experiment. Each participant was tested three times before and after performing the hand-eye coordination training in Experiment 2. None of the participants had any previous experience with OSU or other music games, and this test was an unfamiliar exercise for all participants. It therefore helped to test the effectiveness of the practical application of improving hand-eye coordination skills in a real game. As all participants had no prior experience with OSU or similar rhythm games, we selected the *Normal* difficulty level from the four standard difficulty categories provided in OSU (Easy, Normal, Hard, and Insane), which offers a balanced level of challenge that is accessible to novice players while still requiring precise timing and control.

Evaluation of effectiveness

Sixteen participants were trained with and without EMS. As in Experiment 2, before comparing the results of the two groups of participants, we needed to compare the accuracy in the OSU before and after training for each group separately to assess whether the two training methods were effective. We recorded each participant's accuracy in the OSU before and after training and calculated the average accuracy of both groups of participants before and after training. Below is a comparison of the two groups of participants before and after training (Fig. 6.10). It can be seen that both the non-EMS group and the EMS group showed some improvement in accuracy after training.

The paired samples t-test was used to examine the pre- and post-training data for the two groups of participants trained without and with EMS. We first analyzed the results of the group that did not train with EMS. According to the statistical analysis, the t-value was -11.2519 and, the p-value was 9.7822×10^{-6} . Subsequently, we also analyzed the results of the group that trained with EMS. According to the statistical analysis, the t-value was -15.6149 and, the p-value was 1.0684×10^{-6} . The results of the test confirmed that there was a significant difference between the pre- and post-training performance of the participants who trained without the EMS device at the 0.1 % level. And at the 0.1 % level, there was also a significant difference between the pre- and post-

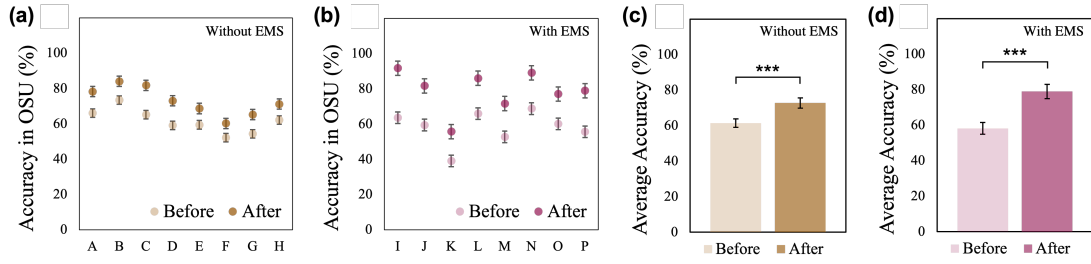


Figure 6.10: Comparison of participants' accuracy in OSU before and after hand-eye coordination training. (a) Comparison of accuracy in OSU before and after training for eight participants without the EMS. (b) Comparison of accuracy in OSU before and after training for eight participants with the EMS. (c) Change in average accuracy in OSU before and after training for participants without the EMS. (d) Change in average accuracy in OSU before and after training for participants with the EMS.

training performance of the participants who trained with the EMS device. Therefore, both participants with and without the EMS device had improved hand-eye coordination skills after training.

Comparison of the two methods

To verify that the training method with EMS proposed in this study is more efficient than the method without EMS (repetition only), we compared the change in average accuracy in the OSU after training between the two groups of participants. The participants without EMS increased their average accuracy by 11.32 % after training, while the participants with EMS increased their accuracy by 20.80 % (Fig. 6.11).

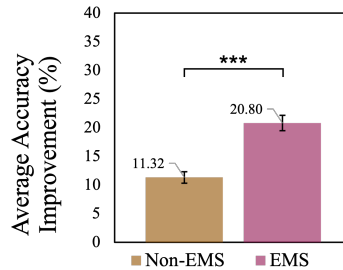


Figure 6.11: Comparison of average accuracy improvement in OSU after hand-eye coordination training in participants with and without EMS.

The mann-whitney u test was used to examine the two sets of data without and with the EMS device. According to the statistical analysis, the u-value was 0.0 and, the

p-value was 0.0002. The test results confirmed that, at the 0.1 % level, the improvement in average accuracy after training was more significant for participants with the EMS device than for those without. Thus, the participants who used EMS for customized hand-eye coordination training gained a more effective improvement in accuracy in the OSU than those who did not use EMS.

6.2.8 Experiment 4: Retained effects after training

As described in Section 6.2.2, we can train a movement by repeating the same process, and when the training is over, there is an aftereffect that retains the effects of our training [106]. Therefore, the retain of the post-training effect is also one of the parameters used to measure the effectiveness of training. In Experiments 2 and 3, we verified that the use of EMS could help participants rapidly improve their hand-eye coordination skills in a custom game, and assessed the actual effects of this improvement in a real music game. These assessments were carried out over a relatively short time. Further experiments were conducted to validate whether the participants' skill gains were maintained over a long period after training.

Experimental Approach

At the end of Experiments 2 and 3, we asked participants not to be exposed to any games or sports similar to the customized game or OSU in this study for the next week. One week later, we tested participants for post-training retained effects. Participants were tested on the custom game and OSU as in the previous experiment after a one-week interval from the previous training without new training. As in previous experiments, we used scores and accuracy to measure participants' hand-eye coordination. Test results were recorded for all participants.

The same 16 participants (19-30 years old, 15 males, 1 female) as before performed the retained effect experiment after a one-week interval. Each participant completed three tests in the customized game and OSU, respectively, without any re-training in hand-eye coordination. To prevent other factors from influencing the tests, participants performed the experiment in the same environment as one week before. All devices used in the experiment, including room temperature and lighting, were not altered in any

way.

Retained effects in a custom game

Sixteen participants were tested after a one-week interval of hand-eye coordination training. To assess whether the two groups of participants, with and without EMS, retained the skill improvements from the previous training after a one-week interval, it was necessary to compare the participants' scores in the custom game before and one week after the hand-eye coordination training. We recorded each participant's score in the custom game after the one-week interval and calculated the average scores for the two groups of participants trained with and without EMS. Below we compare the scores of the two groups of participants after one week of hand-eye coordination training with their pre-training scores. We also compared the scores of the two groups of participants in this test with their scores at the end of the training one week before. It can be seen that both participants with and without EMS had improved scores after one week of interval training compared to the pre-training period (Fig. 6.12). The scores of both groups of participants were not significantly different from those immediately after the end of the training.

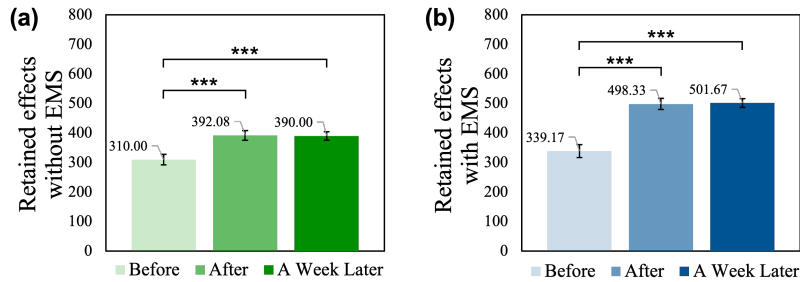


Figure 6.12: Results of the training retained effect test in the custom game. (a) Comparison of average scores in the custom game before, after, and one week after training for eight participants without the EMS. (b) Comparison of average scores in the custom game before, after, and one week after training for eight participants with the EMS.

A paired samples t-test was used to compare the custom game scores of the two groups of participants before training, after training, and after a one-week interval, respectively. The significance level was set at 0.1% (two-tailed test).

The following are the results of the test (Table. 6.1)(Table. 6.2).

Table 6.1: Multiple Comparison of Scores (Non-EMS Group)

Group 1	Group 2	T-Statistic	P-Value	Significant Difference
Before	After	-9.7151	2.5874×10^{-5}	True
Before	A Week Later	-9.2627	3.5364×10^{-5}	True
After	A Week Later	0.5438	0.6034	False

Table 6.2: Multiple Comparison of Scores (EMS Group)

Group 1	Group 2	T-Statistic	P-Value	Significant Difference
Before	After	-9.7930	2.4554×10^{-5}	True
Before	A Week Later	-9.9014	2.2837×10^{-5}	True
After	A Week Later	-0.7886	0.4562	False

The results showed that after a one-week interval, the scores of the participants in the customized game, both with and without EMS, were not significantly different from the scores immediately after the training and remained significantly different from the scores before the training. This showed that both groups of participants retained the skill-enhancing effects of hand-eye coordination training in the customized game after a one-week interval.

Retained effects in real music game

To further verify the retained effect of the training method proposed in this study in real games, sixteen participants were also tested in the OSU. We compared participants' accuracy in the OSU before and one week after hand-eye coordination training to assess whether participants in both groups retained the skill improvements from the previous training after a one-week interval. We recorded each participant's accuracy in the OSU test after a one-week interval and calculated the average accuracy for the two groups of participants trained with and without EMS. Below is a comparison of the accuracy rates of the two groups of participants after a one-week interval of hand-eye coordination training compared to before the training. We also compared the accuracy of the two groups of participants in this test with their accuracy at the end of the training one week before. It can be seen that both participants with and without EMS had an increase in accuracy after one week of interval training compared with the pre-training period

(Fig. 6.13). The accuracy of both groups of participants after a week of interval training was not significantly different from that immediately after the end of training.

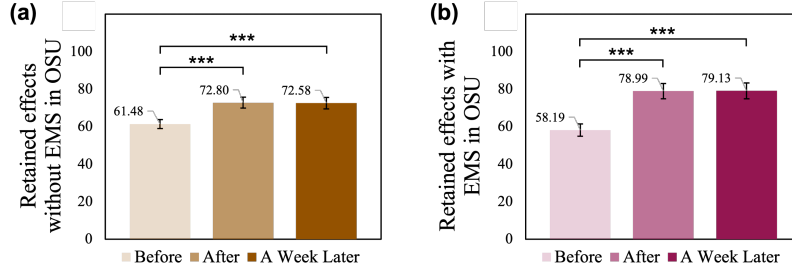


Figure 6.13: Results of the training retained effect test in the OSU. (a) Comparison of average accuracy in the custom game before, after, and one week after training for eight participants without the EMS. (b) Comparison of average accuracy in the custom game before, after, and one week after training for eight participants with the EMS.

A paired samples t-test was used to compare the custom game scores of the two groups of participants before training, after training, and after a one-week interval, respectively. The significance level was set at 0.1% (two-tailed test).

The following are the results of the test (Table. 6.3)(Table. 6.4).

Table 6.3: Multiple Comparison of Accuracy in the OSU (Non-EMS Group)

Group 1	Group 2	T-Statistic	P-Value	Significant Difference
Before	After	-11.2519	9.7822×10^{-6}	True
Before	A Week Later	-8.9992	4.2682×10^{-5}	True
After	A Week Later	0.5428	0.6041	False

Table 6.4: Multiple Comparison of Accuracy in the OSU (EMS Group)

Group 1	Group 2	T-Statistic	P-Value	Significant Difference
Before	After	-15.6149	1.0684×10^{-6}	True
Before	A Week Later	-12.5321	4.7495×10^{-6}	True
After	A Week Later	-0.2894	0.7807	False

The results showed that after a one-week interval, the accuracy of the participants in the OSU, both with and without EMS, was not significantly different from the accuracy immediately after the training and remained significantly different from the accuracy

before the training. This showed that both groups of participants retained the skill-enhancing effects of hand-eye coordination training in the OSU after a one-week interval.

6.2.9 Discussion

This study proposed a method to improve attention allocation using EMS to help participants with hand-eye coordination training. Our study demonstrated that the use of EMS can effectively improve participants' attentional switching and rapidly improve participants' gaming skills in a custom hand-eye coordination game and a music game. And, we verified that the skill improvements participants received through hand-eye coordination training were retained after one week. We will discuss the results of this study for future studies and future work.

How EMS Supports Learning and Retention of Control Strategies

The retention of performance improvements observed one week after training suggests that EMS-assisted practice supported not only temporary facilitation but also the acquisition of effective control strategies. Rather than relying on stimulation cues, participants appear to have internalized task-specific “knacks” related to attention allocation and visuomotor coordination.

In the custom hand-eye coordination task, EMS actuation coincided with task-relevant events, which may have accelerated the formation of stable associations between visual cues and appropriate motor responses. Similar to the effects observed in finger control training (Section 5.3.7), the consistent coupling of intention, sensory feedback, and movement execution likely reduced variability during early learning and facilitated the establishment of reliable response patterns [175, 176].

In both the custom game and OSU, successful performance required rapid attentional switching and precise timing. EMS-assisted execution may have helped participants experience what correct timing and control “felt like,” leading to an embodied understanding of effective play. Once learned, these strategies could be reproduced without stimulation, explaining the observed retention effects. This interpretation is consistent with motor learning mechanisms in which temporally aligned sensory and motor events promote the refinement of internal models and skill consolidation [156].

Overall, these findings suggest that EMS facilitates learning by guiding participants toward effective attention allocation and control strategies during training, allowing these strategies to be internalized and retained beyond the stimulation period.

Fatigue of training

Many studies have shown that maintaining concentration during games can easily lead to mental fatigue [140, 200, 201]. Hand-eye coordination is highly dependent on visual and tactile coordination, and prolonged concentration during training can easily lead to fatigue, which affects the training effect. Study [141] mentioned that when training with EMS, participants are stimulated by external electrical stimuli, so they do not need to maintain high concentration as in the previous method (which relies on their judgment), which makes participants less likely to become fatigued in the EMS training mode. In this study, we investigated the potential for fatigue during hand-eye coordination training.

Figure. 6.14 shows the change in average scores between the first and second rounds of training with and without the EMS.

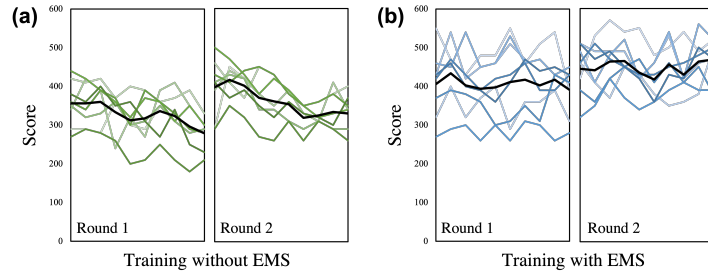


Figure 6.14: Comparison of training results between two groups of participants with and without EMS. The black line in this case is the trend of the average score change. (a) Participants who did not use EMS showed a decrease in their scores in both the first and second rounds of training. (b) Participants using the EMS had relatively stable score changes in both rounds of training.

Participants who trained without EMS had scores that tended to decrease for the training session, whether in the first or second round. Participants who trained without EMS took a 10-minute break at the end of the first round, and their scores increased at the beginning of the second round, but then gradually decreased for the following

session. In contrast, the participants who trained with EMS did not show a decreasing trend in their scores during either the first or second round, and the average scores of the participants were generally stable. We suggest that this is because EMS training is less likely to cause mental fatigue in the participants, thus stabilizing their average scores over the two rounds of training. This is a subject for future research.

Applications of this study

Whether EMS can be effectively used to train hand-eye coordination in other games or sports remains a topic for future research. However, we will list some application scenarios for hand-eye coordination training with the EMS when future studies are completed.

Hobbyist gamers training: In this study, the participants had never been exposed to the customized game and the OSU before, but all of the participants' skills improved rapidly after the hand-eye coordination training. Hand-eye coordination plays an important role when people are exposed to unfamiliar sports [135]. Thus, we believe that the method proposed in this study is well-suited for hobbyist gamers in sports or games. Most people participate in sports or video games as a hobby or recreation, and very few are professional players [202, 203]. Many hobbyist gamers devote relatively less time to training and want to enjoy the game without having to put a lot of effort into training. These players make up a large percentage of the total sales of gaming devices or sporting goods and may consider purchasing an EMS device. By using EMS for hand-eye coordination training, hobbyist gamers can quickly improve their skills in unfamiliar sports, which may greatly improve their experience.

Competitive activities: In many competitive activities, the competition between athletes is very intense, and as a result, unlike hobby players, professionals need to train at a high level and for long periods to ensure that they can be victorious in competitions. Previous studies have shown that the cumulative training load of professional athletes in both sports and eSports over long periods leads to an increased probability of injuries and illnesses [190, 114, 130]. Hand-eye coordination plays an important role in sports and eSports training [132, 204, 112]. Therefore, we believe that the method proposed in this study can be applied in some sports or eSports. Improving hand-eye coordination may help to increase the training efficiency of these sports and shorten the training time

to ensure that these athletes do not accumulate excessive training loads, thus improving physical health.

Limitation

We conducted experiments using only a custom game and a musical game (OSU). The control in both the custom game and the OSU is only one way of playing a game of many types, and we did not experiment with other control methods that currently exist. In the custom game, we set up only one type of target and moved in only one way (just random movements on a flat surface). The controls in OSU also use only the mouse and keyboard to track and hit a single target. In other games, the player may face more complex environments with more complicated target movement. The controls in some games may include multiple control modes. Nonetheless, we believe that this study explores the potential of using EMS to train players' hand-eye coordination in games, which is the value of the present study. Our study provided a novel method for training hand-eye coordination in games for those who require it. Future studies will involve more complex experiments in more genres of games to further validate the feasibility of using EMS to train players' hand-eye coordination in games.

We only investigated participants' retained effects after a one-week interval. In this study, we verified that participants retained the training effect after one week of hand-eye coordination training, which is a relatively short cycle. We did not test participants' retained effects over a relatively long time, such as one month or six months. In general, the effects of training diminish over time, and it is necessary to validate participants' retained effects over longer cycles. We plan to investigate the retained effects of hand-eye coordination training using EMS over a long time in future work.

In the custom game and OSU experiments, we only collected data from sixteen participants and did not conduct a broader experiment. And we only quantitatively analyzed players' scores and accuracy in the game. Considering the individual differences among participants, in future studies, we will expand the number of participants and conduct more extensive investigations. We also plan to conduct qualitative analyses by asking participants to respond to a questionnaire with items reflecting their gaming experience as well as fatigue, comfort, and so forth.

We only trained and tested novice players in this study and did not experiment with experienced players. Considering the diversity of the player population, players with relevant game experience should be included as a control group in future studies to further evaluate the training method proposed in this study. Comparing the training effects of novice and experienced players will help to better evaluate and examine the applicability of the method proposed in this study.

6.2.10 Conclusion and Future Work

In this study, we proposed a method of using EMS to help players train their hand-eye coordination. In a series of experiments, we confirmed that the use of EMS can help participants rapidly improve their scores in a custom game and a real music game. The participants retained the training effect one week after the training. Hand-eye coordination training using EMS has the following advantages: (1) It can improve hand-eye coordination in a short time, thus improving players' game skills. (2) Improved hand-eye coordination can help players quickly master unfamiliar game controls. (3) EMS is non-invasive and easy to implement, so players can train with a simple configuration.

In conclusion, we only verified the possibility of using EMS for hand-eye coordination training in a customized game and a music game. Whether EMS devices can help players train effectively in hand-eye coordination in other games or sports remains a topic for future research. This method may be more suitable for hobbyist gamers who wish to improve their gaming skills quickly without putting in the time and effort. And, because hand-eye coordination plays an important role in sports and eSports training, the results of this study could be applied to the training of professional athletes when future research is completed. This study could provide a reference for such investigations.

As for future work, we will further validate the feasibility of using EMS to train hand-eye coordination. We will collect data from more participants and validate the effectiveness and generalisability of hand-eye coordination training using EMS in more types of games. And, we will also conduct a longer period of retained effect experiments. Moreover, not limited to quantitative analyses, we will also conduct qualitative analyses to further validate the effectiveness of hand-eye coordination training using EMS.

6.3 EMS-Based Training for Musical Instrument Learning

Based on “Hand-In-Hand Learning: A Novel Method for Instrument Skill Training with Electrical Muscle Stimulation.” – Zhou, Shikida, and Segawa (IFIP ICEC 2025)

Learning to play a musical instrument is a demanding task that requires precise motor coordination and synchronization between sensory and motor systems. For novices, establishing correct movement patterns in the early stages is often difficult and time-consuming. EMS offers a unique approach by providing direct muscular guidance, enabling learners to experience and reproduce expert movements more intuitively. In this section, we introduce an EMS-based training method for instrumental performance and evaluate its effectiveness in supporting beginners’ skill acquisition.

6.3.1 Introduction

Instrumental performance is generally regarded as a complex skill that heavily relies on proprioception and hand-eye coordination, involving precise control of limb movements and the integration of visual, auditory, and motor sensory information [205, 206, 207]. Research by Platz et al. has demonstrated that skilled performers can effectively integrate these multimodal sensory inputs through extensive long-term practice, resulting in stable and accurate motor patterns [208]. However, for beginners, achieving a high level of motor coordination during the early stages of learning is particularly challenging. This lack of coordination not only hinders the rapid acquisition of skills but may also lead to the long-term consolidation of incorrect motor patterns [135].

Instrumental training typically relies on sustained and repetitive practice of fundamental skills. Some studies have explored the use of assistive technologies to support this training process. For example, Rutkowski et al. utilized virtual reality (VR) to enhance hand-eye coordination during musical practice, thereby improving training outcomes [197]. Furuya et al. developed a wearable hand exoskeleton system to support fine motor control in pianists, aiming to overcome the so-called ceiling effect in piano performance [138]. Despite these advancements, most beginners still require continuous guidance and feedback from expert instructors before they can effectively engage

in long-term practice. In reality, many learners do not have access to professional instruction, particularly in regions lacking educational resources. Furthermore, even with expert supervision, beginners often struggle with accurately interpreting and executing movement instructions, leading to inefficient learning or the development of incorrect techniques.

Previous studies have shown that EMS can effectively improve motor performance and support learning. Kasahara et al. found that EMS has the potential to enhance user reaction speed [34]. Zhou and Segawa further demonstrated that EMS can significantly improve sensorimotor abilities within a short period of time, highlighting its feasibility for rapid skill training [141]. In addition, they proposed an EMS-based hand-eye coordination training method and verified its short-term effectiveness, as well as its potential applicability in real-world gaming environments [159, 142]. Unlike other assistive technologies, EMS offers a unique advantage by directly engaging the user’s musculature and facilitating the formation of muscle memory within a short timeframe, thereby accelerating the learning of related skills. By providing immediate and intuitive physical feedback, EMS helps learners overcome comprehension-related barriers often encountered in traditional teaching methods.

Based on these insights, this study proposes a novel EMS-based training method for instrumental skill acquisition. This method involves capturing and recording the precise movements of expert performers in real time and translating them into electrical stimulation signals that directly control the learner’s limb movements. In doing so, the system achieves a literal “hand-in-hand” mode of instruction. We believe that this training approach, which combines expert demonstration with physical sensory feedback, can help beginners establish correct motor patterns more quickly and accurately during the initial stages of learning. Ultimately, this may significantly shorten the time required to progress from novice to proficient instrumentalist. This study aims to design and evaluate the effectiveness and practicality of this EMS-based training method and explore its potential for application in real-world educational contexts, offering a novel and efficient pathway for future music instruction.

6.3.2 System Composition

As an essential component of musical performance, percussion instruments such as drums require not only a high degree of coordination between the hands and feet but also the integration of multiple motor and sensory abilities, including rhythm perception, movement speed, and force control. The multimodal nature of these skills makes percussion training an ideal context for evaluating and enhancing the efficiency of skill acquisition among beginners. Therefore, this study focuses on drum-based percussion instruments as the primary training target to explore the potential of EMS in instrumental skill training.

To this end, we developed an EMS-based drum training system (see Appendix B.2). This system captures the expert performer’s motion data in real time during drumming and translates these movements into precise electrical stimulation signals, which drive the learner’s hand and foot muscles to replicate the corresponding actions. With this system, beginners can physically experience the expert’s performance without needing a complete cognitive understanding of the movement, enabling more intuitive and efficient skill guidance and acquisition.

EMS Device

The drum training system developed in this study incorporates an EMS device composed of a power supply, control module, and electrodes. This device is designed to assist learners in physically imitating professional drumming movements and receiving corresponding motor feedback during training.

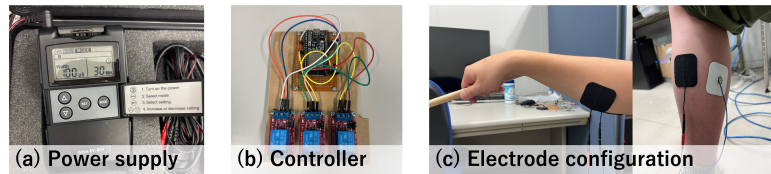


Figure 6.15: EMS Device Configuration. (a) Power supply. (b) Controller. (c) Electrode placement.

The system uses the iStim EV-804 [162] as the EMS power supply (Fig. 6.15 (a)). This device is widely used for muscle training and provides stable and safe pulse output (with a

maximum voltage of approximately 10V). Given that the primary objective of this study is to drive the learner's hand and foot muscles with moderate electrical stimulation to simulate drumming actions, this device was selected to balance stimulation effectiveness with user comfort, avoiding excessive interference with natural muscle function.

In terms of control, the system employs an ESP32 microcontroller [87] in combination with a TONGLING relay module [124] to manage EMS output (Fig. 6.15(b)). The EMS signal is modulated through relay switching controlled by an Arduino-based program. Upon activation, the system delivers a pulse of 50–100 μs to the designated muscle groups, triggering the learner to perform the corresponding movement. To accommodate individual differences in muscle sensitivity and physical condition, both pulse width and output intensity were individually adjusted. In practice, stimulation was initiated at a short pulse width (50 μs) and gradually increased until the participant's target muscles (e.g., forearm or lower-leg muscles) exhibited a clear and reliable contraction that produced a small but observable movement. The intensity was further tuned to ensure that the induced movement was sufficient to support the task execution while remaining comfortable and not causing discomfort or sensory interference that could distract the participant. This calibration strategy aimed to achieve functional assistance rather than forceful actuation.

Electrode placement was adapted from the configuration proposed by Tamaki et al. [54], with modifications to suit the drumming training context of this study (Fig. 6.15(c)). For the upper limbs, electrodes are attached to the wrist extensor and flexor muscle groups to facilitate hand striking movements. For the lower limbs, electrodes are placed on the tibialis anterior and gastrocnemius muscles of the lower leg to replicate bass drum pedal actions. This configuration ensures effective activation of muscles essential for drumming performance while minimizing interference with non-target muscle groups, thereby improving movement accuracy while preserving the natural fluidity of motion.

Detection of Instructional Movements

To capture the instructor's drumming movements, this system employs an accelerometer (Seeed XIAO nRF52840 Sense) [209] mounted on the drumsticks and a pressure sensor (FSR-402) [210] placed on the bass drum pedal (Fig. 6.16). These sensors are used to

record the timing and force of both hand and foot strikes performed by the instructor.

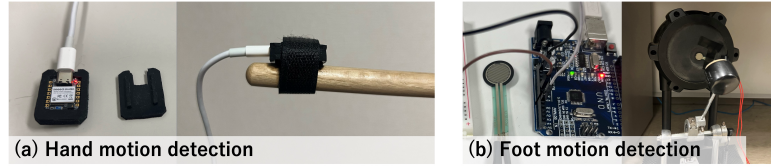


Figure 6.16: Sensor Configuration. (a) Hand motion detection. (b) Foot motion detection.

For hand motion detection (Fig. 6.16 (a)), the accelerometer captures three-dimensional acceleration data along the X, Y, and Z axes. The collected data is transmitted in real time to an Arduino UNO [86] for preliminary processing and then sent via serial communication to a computer running a Python program. The system analyzes the incoming acceleration data and identifies a strike event when the acceleration magnitude in any direction exceeds a predefined threshold.

For foot motion detection (Fig. 6.16 (b)), a pressure sensor attached beneath the bass drum surface monitors the force applied by the instructor’s foot. When the pressure exceeds the threshold, a signal is similarly sent through the Arduino to the computer for further analysis, enabling the system to comprehensively detect both hand and foot strike events.

To prevent multiple triggers from a single strike, the system implements a “trigger flag” mechanism. This mechanism works like a switch: when the sensor detects an acceleration that exceeds the threshold, the switch is turned on, and a single electrical stimulation is triggered. The switch remains off until the acceleration value drops below the threshold again, at which point it is reset to allow detection of the next valid strike. This approach ensures that each physical strike triggers the EMS output only once, avoiding false positives caused by hand tremors or sensor noise and improving the accuracy and reliability of the system.

Connecting Instructor and Learner

We developed a Python-based system to establish real-time connectivity between the motion detection sensors worn by the instructor and the EMS device worn by the learner. As the instructor begins playing, their hand and foot movements are captured by the

system in real time and converted into corresponding electrical stimulation signals, which activate the learner’s limbs to perform synchronized drumming actions.

In traditional percussion training, learners primarily rely on visual and auditory cues to observe and imitate the instructor’s gestures and rhythm. While this observational learning approach is intuitive, it can be challenging for beginners who lack motor experience or physical coordination. Relying solely on sensory observation often makes it difficult to accurately replicate fine motor details, particularly in terms of rhythm control and muscle engagement.

By incorporating EMS, the learner’s hand and foot muscles can be automatically activated through electrical stimulation during training. This enables the learner not only to perceive the instructor’s rhythm but also to physically execute the same movement patterns. Even at an early learning stage—before the learner has fully mastered voluntary motor control—EMS allows them to experience and internalize the correct performance through direct bodily engagement.

The strength of this system lies in its integration of physical demonstration and motor guidance. Through EMS, learners who have not yet developed the capacity for precise voluntary control can passively perceive and imitate professional performance movements. This training mechanism facilitates the rapid development of correct motor patterns and accelerates the formation of muscle memory, offering a more intuitive and effective pathway for skill acquisition in beginners.

6.3.3 Evaluation of the Proposed Method

To conduct a preliminary evaluation of the effectiveness and usability of the EMS-based instrumental training method proposed in this study, participants underwent training using the system developed in Section 6.3.2. A user survey was administered following the training, and the results were analyzed and assessed accordingly.

Participants

We recruited eight participants (aged 19–29; 6 males and 2 females). All participants were in good health and reported no physiological or cognitive impairments that could affect the experiment. None of them had received any prior professional or targeted

training related to music. Therefore, the experiment served as a completely new experience for all participants. These selection criteria were intended to objectively evaluate the actual effectiveness of EMS in instrumental training.

Training Process

To evaluate the EMS-based drum training system, eight participants completed the experiment following the procedure outlined below.

First, participants practiced a basic 8-beat rhythm without the use of EMS. During this phase, they observed and imitated a demonstration performed by an expert drummer, following a method commonly used in traditional percussion training. To assist understanding, especially for beginners unfamiliar with standard musical notation, a simplified musical notation was provided alongside the demonstration instead of formal sheet music, in order to reduce cognitive load and improve accessibility (Fig. 6.17).

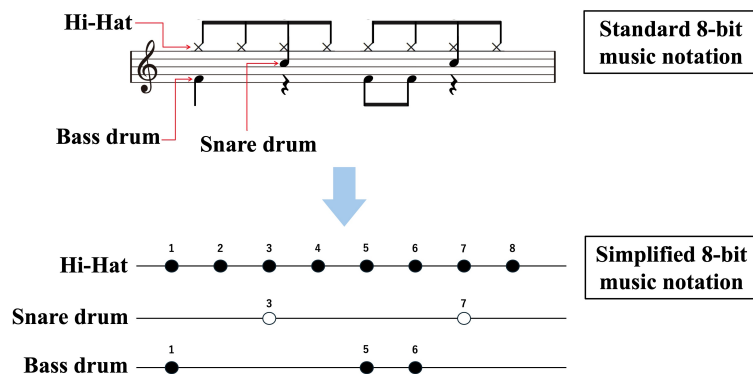


Figure 6.17: Comparison between standard 8-bit music notation and simplified 8-bit music notation. The simplified representation abstracts rhythmic events into discrete time steps, reducing notational complexity while preserving essential timing information for interactive training tasks.

To avoid participants mastering the rhythm through prolonged practice—which could potentially compromise the subsequent evaluation of the EMS system—the duration of this phase was limited to approximately three minutes. This time frame was chosen based on the assumption that beginners are unlikely to fully master the rhythm in such a short period, thereby allowing the evaluation to focus on the immediate effects of

EMS-based training. After this phase, participants were asked to mentally reflect on their current level of skill acquisition.

Following the conventional training, a rest period of at least one hour was provided to minimize the carryover effects of the previous training before initiating the EMS-assisted session.

After the break, participants were equipped with the EMS device and proceeded with the second phase of training. During this phase, they practiced the same 8-beat rhythm for three minutes, but this time the system provided real-time electrical stimulation to the hands and feet based on motion data from the instructor (as described in Section 6.3.2). As in the previous phase, the simplified musical notation was made available to support participants in understanding and reinforcing the rhythm and movement structure.

User Survey

After completing the training, participants were asked to complete a questionnaire based on their subjective impressions. The questionnaire included the following three items: (1) whether the EMS-based training method was perceived to be more efficient than traditional methods; (2) whether the electrical stimulation feedback provided by the system was easy to understand; and (3) whether the EMS-based training method was considered to have practical applicability.

Because all participants were novices with no prior experience in the target skill, the questionnaire was designed to capture perceived usability and experiential effectiveness rather than expert-level evaluations. In particular, participants were asked to reflect on their own learning experience during the experiment, such as whether the training felt easier to follow, whether the feedback was intuitive, and whether the method appeared useful for beginners at an early learning stage. Therefore, the subjective evaluations were interpreted as indicators of perceived learnability and accessibility, rather than as judgments of long-term training effectiveness or professional applicability.

All questions were rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). The questionnaire was designed to evaluate the proposed system across three dimensions: training efficiency, clarity of feedback, and practical usability, aiming to

collect participants' subjective assessments and overall acceptance of the EMS-based training experience.

IRB Process

This study was reviewed and approved by the local ethics committee of Kyoto Sangyo University (Approval No.: KSU Ethics 0168-1; Study title: "Game Control Systems Using Electrical Muscle Stimulation"). All experiments were conducted with the informed consent of the participants, who were fully informed of the study's purpose, procedures, and potential risks prior to participation.

Results

Through statistical analysis of the questionnaire responses from eight participants, we obtained the following evaluation results regarding their experience with the system (Fig. 6.18):

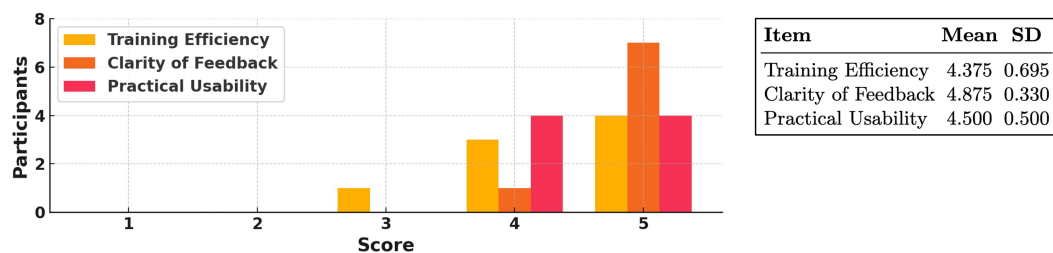


Figure 6.18: Distribution of participant responses for each questionnaire item on a 5-point Likert scale.

Perceived Training Efficiency. In response to the question "Whether the EMS-based training method was perceived to be more efficient than traditional methods", the average score was 4.375 with a standard deviation of 0.695. Overall, most participants perceived the system as having a positive impact on training efficiency, suggesting that EMS can effectively support skill acquisition within a short period of time.

Clarity of Electrical Stimulation Feedback. For the question "Whether the electrical stimulation feedback provided by the system was easy to understand", the average score was 4.875 with a standard deviation of 0.330. The results indicate that participants generally found the EMS feedback to be clear, intuitive, and easy to inter-

pret. This supports the effectiveness of the system’s feedback mechanism in conveying motion guidance.

Perceived Practical Usability. In response to the question “Whether the EMS-based training method was considered to have practical applicability”, the average score was 4.5 with a standard deviation of 0.5. The responses show that participants broadly recognized the system’s practical potential, particularly for novice users in instrumental skill training.

To further evaluate the reliability of the questionnaire, we calculated the Cronbach’s alpha coefficient across the three items, which yielded a value of 0.847. According to common benchmarks, a Cronbach’s alpha above 0.8 indicates good internal consistency of the scale [211].

In summary, the experimental results demonstrate that the EMS-based instrumental training system proposed in this study received positive user evaluations in terms of efficiency, clarity of feedback, and practical usability, indicating a high level of usability and user acceptance.

6.3.4 Discussion

While the findings of this study suggest that EMS-based training may offer benefits in instrumental skill acquisition, several limitations must be acknowledged.

First, the evaluation relied solely on subjective responses collected through a user questionnaire. Although participants provided valuable feedback regarding efficiency, feedback clarity, and practical usability, the absence of objective performance metrics (e.g., timing accuracy, consistency, or motion analysis) limits the ability to quantitatively validate the system’s effectiveness. Future studies should incorporate objective measures to assess skill improvement more rigorously.

Second, the number of participants was relatively small ($n = 8$), which restricts the statistical power and generalizability of the results. A larger and more diverse participant pool is necessary to verify the broader applicability of the proposed system across different user profiles.

Third, this study focused exclusively on drumming as the target instrument. While percussion is well-suited for evaluating motor coordination and rhythmic accuracy, the

generalizability of EMS-based training to other instrument types—such as string, wind, or keyboard instruments—remains unexplored.

As this study remains a work in progress, further investigations will be conducted to address the limitations discussed above.

6.3.5 Conclusion and Future Work

This study proposed an EMS-based instrumental training method and developed a real-time training system focused on basic rhythm learning in percussion instruments (specifically drums). The system detects the instructor’s drumming movements and delivers electrical stimulation to the learner’s hand and foot muscles, providing physical guidance in a “Hand-in-Hand” manner. This approach is particularly beneficial for beginners who lack prior motor experience. A user study involving eight participants with no musical background was conducted, including training sessions and a questionnaire-based evaluation. The results indicated that participants generally recognized the system’s potential in improving training efficiency, feedback comprehensibility, and practical usability.

Future work will address the current limitations of this study. First, we plan to incorporate objective evaluation metrics to enable a more systematic and quantitative analysis of training outcomes. Second, we will expand the number of participants in future experiments to further validate the effectiveness and generalizability of the proposed method. In addition, we aim to explore the applicability of the EMS-based training system to other types of musical instruments, thereby broadening the potential use cases of EMS in music education.

We believe that, as the research progresses, the proposed approach can offer new directions and practical insights for instrumental skill training, especially in the context of rhythm learning.

6.4 Chapter Summary

This chapter focused on coordination augmentation, examining the role of EMS in hand–eye coordination and musical instrument learning. The results of two studies demonstrated that EMS can provide effective support in multi-limb collaborative tasks. First, in hand–eye coordination training, EMS offered immediate guidance at critical action points, enabling users to switch between visual attention and motor actions more quickly, thereby improving task accuracy and response efficiency. Second, in the musical instrument learning experiment, EMS assisted learners in establishing correct mappings between rhythm and movement, allowing them to acquire basic bimanual playing patterns within a shorter period of time and showing partial retention effects in subsequent tests. These findings confirm the feasibility and value of EMS for coordination augmentation.

Overall, the results presented in this chapter indicate that EMS not only enhances performance at the sensorimotor level for isolated actions but can also extend to complex tasks involving bimanual, multi-finger, and cross-modal integration. By improving coordination, EMS demonstrates broad potential for applications in skill training and education. These outcomes provide a foundation for further exploring higher-level augmentation applications—namely, the regulation of physiological states and emotions. Building on this, the next chapter investigates how EMS can be combined with physiological signals to regulate users’ emotional and bodily states under high-pressure conditions.

Chapter 7

Affective and Physiological State Augmentation

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7.1 Overview of Affective and Physiological State Augmentation

Within the framework of Augmented HCI, in addition to enhancing sensorimotor and coordination abilities, supporting the regulation of physiological states and emotions represents an important yet still underexplored research direction. In high-pressure

situations, even users with well-developed operational skills may experience performance degradation due to tension, anxiety, or physiological fatigue. Therefore, investigating technological approaches that can potentially assist users in maintaining more stable physiological states and emotional balance during interaction is of growing interest in Augmented HCI research.

Research in this area has often relied on biofeedback-based approaches, in which physiological signals such as heart rate are monitored and translated into visual or task-related cues to encourage self-regulation. While such methods can raise users' awareness of their internal states, they primarily depend on conscious attention and voluntary adjustment, which may be difficult to sustain under cognitively demanding or time-critical conditions. As a result, there is a need to explore alternative forms of intervention that operate more directly at the bodily level.

EMS offers a promising but largely exploratory perspective for addressing this challenge. Unlike cue-based cognitive or visual feedback, EMS can act directly on respiratory or related muscle groups and can be coupled with physiological signals to enable real-time bodily-level feedback and intervention. Compared with visual or auditory cues, such bodily-level interventions are more direct and less reliant on users' sustained attention, suggesting potential advantages in high-pressure or cognitively demanding contexts. However, the effectiveness and generalizability of EMS-based approaches for physiological and emotional regulation remain to be systematically validated.

Accordingly, this chapter adopts a stepwise exploratory approach through two complementary studies. The first study investigates a heart rate-based stress control training method that uses physiological feedback without bodily stimulation, serving as a biofeedback baseline to examine the feasibility of supporting stress regulation within an e-sports task. Building on this foundation, the second study explores an EMS-based respiratory rhythm regulation system that introduces direct bodily intervention, examining its applicability to rhythmic breathing support and gaming scenarios. Together, these studies aim to provide preliminary insights into how physiological feedback and EMS-based bodily intervention may jointly contribute to future research on physiological and emotional state augmentation in interactive systems.

7.2 Heart Rate Sensor–Based Training for Stress Control

*Based on “Method for Training Player Emotion in a Custom FPS Game Using Heart Rate.” – Zhou
and Segawa (IFIP ICEC 2023)*

Managing stress is a critical factor in competitive gaming, where excessive tension is often associated with performance errors and reduced control. In FPS games, players are required to remain composed and execute precise actions under time pressure, yet many experience difficulty regulating their emotional and physiological responses during intense gameplay. Rather than assuming that such regulation can be readily achieved, this study explores whether physiological feedback can be leveraged as a supportive training mechanism in this context.

To this end, we introduce a heart rate–based training approach that monitors players’ physiological responses in real time and provides guidance intended to support breathing regulation during gameplay. Instead of aiming to offer a definitive solution for stress management, this approach is designed as an exploratory method to examine the feasibility of integrating heart rate analysis into training systems for competitive FPS games. In this section, we present an experimental evaluation conducted in a custom FPS game to assess the feasibility and preliminary effects of this method on players’ stress regulation and task performance.

7.2.1 Introduction

In recent years, an increasing number of players have participated in e-sports entertainment events and competitions [90] [91]. Although the e-sports category is not considered a sport in the traditional sense, it has a large user base and business value. As a part of e-sports, first-person shooter (FPS) games are extremely competitive and playable, and many players devote their time and energy to them. For players, control and experience in the game are important, as these elements directly affect their score in the game [212]. To enhance the in-game control and compensate for the lack of experience, players often need to spend time improving their game skills [102] [103]. Various training software for FPS games have powerful features for situational simulation and customization, and

players can improve their gaming skills by training repeatedly using such software [105].

In addition to mastering shooting techniques, emotional control also plays a vital role for players in FPS games [213]. In high-intensity situations, where swift elimination of enemies is crucial to survival, players must maintain composure and exhibit precise control of their mouse or controller. However, not all players are adept at managing their emotions effectively. Novice or average players can easily succumb to excessive stress during gameplay, leading to costly mistakes and potential defeat. Therefore, it becomes essential to explore methods for training players to regulate their emotions and remain calm while immersed in FPS games.

Previous studies have indicated the potential of using biological information to analyze the physical and psychological state of players in the game and using the information to optimize the player's control in the game and improve the gaming experience [100, 101]. Among the various biological indicators, heart rate is considered particularly effective in real-time stress analysis [214]. Therefore, we propose a novel training approach: using heart rate analysis to gauge a player's stress levels during gameplay and using this data as a parameter to guide players in adjusting their emotions and maintaining a calm state.

Our objective is to train players through a customized FPS game that integrates real-time heart rate monitoring. By doing so, players can acquire the skills necessary to regulate their emotions, maintain composure, and ultimately reduce control mistakes, thus improving their overall gaming experience.

7.2.2 System Composition

Here, we build a system for training emotion in a custom FPS game based on the player's heart rate in real-time (Fig. 7.1).

System Implementation

During gameplay, the player's primary task involves shooting at targets using the mouse. In this proposed system, the player's heart rate will be continuously monitored in real-time. The change in the player's heart rate will serve as a parameter to adjust the speed of the target's movement within the game. Consequently, when the player's heart rate

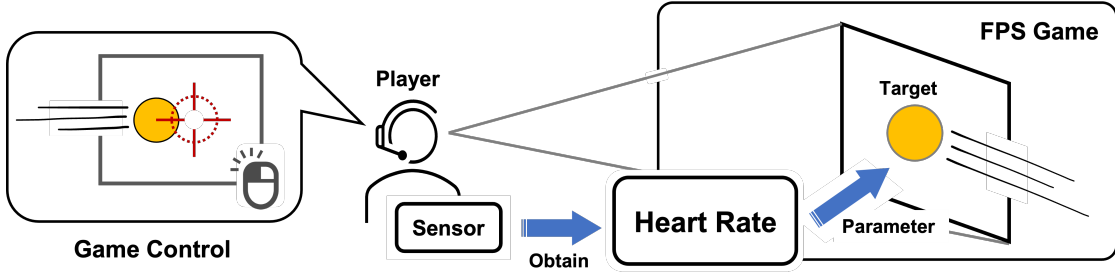


Figure 7.1: In a custom FPS game, the target changes speed based on the player’s heart rate. The higher the player’s heart rate, the faster the speed of the target. In the game, the player needs to stay as calm as possible and defeat the target as soon as possible.

is within a normal range, the motion of the target will remain manageable, allowing the player to successfully hit the target. However, as the player’s heart rate rises due to increased stress, the target’s speed will correspondingly increase, posing a greater challenge for the player to hit accurately. Thus, throughout the game, players will be compelled to regulate their emotions, maintaining a calm state and ensuring their heart rate remains within a normal range, enabling them to effectively hit the target. By implementing this system, players can be trained to control their emotions while engaged in the game.

Heart rate recording

To acquire the player’s real-time heart rate data during the game, we developed a device using the Arduino Uno microcontroller and the heart rate sensor called PulseSensor [215] (Fig. 7.2). The PulseSensor (Fig. 7.2 (a)(b)) is inexpensive and easy to set up. By attaching the heart rate sensor to the player’s wrist (Fig. 7.2 (d)), we are able to continuously gather real-time heart rate data throughout the engagement from the player during the FPS game. This data allows us to analyze the player’s stress level and monitor changes in their heart rate.

Customized FPS game

To establish a connection between the player’s heart rate and the game, we developed a custom FPS game (see Appendix C.1) using Python and the Ursina engine (Fig. 7.3). The Ursina engine [126], an open-source platform, offers numerous templates for de-



Figure 7.2: The device used to obtain the real-time heart rate. (a) Front of PulseSensor. (b) Back of PulseSensor. (c) Connection between the Arduino and the PulseSensor. (d) Attaching the sensor on the player's wrist.

signing 3D games. Leveraging this engine, we created a straightforward FPS game and configured a shooting training mode using Python. We successfully integrated the Arduino device with the game, enabling us to measure, analyze, and display the player's real-time heart rate fluctuations during gameplay.

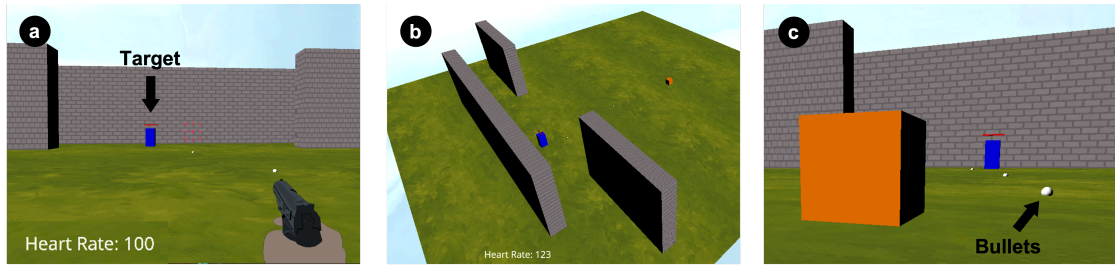


Figure 7.3: A custom FPS game. (a) The target in the game is a blue square that moves at a speed that changes based on real-time heart rate. (b) The target moves in front of a wall, and part of its motion path is covered by two other walls. (c) In the game, the target will continuously shoot at the player, and the player needs to dodge bullets to counterattack.

Within the game, the player operates the mouse to aim at an enemy target while using keyboard controls to move in a first-person view. To simulate a typical FPS-like situation, the scene includes three wall objects that partially obstruct the view and constrain the visible region of the enemy and its motion (Fig. 7.3(b)). The player fires by holding the left mouse button, and each successful hit on the enemy reduces its health by 10 points. The enemy starts with 100 health point (HP), and the game ends when the enemy's health reaches zero. We recorded the completion time (from the beginning of the session to the moment the enemy is defeated) as the primary performance metric.

The enemy continuously moves along the horizontal axis using a sinusoidal trajectory and is constrained within a fixed range ($x \in [-16, 16]$) at a constant depth ($z = 15$). Importantly, the enemy movement speed is dynamically determined by the participant's heart rate measured in real time: the game reads heart rate values from an Arduino via a serial connection (115200 baud), and updates the enemy speed according to

$$v = (\text{HR} - 50) \times 1.5,$$

where HR is the current heart rate in beats per minute (BPM). Consequently, higher heart rate leads to faster target motion, increasing the visuomotor difficulty of aiming and timing.

In addition to evasive demands, the enemy shoots at the player automatically at a fixed interval of 1 Hz (one bullet per second). Each bullet is spawned at the enemy position and travels toward the player along the normalized direction vector from the enemy to the player, with a constant bullet speed of 30 (Ursina units per second). Although bullet hits do not impose explicit penalties such as health reduction, score loss, or time penalties in the current implementation, participants were instructed at the beginning of the experiment to actively avoid incoming bullets during gameplay. As a result, being targeted by enemy fire still imposed practical visuomotor and attentional pressure, requiring participants to continuously adjust their movement and attention while maintaining shooting performance. The evaluation metric (completion time to defeat the enemy) therefore depended solely on shooting effectiveness under this imposed pressure rather than on explicit damage mechanics.

Mapping heart rate to target speed

To facilitate emotion control training, we established a direct correlation between the player's real-time heart rate and the speed of the target's motion. Before the game started, the device records the player's average heart rate under normal conditions, which serves as their resting heart rate benchmark. At the beginning of the game, the target moves at an initial speed determined by the player's reaction time. As the player experiences increased stress from failing to hit the target swiftly, the target's speed

will become faster with the rise in heart rate. For instance, consider a player with a resting heart rate of 70 BPM. In this scenario, we set the target's initial speed to 10. During gameplay, for every 5-unit increase in the player's heart rate, the target's speed increases by 5 units as well. Consequently, if the player's heart rate elevates to 100 BPM due to stress, the target's speed will reach 40 (four times the initial speed), significantly impeding the player's ability to hit the target. Conversely, when the player consciously tries to calm down and their heart rate decreases, the target's speed gradually decreases, eventually returning to normal levels.

Emotion Control Training

During the game, the player's heart rate fluctuates in response to emotional arousal. When players feel pressure to defeat the target quickly, their heart rate tends to increase, which in turn causes the target to accelerate and become more difficult to hit. This interaction may lead to a negative feedback loop in which elevated arousal degrades motor control and further increases task difficulty.

Similar biofeedback-based game mechanisms have been explored in earlier work, such as the study by Munakata et al. [216], which demonstrated that reflecting players' physiological signals (e.g., skin conductance) back into gameplay can significantly influence psychological state and performance. Building on this line of research, our system extends biofeedback-driven interaction by directly coupling heart rate to enemy behavior, thereby making emotional regulation an explicit component of successful gameplay.

To overcome the increasing difficulty induced by heightened arousal, players must recognize that remaining calm, regulating their emotions, and maintaining smooth and controlled shooting movements are critical for rapid target defeat. Through repeated exposure to this heart-rate-dependent game mechanism, players can actively train themselves in situ and develop improved emotional self-regulation skills alongside motor performance.

7.2.3 Evaluation of the Proposed Method

This study focuses on constructing a real-time heart rate-based system for emotion training in a customized FPS game. To assess the viability of this training method, a

series of experiments were conducted. Firstly, it was crucial to verify the feasibility of employing heart rate as a training parameter. Subsequently, a controlled experiment was conducted to illustrate the effectiveness of the heart rate-based training method compared to conventional repetitive training approaches.

Experimental method

In the custom game detailed in Section 7.2.2, the enemy target was initialized with a HP value of 100, and each successful hit reduced the HP by 10. For the baseline configuration, the enemy’s nominal movement parameter was set to `speed = 10`, which corresponds to the amplitude scaling factor used in the sinusoidal horizontal motion update per frame in the Ursina engine.

Specifically, the enemy’s horizontal displacement was computed as a function of elapsed time using a sine function, and the speed parameter determined the magnitude of positional change per second when multiplied by the frame time step (`time.dt`). Under this baseline setting, the enemy exhibited smooth lateral motion within the constrained range ($x \in [-16, 16]$), providing a moderate visuomotor challenge suitable for repeated trials.

At the beginning of the experiment, each participant completed the game five times to establish a baseline completion time. The participant then performed 20 training sessions under the same game configuration. After training, the participant completed the game five additional times, and the completion times were recorded. Throughout all gameplay sessions, the participant’s heart rate was continuously recorded in real time for subsequent analysis.

For experiments, we use the following two training methods (Fig. 7.4).

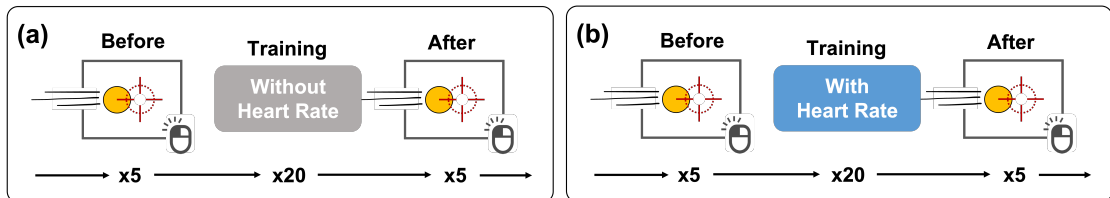


Figure 7.4: Two training methods. (a) Training without heart rate (repetitive training). (b) Training with heart rate.

Without heart rate: During the training sessions, the participant followed a training method that did not incorporate the use of heart rate. In this condition, participants wore the same heart rate sensing device as in the heart rate-based condition; however, the measured heart rate was not used to influence any game parameters. The speed of the target within the game remained constant at 10, and the participant engaged in repetitive gameplay without any adjustments based on heart rate fluctuations.

With heart rate: The participant underwent heart rate-based training. In this method, participants wore the same heart rate sensing device, and the speed of the target within the game was dynamically adjusted based on the participant's real-time heart rate, as described in Section 7.2.2. The objective for the participant was to successfully complete the game while consciously maintaining a state of calmness and striving to keep their heart rate as close to a normal resting level as possible.

In this study, only the author's data (a male, 27 years old, with experience in FPS games) was collected because the study is still a work in progress.

Experiment 1: Feasibility of the training method using heart rate

Before comparing the results of the two methods, we need to confirm that the method of training in a custom FPS game using heart rate is feasible. We recorded the time taken by the participant to beat the target before and after training with the heart rate and the average heart rate of the participant during the game. The results (Fig. 7.5) showed that the participant spent an average of 17.36 s and an average heart rate of 90 BPM the five times before training, while the participant spent an average of 12.91 s and an average heart rate of 77 BPM the five times after training.

A Mann-Whitney U test was used to test the validity of the method of training using heart rate. We first compared the time taken by the participant to complete the game before and after training. The significance level was set at 5% (a two-tailed test). According to the statistical analysis, the u-value was 23.0, and the p-value was 0.0317. The test results confirmed that the participant took significantly less time to defeat the target after training with heart rate compared to before. We then compared the mean heart rate of the participant during the game before and after training. The significance level was set at 1% (a two-tailed test). According to the statistical analysis, the u-value

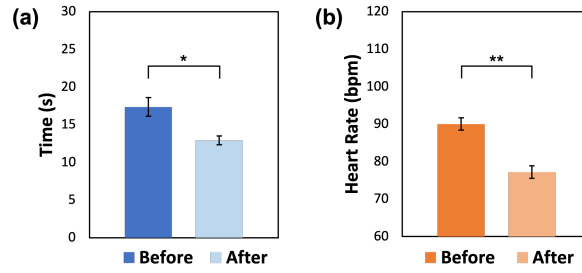


Figure 7.5: Comparison between the time taken by the participant to complete the game and the mean heart rate before and after training. (a) After training, the average time taken by the participant to complete the game decreased by 4.45 s. (b) After training, the average heart rate of the participant during the game decreased by 12 BPM.

was 25.0, and the p-value was 0.0079. The test results confirmed that the increase in the participant's heart rate during the game was controlled after training with heart rate compared to before.

Overall, these results suggest that heart-rate-based training may help participants regulate physiological arousal during gameplay. Specifically, after training, the participant showed both a shorter completion time and a lower mean heart rate during the game. However, because heart rate is an indirect physiological indicator and does not uniquely reflect psychological stress, these findings should be interpreted as improved heart-rate regulation (i.e., reduced heart-rate elevation under task demands) rather than as definitive evidence of stress control.

Experiment 2: Control experiment

To determine the effectiveness of the heart rate-based training method compared to the non-heart rate method (repetitive training), the participant underwent training using both approaches. The participant's time to defeat the target and average heart rate during the game were then compared. The results (Fig. 7.6) showed that the participant spent an average of 15.20 s and an average heart rate of 86 BPM to complete the game five times after training without the heart rate, while the participant spent an average of 12.91 s and an average heart rate of 77 BPM to complete the game five times after training with the heart rate.

The Mann-Whitney U test was used to test whether there was a significant difference

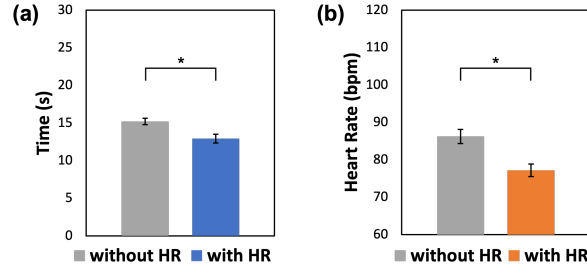


Figure 7.6: Comparison of the time taken to complete the game and the average heart rate of the participant after training with the two methods respectively. (a) The participant’s average time to complete the game after training with the heart rate was 2.29 s less than without the heart rate. (b) The participant’s average heart rate during the game after training with the heart rate was 9 BPM less than without the heart rate.

between the results of training using the two methods. The significance level was set at 5% (two-tailed test). We first compared the time taken by the participant to complete the game after training using the two methods. According to the statistical analysis, the u-value was 23.0 and the p-value was 0.0317. The test result confirmed that the participant trained using the heart rate method spent significantly less time defeating the target compared to the method trained without the heart rate method. We then compared the mean heart rate of the participant during the game after training using both methods. According to the statistical analysis, the u-value was 23.0 and the p-value was 0.0361. The test results confirmed that the participant trained with the heart rate method had better-controlled increases in heart rate during the game compared to that without the heart rate method.

Experimental results showed that training with heart rate allows players to better control their stress in customized FPS games compared to training without heart rate.

Discussion

In this section, we conducted a series of experiments to examine whether heart rate-based training in a custom FPS game could assist players in regulating their physiological responses during gameplay. First, we verified that training with heart rate feedback was associated with reduced heart-rate elevation and faster target completion. Next, we demonstrated through a controlled comparison that the heart rate-based training

method led to larger performance improvements than repetitive training without heart rate coupling.

One potential concern in interpreting these results is the possibility of order effects, as participants may improve simply due to repeated exposure to the task rather than the heart rate-based training itself. To mitigate this issue, both training conditions followed the same overall structure, used identical game settings, and involved comparable numbers of trials. Moreover, the control condition also involved repeated gameplay, allowing general practice effects to be reflected in both conditions.

Importantly, despite the presence of repeated practice in both methods, participants showed greater improvements in performance and reduced heart-rate elevation when training incorporated heart rate feedback. This suggests that the observed differences cannot be explained solely by order or repetition effects, but are likely attributable to the additional self-regulation demands introduced by heart rate coupling.

Taken together, while order effects cannot be entirely ruled out, the comparative design and the consistent advantage observed for heart rate-based training support the conclusion that integrating heart rate feedback provides added benefits beyond repetition alone. These findings indicate that heart rate-based training may facilitate improved regulation of physiological responses and task performance in a custom FPS game context.

Nevertheless, extensive follow-up studies are required to further substantiate these findings and to clarify the generalizability of heart rate-based training effects across different tasks, populations, and experimental settings.

7.2.4 Conclusion and Future Work

In this study, we propose a method for training player emotions using heart rate in FPS games. Our experimental findings confirm that this heart rate-based training can aid participants with stress and help the participant to control during a custom FPS game. Nevertheless, it is important to acknowledge certain limitations of our study: (1) Data collection was restricted to the authors, and we did not conduct broader experiments. (2) The experiments were limited to a custom game and did not involve existing FPS games. (3) The experiment duration was short, and the long-term sustainability of the

training effects was not assessed. (4) Heart rate is only one possible parameter to observe stress in players.

In conclusion, this study represents an ongoing effort, and the effectiveness and generalizability of the heart rate-based method for training player emotions in FPS games remain topics for future investigation. However, our study introduces a novel approach to training player emotions. When future studies were completed, we believe that this method could be applied to other games and sports. This study could provide a reference for such investigations.

As for future work, we will conduct further experiments to collect data from more participants to verify the effectiveness of the training method using heart rate in general. In addition, we will also use some existing FPS games to further validate the effectiveness of the method. Whether the training effect can be retained in the long term will also be investigated in the future long-term process.

7.3 EMS-Based System for Respiratory Rhythm Regulation

Based on “Stimulate to Calm: Exploring EMS-Based Breathing Control for Emotion Regulation in Games.” – Zhou and Segawa (CHI PLAY 2025)

In competitive gaming, managing emotional and physiological responses such as anxiety and stress is widely recognized as an important yet challenging factor influencing performance. Excessive tension can impair cognitive processing, reaction speed, and sustained attention, particularly in high-pressure gameplay situations. Prior research suggests that breathing regulation, which is associated with activation of the parasympathetic nervous system, may contribute to reduced anxiety and improved physiological stability. However, under high-intensity gaming conditions, breathing techniques that rely on sustained voluntary control are often difficult to maintain in practice.

Motivated by this limitation, this study explores the possibility of using electrical muscle stimulation as an external means of supporting breathing rhythm regulation during gameplay. Specifically, we investigate an EMS-based approach that stimulates respiratory muscles near the diaphragm to provide rhythmic bodily guidance, rather than requiring users to consciously regulate their breathing. This intervention is not intended as a definitive method for emotional regulation, but as an exploratory attempt to examine whether EMS-assisted breathing support can influence physiological indicators associated with stress during gameplay. In this section, we report an exploratory study with six participants, focusing on changes in heart rate before and after EMS intervention to assess the feasibility and preliminary potential of this approach for supporting physiological stability under high-pressure gaming conditions.

7.3.1 Introduction

In fast-paced and highly competitive gaming environments, players often face persistent psychological stress and emotional fluctuations. This is especially true in competitive games, where intense confrontations and complex operational demands significantly elevate players’ stress levels, affecting attention allocation, control precision, and overall

performance [217]. Prior studies have shown that emotional states can greatly influence decision-making quality and reaction speed during gameplay [218]. Therefore, effectively managing stress and anxiety during gameplay has become a critical issue for enhancing gaming performance and optimizing the user experience.

Among various self-regulation techniques, breathing control has gained considerable attention due to its direct impact on the autonomic nervous system. By slowing the breathing rate and deepening inhalation, players can activate the parasympathetic nervous system and reduce heart rate, thereby restoring emotional balance and alleviating tension [219]. Such techniques have been widely applied in areas like meditation, athletic training, and public speaking, and have recently been introduced to studies of user experience in digital games and virtual reality environments [220, 221]. However, these methods typically require individuals to engage in active, sustained practice and focused control, making them difficult to implement effectively under cognitively demanding gaming conditions.

EMS is non-invasive and induces muscle contractions through controlled electrical pulses. Previous studies have shown that EMS can be effectively applied to respiratory-related interventions, such as improving inspiratory function in patients with paralysis [222] and alleviating obstructive sleep apnea [223]. Beyond medical applications, recent research has demonstrated that EMS can enhance physical performance and motor coordination in interactive contexts, supporting rapid skill acquisition and control improvement [34, 141, 142]. Building on these findings, the present study applies EMS to the modulation of breathing rhythm, aiming to assist emotional regulation and stress reduction during gameplay.

Building on this background, this study proposes an EMS-based breathing control method designed to facilitate emotional regulation and reduce stress levels during gameplay. The method applies EMS to respiratory muscles near the diaphragm, using external stimulation to guide players' breathing rhythms and assist them in maintaining emotional balance during intense gaming. We argue that this approach can help players maintain stable breathing control even in highly focused gaming scenarios, thereby keeping stress at manageable levels and improving performance. This research aims to explore the feasibility of using EMS to reduce in-game stress, offer new perspectives

for emotional regulation and user experience optimization, and broaden the potential applications of EMS in gaming contexts.

7.3.2 Related Work

To better explain the content of this study, we provide further elaboration on breathing control, emotional regulation, and electrical muscle stimulation in the following sections.

Breathing Control and Heart Rate

Breathing is one of the fundamental physiological activities of the human body, carried out by coordinated actions of key respiratory muscles such as the diaphragm and intercostal muscles [224, 225, 226]. The diaphragm, located between the thoracic and abdominal cavities, is the primary muscle responsible for inhalation, while the intercostal muscles assist in adjusting breathing depth and rhythm by expanding and contracting the rib cage.

Under the regulation of the autonomic nervous system, breathing not only supports gas exchange but also plays a significant role in modulating emotional and physiological states [227]. Prior studies have shown that slow and rhythmic breathing can activate the parasympathetic nervous system, reduce heart rate, and increase heart rate variability, thereby alleviating tension and anxiety [228, 229]. By adjusting breathing frequency and the inhalation–exhalation ratio, individuals can indirectly regulate cardiac rhythm and achieve effective emotional self-regulation.

Emotional Stress During Gameplay

In high-pressure gaming scenarios, sustained psychological stress often leads to operational errors and lapses in attention, negatively affecting both player performance and overall experience [230]. Matthew et al. analyzed players' stress states and emotional regulation mechanisms during gameplay using real-time heart rate monitoring [231]. Zhou and Segawa proposed a heart rate–based emotional training system aimed at enhancing players' self-regulation capabilities in managing anxiety during competitive gaming [141].

However, these methods primarily rely on cue-based feedback, requiring players to

consciously perceive and adjust their internal states. In cognitively demanding and high-intensity gaming tasks, such approaches are often difficult to sustain effectively. In contrast, automated or passive physiological interventions remain underexplored, with limited research available in this area. Therefore, the present study focuses on achieving automated emotional regulation during gameplay by leveraging EMS technology to provide real-time, responsive physiological support without the need for conscious user effort.

EMS for Breathing Control

EMS was originally widely used in the field of medical rehabilitation, particularly for maintaining respiratory function and promoting muscle recovery in patients [232, 233]. In recent years, EMS technology has gradually been introduced into gaming and human-computer interaction contexts, where it has been used to enhance bodily awareness, motor performance, and cognitive function, demonstrating notable potential in improving gameplay precision and reaction speed [159, 12, 119].

However, to date, no studies have applied EMS to respiratory control in games as a means of automated emotional regulation. Therefore, this study focuses on the feasibility of applying EMS to the diaphragm area to automatically modulate breathing rhythms during gameplay, aiming to alleviate player stress. This exploration not only expands the application scope of EMS, but also provides a new perspective for developing emotion regulation methods in interactive systems.

7.3.3 EMS-Based Breathing Control System

To support the exploration of stress regulation during gameplay, this study developed an EMS-based breathing control system (see Appendix C.2). The system integrates a heart rate sensor and an EMS setup to deliver real-time electrical stimulation to the diaphragm and related respiratory muscles based on the player's heart rate. This design aims to provide external rhythmic guidance to breathing and to examine the feasibility of EMS-assisted breathing support as a bodily-level intervention for stress-related physiological regulation during gameplay.

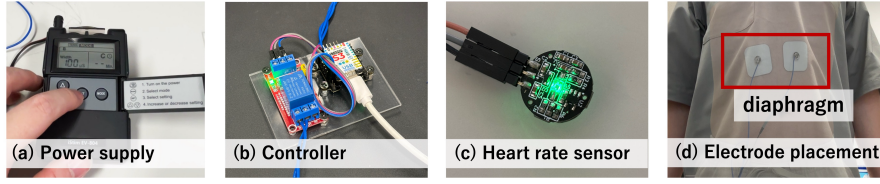


Figure 7.7: System Architecture. (a) Power supply. (b) Controller. (c) Heart rate sensor. (d) Electrode placement.

EMS device

This study employed an EMS device composed of a power supply, control module, and electrodes, designed to automatically activate players' respiratory muscles and regulate their breathing rhythm.

For the electrical stimulation unit, we selected the iStim EV-804 [162] as the power supply (Fig. 7.7(a)). This device provides stable and safe pulse output, meeting the study's requirements for a balance between stimulation intensity and user comfort, and minimizing discomfort or muscle fatigue caused by excessive stimulation.

The control module (Fig. 7.7(b)) consists of an M5StampS3 [234] microcontroller combined with a TONGLING [124] relay module, enabling precise control of EMS output. Through an Arduino program, the system controls the relay in real time, allowing the stimulation signals to be triggered on demand and adapted to individual differences and comfort requirements. Additionally, the system allows fine-tuning of pulse parameters, such as pulse width and frequency, to ensure effective muscle activation while optimizing user experience.

Electrode placement (Fig. 7.7(d)) was guided by physiological knowledge of respiration and related work, targeting key respiratory muscles such as the diaphragm and intercostal muscles [235, 236]. This ensures effective intervention in breathing rhythm while minimizing unintended stimulation of non-target muscles, thereby improving both the specificity and effectiveness of EMS application.

Emotional Stress Assessment

Heart rate is widely regarded as a key physiological indicator for assessing psychological stress levels. It is commonly used in medical and psychophysiological research to deter-

mine an individual's stress state. To enable real-time monitoring of stress changes during gameplay, this system integrates a PulseSensor [215] heart rate sensor (Fig. 7.7(c)) to capture dynamic heart rate fluctuations and infer physiological stress levels. The heart rate sensor can be positioned on the fingertip, wrist, or earlobe. With appropriate program adjustments, it provides faster and more real-time heart rate feedback compared to standard smartwatches.

Heart rate data are transmitted in real time to a computer via serial communication and processed by a Python program, which continuously records and analyzes the data. Based on the trend of heart rate changes, the system automatically assesses the player's current stress state. When an individual is under high tension or sustained stress, the sympathetic nervous system becomes active, often leading to a noticeable increase in heart rate. Although there is no universally defined threshold, many studies have reported that heart rate tends to increase by approximately 10–15% above the resting level during mild stress conditions [237, 238].

In this study, we set the stress detection threshold at 115% of the individual's resting heart rate. For instance, if a participant's resting heart rate is 74 BPM, a heart rate exceeding approximately 85 BPM during gameplay is regarded as a sign of stress. This approach provides a fundamental quantitative basis for evaluating the impact of EMS intervention on players' psychological stress.

Breathing Control

In this system, we integrate an EMS device with a heart rate sensor to enable automated regulation of players' breathing rhythms during gameplay. Through electrical stimulation, players receive physiological cues that support stress regulation without requiring conscious effort or deliberate breathing control, thereby maintaining an uninterrupted gaming experience.

When the system detects that a player's heart rate exceeds 115% of their resting rate and this condition persists for more than 3 seconds, the EMS device is automatically activated. It delivers continuous and rhythmically stable electrical stimulation to the respiratory muscles, providing clear somatic cues that encourage a more regular breathing rhythm. Importantly, the stimulation intensity is calibrated to a level at which partici-

pants can clearly perceive rhythmic contraction of the respiratory muscles, sufficient to prompt adjustment of breathing timing, but not strong enough to forcibly drive or mechanically control respiration. Thus, the system does not impose involuntary breathing, but instead guides breathing rhythm through perceptible physiological feedback.

This mechanism is designed to mitigate physiological stress responses associated with sympathetic nervous system activation by facilitating slower and more regular respiration, which is known to support autonomic regulation. Stimulation parameters are individually adjusted to ensure both effectiveness and safety. Typically, the stimulation frequency is set between 1–5 Hz and the pulse width ranges from 50–150 μ s. These parameters were selected to elicit noticeable but comfortable muscle contractions without inducing discomfort or respiratory distress.

Through this approach, players experiencing high-pressure states can engage in passive breathing modulation via externally provided rhythmic cues, reducing sympathetic arousal and contributing to improved emotional stability while preserving player safety.

7.3.4 Experiment 1: Improvement of Stress Levels

In this study, heart rate was used as the primary physiological indicator for assessing participants' stress levels. To verify the effectiveness of the EMS-based breathing control system in regulating stress, we designed and conducted an experiment aimed at evaluating improvements in stress levels after EMS application.

Experimental Procedure

This experiment was conducted based on the system developed in Section 7.3.3, with the aim of evaluating the effectiveness of EMS in regulating breathing and facilitating heart rate recovery under stress. To achieve this, it was first necessary to induce short-term stress responses in participants under controlled conditions—that is, to significantly elevate their heart rate within a short period without introducing uncontrolled variables, thereby ensuring experimental consistency and repeatability.

To induce a controlled and repeatable stress response, participants were first exposed to the same short video clip containing a clear jump-scare event. The clip was selected to elicit a rapid and transient increase in heart rate rather than prolonged emotional

distress. Immediately after the jump-scare event, the video playback was stopped, and no further visual or auditory stimuli were presented. This design aimed to minimize lingering emotional effects that could differentially influence recovery dynamics.

All participants exhibited heart rates exceeding 115% of their resting levels following the clip, which was defined as the onset of the experimental “stress state.” After stimulus termination, participants entered the recovery phase and underwent two breathing regulation conditions: (1) self-regulated breathing without EMS, and (2) EMS-assisted passive breathing regulation. Importantly, both conditions were evaluated under identical stress induction procedures, ensuring that differences in recovery were attributable to the regulation method rather than to the stimulus itself.

The system continuously recorded heart rate data during the recovery phase. The primary evaluation metric was the time required for the participant’s heart rate to return below 115% of the resting rate, which was defined as recovery to the “non-stress state.” By focusing on post-stimulus recovery under a standardized stress induction, this protocol reduced variability related to stimulus content and allowed a fair comparison between breathing regulation conditions.

A total of six male participants, aged between 19 and 30, were recruited. Each participant completed three trials under both EMS and non-EMS conditions, alternating between the two to minimize order effects and random error (six trials in total). To ensure data reliability and natural responses, all participants were confirmed to have no prior exposure to the selected video clips and no previous training in breathing regulation. Additionally, since resting heart rate can vary depending on the time of day, all trials for each participant were conducted within the same general time window whenever possible.

This study was reviewed and approved by the local ethics committee of Kyoto Sangyo University (Approval No.: KSU Ethics 0168-1; Study title: “Game Control Systems Using Electrical Muscle Stimulation”). All experiments were conducted with the informed consent of the participants, who were fully informed of the study’s purpose, procedures, and potential risks prior to participation. Because the experiment involved breathing-related regulation, all participants were screened in advance to confirm that they were in good health and had no known respiratory, cardiovascular, or neurological conditions

that could be affected by the experimental procedures.

Results

All six participants completed the tests under both EMS and non-EMS conditions. For each trial, we measured the time required for participants to recover from the defined “stress state” (heart rate exceeding 115% of resting level) to the “non-stress state” (heart rate falling below this threshold), and calculated the average recovery time across three trials for each condition. Fig. 7.8(a) presents the average recovery times for each participant (P1–P6) under both conditions.

In this experiment, recovery time was used as an indicator of how efficiently participants were able to regulate their physiological arousal following a stress-inducing stimulus. A shorter recovery time reflects faster heart-rate stabilization, which serves as a proxy for physiological recovery. However, it should be noted that heart rate is an indirect measure and does not uniquely represent psychological stress. Therefore, the recovery time in this context is interpreted as heart-rate regulation efficiency rather than as definitive evidence of stress reduction.

The results (Fig. 7.8) showed that for all participants, the recovery time under the EMS-assisted breathing condition was noticeably shorter than that under the non-EMS condition. The average recovery time with EMS was 46.33 seconds, compared to 74.67 seconds without EMS, indicating a consistent difference between the two conditions.

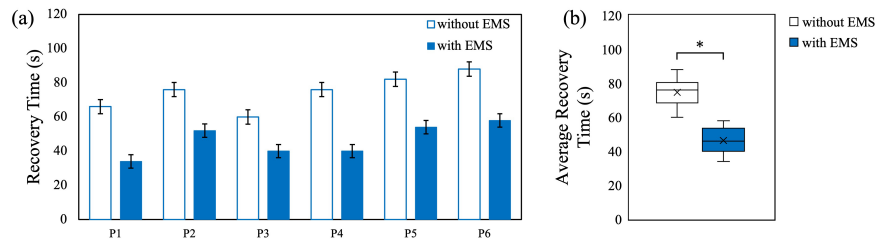


Figure 7.8: Participants’ results in the stress recovery test. (a) Average recovery time for each participant with and without EMS. (b) Overall comparison of recovery times.

To further verify the statistical significance of this trend, we conducted a Wilcoxon signed-rank test on the paired data. The test yielded a test statistic of $W = 0.0$ with a two-tailed p -value of 0.03125. At a significance level of $\alpha = 0.05$, the difference between

the two conditions was statistically significant. These findings suggest that EMS-guided passive breathing regulation can effectively accelerate physiological recovery from stress, helping to reduce sympathetic nervous system activity and improve emotional states in high-pressure environments.

7.3.5 Experiment 2: Improvement of Stress Levels in Gameplay

Unlike the controlled stress-induction scenario used in Experiment 1, stress variations in real gameplay environments are more continuous and fluctuating in nature. The stress states experienced by players during gameplay are not isolated, abrupt responses, but rather part of an ongoing, cumulative, and dynamically regulated process. Therefore, when evaluating the effectiveness of stress reduction during gameplay, it is insufficient to rely solely on a single metric such as “heart rate over time.”

To more comprehensively capture changes in participants’ physiological and emotional states during real gameplay, a multifaceted analysis is required. This includes metrics such as the overall average heart rate, the range of heart rate fluctuations reflecting the intensity of tension, and the proportion of time spent in high-stress states indicating stress persistence. Together, these indicators provide a multi-perspective quantitative assessment of players’ ability to regulate psychological stress during high-intensity interactive experiences.

Experimental Procedure

In this experiment, heart rate remained the primary physiological indicator for evaluating players’ stress states. However, to more comprehensively reflect the physiological stress variations experienced in dynamic real-game scenarios, additional parameters were introduced. Specifically, we measured: (1) average heart rate, (2) heart rate fluctuation range (the difference between maximum and minimum values), and (3) proportion of time spent under stress (i.e., the duration during which heart rate exceeded 115% of resting level, expressed as a percentage of total gameplay time).

To construct a representative high-pressure gaming scenario, we selected *Dark Souls III* as the experimental platform. This action role-playing game is known for its high difficulty level, and boss battles often impose sustained psychological pressure, where minor

mistakes can lead to failure and trigger strong physiological responses. In this experiment, all participants faced the same boss, *Iudex Gundyr*, which is the first mandatory boss encountered in the game.

Because none of the participants had prior experience with *Dark Souls III*, all participants first completed the standard in-game tutorial sequence provided at the beginning of the game. This tutorial introduces basic movement, camera control, attacking, guarding, and stamina management, allowing participants to acquire familiarity with the fundamental control mechanics before the experimental task. Only after completing this guided introduction did participants proceed to the boss battle with *Iudex Gundyr*.

All participants played under identical game settings and conditions to ensure task consistency and result comparability. During each trial, heart rate recording was automatically initiated at the start of the boss battle and continued until the battle concluded, regardless of success or failure. Based on the full heart rate time series, we calculated each participant's average heart rate, heart rate fluctuation range (max–min), and the percentage of time during which heart rate exceeded 115% of resting level, which were used as quantitative indicators of physiological stress responses during gameplay.

As in Experiment 1, all six participants completed three trials under both with and without EMS conditions, with the test order alternated to control for order effects and random error. This experiment also followed the same IRB process to ensure compliance and informed consent from all participants.

Results

All six participants completed the boss battle task in *Dark Souls III* under both EMS and non-EMS conditions. We recorded each participant's heart rate throughout the entire battle and calculated three key stress-related physiological indicators: average heart rate, heart rate fluctuation range, and proportion of time spent under stress, to comprehensively assess physiological stress responses in a high-pressure gaming scenario.

The results (Fig. 7.9) showed that under EMS-assisted breathing regulation, all participants exhibited improved stress control across all three indicators. Specifically, the average heart rate decreased from 84.17 BPM (without EMS) to 77.33 BPM (with EMS); the heart rate fluctuation range decreased from 37.67 BPM to 24.83 BPM; and the pro-

portion of time spent in a stress state dropped significantly from 61.04% to 23.95%. These findings suggest that the EMS-induced passive breathing rhythm control mechanism not only reduced overall heart rate levels but also mitigated intense heart rate fluctuations and shortened the duration of high-stress periods.

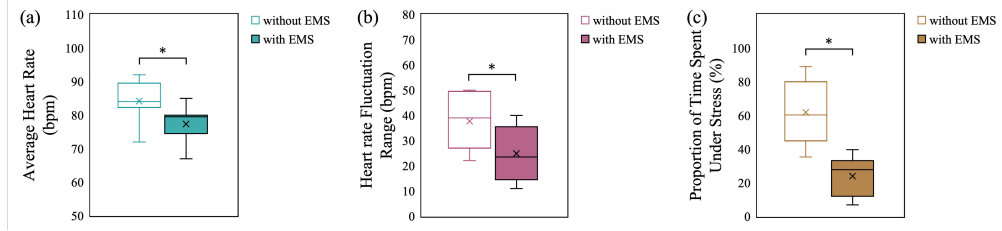


Figure 7.9: Participants’ results in Dark Souls III. (a) Average heart rate with and without EMS conditions. (b) Heart rate fluctuation range. (c) Proportion of time spent in a stress state.

To further verify the statistical significance of these trends, we performed Wilcoxon signed-rank tests on all three indicators. The results yielded $W = 0.0$ and $p = 0.03125$ for each indicator, representing the smallest attainable p -value for the current sample size using the Wilcoxon test. At a significance level of $\alpha = 0.05$, all three differences were statistically significant. These results indicate that EMS-assisted breathing regulation can effectively alleviate physiological stress during real gameplay tasks, enabling players to return to a stable state more quickly and enhancing their self-regulation capacity and performance stability under pressure.

It is worth noting that although the three physiological indicators exhibited consistent trends across participants, this consistency should be interpreted with caution given the exploratory nature of the study and the limited sample size. Rather than indicating a universal or definitive effect, the observed pattern suggests that EMS-assisted breathing support was associated with similar directional changes in physiological indicators related to stress across participants. Specifically, under EMS-assisted conditions, participants tended to show lower average heart rates, reduced fluctuation ranges, and shorter durations of elevated heart rate states compared to non-EMS conditions. These results provide preliminary evidence that the proposed system may influence multiple stress-related physiological dimensions in a consistent manner, warranting further investigation in larger and more diverse samples.

7.3.6 Discussion

Although the results of this study indicate that EMS-based breathing regulation has a significant effect in alleviating physiological stress during gameplay, several limitations remain and warrant further investigation and refinement.

First, the study relied solely on heart rate as the physiological indicator for stress assessment. While parameters such as average heart rate, fluctuation range, and proportion of time under stress offer valuable insights, the absence of additional physiological or psychological measures—such as electrodermal activity, respiration rate, or subjective emotional reports—limits the comprehensiveness of our understanding of players' stress states. Future research should incorporate a wider range of measurement dimensions to establish a more systematic and scientifically grounded evaluation framework.

Second, the sample size was relatively small ($n = 6$), and the participant profile was homogeneous (all male, aged 19–30), which limits the statistical power and general applicability of the results. Expanding the sample size and including participants of varying genders and age groups would enhance the representativeness of the study and improve the generalizability of the findings.

Third, the experimental scenario was limited to a specific boss battle in *Dark Souls III*. Although this task effectively induced a high-pressure state, its stress type and interaction style are relatively narrow. The applicability of EMS-based breathing regulation in other game genres—such as timed challenges or competitive multiplayer games—remains untested and should be explored in future studies.

Finally, the effectiveness of the system was demonstrated only under short-term experimental conditions, and its long-term impact and user adaptation remain unknown. Future work should examine whether the stress-reducing effects of EMS persist over extended use, whether habituation occurs, and how users perceive the system's comfort and usability over time.

In summary, as an initial exploration of EMS-based stress regulation in gaming, this study remains in an early stage. Future research will address the above limitations through more comprehensive and systematic investigations to improve the system's applicability, scalability, and ecological validity in real-world gaming scenarios.

7.3.7 Conclusion and Future Work

This study proposed an EMS-based breathing regulation system designed to alleviate physiological stress during gameplay. The system integrates real-time heart rate monitoring with electrical muscle stimulation applied to the diaphragm and related respiratory muscles, enabling passive and adaptive control of breathing rhythm. Two experiments were conducted to evaluate the system’s effectiveness: a short-term stress recovery task using controlled stimuli, and a real-game scenario using *Dark Souls III*. In both cases, EMS-assisted breathing regulation led to significantly better outcomes across multiple physiological indicators, including average heart rate, fluctuation range, and duration of stress states. These findings demonstrate the potential of EMS as a real-time physiological intervention for enhancing emotional regulation and maintaining performance stability in high-pressure gaming environments.

Future work will address the current limitations of this study. First, we plan to incorporate additional physiological and psychological metrics—such as electrodermal activity, respiration rate, and subjective emotional reports—to provide a more comprehensive and multidimensional understanding of stress responses. Second, we will expand the participant pool in terms of both size and demographic diversity to improve the statistical robustness and generalizability of the findings. Third, we aim to test the EMS-assisted breathing system across a broader range of game genres and stress-inducing contexts, such as competitive multiplayer or timed challenges, to validate its applicability in diverse gaming scenarios. Finally, we intend to investigate long-term usage effects, including potential habituation and sustained user experience.

We believe that this research lays important groundwork for the integration of EMS into interactive systems aimed at emotional regulation. As development continues, the proposed approach may offer promising insights and practical solutions for stress management not only in gaming, but also in broader domains involving high cognitive load or emotional demand.

7.4 Chapter Summary

This chapter examined the augmentation of physiological states and emotional regulation through an exploratory, stepwise investigation, with the primary goal of assessing the feasibility and potential of bodily-level interventions in high-pressure interactive contexts. Rather than assuming the effectiveness of EMS-based regulation a priori, the chapter first considered the role of physiological feedback as a baseline approach, and then explored the introduction of direct bodily intervention using EMS.

Through two complementary exploratory studies, the results suggested that physiological signals can be meaningfully integrated into interactive systems to support stress-related regulation. The heart rate-based training study, which relied on physiological feedback without bodily stimulation, indicated that feedback-driven support may assist breathing-related self-regulation under heightened tension, contributing to more efficient physiological recovery and improved interaction performance. Building on this baseline, the breathing rhythm regulation study explored the use of EMS as a direct bodily intervention, suggesting that EMS-assisted rhythmic guidance may help users regain composure more quickly and maintain concentration during demanding tasks. Together, these findings provide initial insights into how EMS-based bodily intervention, when combined with physiological signals, may extend state-level support beyond conventional skill-focused augmentation.

Overall, the results presented in this chapter highlight the feasibility and promise of EMS-based approaches for physiological and emotional state augmentation, while stopping short of definitive validation. By integrating external physiological signals with bodily-level interventions, EMS shows potential as a foundation for closed-loop augmentation systems in contexts such as gaming, education, and work. At the same time, the exploratory nature of the studies underscores the need for further investigation into issues such as user agency, long-term effects, and safety considerations to ensure the responsible and sustainable application of such technologies. Building on these preliminary findings, the next chapter provides an integrated discussion of the dissertation's overall contributions, limitations, and broader implications.

Chapter 8

Discussion and Applications

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8.1 Overall Feasibility and Research Contributions

Through the empirical studies conducted in this dissertation—focusing on sensorimotor augmentation, coordination augmentation, and physiological and emotional regulation—the results collectively suggest that EMS is a feasible and promising technology within the framework of Augmented HCI. Across multiple experimental contexts, the findings indicate that EMS can facilitate short-term performance improvements and, in certain task settings, support early-stage skill learning and performance persistence after stimulation is removed. Rather than serving as definitive proof, these results provide converging empirical evidence that supports the exploration of EMS beyond its traditional use in rehabilitation and training, toward broader forms of interactive augmentation.

At the sensorimotor level, the studies demonstrated that EMS can support improvements in timing control and fine finger movement tasks. Whether assisting users in forming faster response patterns in shooting tasks or improving clicking speed and ac-

curacy in finger control tasks, EMS showed consistent facilitation effects on basic sensorimotor coordination. In addition, several experiments observed that performance gains persisted after the removal of EMS, suggesting that EMS may contribute to learning-related processes or aftereffects, rather than functioning solely as a momentary assistive mechanism.

At the coordination level, EMS was further examined in hand–eye coordination and musical instrument learning tasks. By providing targeted stimulation at task-relevant moments, EMS appeared to support the formation of more efficient mappings between perceptual information and motor execution, resulting in improvements in task efficiency and accuracy. In the context of musical instrument learning, EMS-assisted stimulation helped beginners acquire bimanual performance patterns more rapidly during early training stages, with partial retention effects observed after stimulation was removed. These findings suggest that EMS has the potential to support complex multi-limb and multi-modal coordination tasks, particularly during the initial phases of skill acquisition, while longer-term learning and transfer remain topics for future investigation.

At the physiological and emotional regulation level, the studies presented in Chapter 7 provided an exploratory examination of how physiological signals and bodily-level interventions may contribute to state regulation in interactive contexts. The heart rate–based stress control study served as a biofeedback baseline, indicating that physiological feedback alone can support breathing-related self-regulation when heart rate increases, contributing to physiological recovery and task performance stability. Building on this baseline, the breathing rhythm regulation study explored EMS as a direct bodily intervention, suggesting that EMS-assisted stimulation of respiratory muscles may help stabilize breathing rhythms and support users in maintaining focus and composure under high-pressure conditions. Taken together, these studies provide preliminary insights into the potential of EMS-based closed-loop approaches, in combination with physiological feedback, as a promising direction for future research in stress regulation and related applications.

Overall, the empirical findings of this dissertation indicate that EMS can support augmented interaction across multiple levels, although the strength and scope of evidence vary depending on the study design, task domain, and evaluation period. From

short-term performance facilitation to early-stage skill acquisition and partial retention, and from multimodal coordination to physiological and emotional regulation, EMS demonstrates broad potential as an augmentation technology. While further large-scale, longitudinal, and ecologically valid studies are required to clarify long-term learning effects and transferability, these results support the technical feasibility of EMS and conceptually motivate the proposal of “EMS-based Augmented HCI” as an emerging paradigm—one that explores how direct engagement with muscular and physiological systems can open new directions for human–computer interaction.

8.2 Limitations, User Experience, and Potential Risks

Although this dissertation has verified the feasibility and potential of EMS in Augmented HCI, the findings and broader application of this technology remain subject to several limitations and challenges. These constraints stem not only from experimental design and technical implementation but also from issues related to user experience, long-term usability, and ethical considerations.

First, in terms of experimental design, the sample size of this research was relatively limited, and participants were primarily young and healthy university students. This demographic concentration restricts the generalizability of the results, meaning that the conclusions may not directly apply to older adults, individuals with motor impairments, or participants from different cultural backgrounds. Furthermore, most experimental tasks focused on gamified and learning-oriented contexts, which, while effective for testing augmentation effects, do not yet reflect applications in real-world work environments or complex scenarios. Future studies should employ larger and more diverse participant samples and design tasks that more closely resemble practical use cases to further validate the robustness of these findings.

Second, from a technical perspective, the effectiveness of EMS is influenced by multiple physical conditions. Variations in skin impedance, muscle thickness, and sensitivity across individuals lead to considerable differences in stimulation effects under identical parameters. In addition, issues such as poor electrode contact, dry skin, or electrode displacement during movement can reduce stimulation stability and efficiency. Long-term

use of EMS may also cause muscle fatigue or localized discomfort, limiting its applicability in extended tasks. Therefore, developing adaptive systems capable of real-time parameter adjustment and improving electrode materials and wearability remain key challenges for future technical advancement.

Third, regarding user experience, the use of EMS may affect users' sense of agency and control. When the stimulation intensity is too high or the timing of activation is inappropriate, users may feel passive or "controlled," which diminishes the quality of interaction and can even lead to resistance. In short-term training, such external guidance can help users quickly acquire correct movement patterns; however, over prolonged use, continuous reliance on external stimulation may weaken autonomous control and even lead to psychological resistance. Achieving a balance between effective augmentation and maintaining users' sense of autonomy is thus a critical issue for EMS-based interaction design.

Related to this, the issue of dependency represents another potential risk in EMS applications. Because EMS can produce rapid and noticeable performance improvements, users may develop a tendency to repeatedly rely on external assistance, thereby reducing their intrinsic motivation for self-directed practice. Such dependency may not only limit skill transfer to non-EMS contexts but also result in performance decline once the stimulation is removed. To mitigate this issue, system designs should gradually reduce stimulation intensity or frequency over time, guiding users from external reliance toward autonomous control and achieving a balance between enhancement and independence.

Finally, the potential long-term risks associated with EMS use warrant careful attention. Although EMS is a non-invasive technology, extended or high-intensity usage may lead to muscle fatigue, skin irritation, or mild tissue damage. For instance, excessive stimulation frequency can accelerate local muscle fatigue, while prolonged electrode attachment may cause skin irritation or allergic reactions. Moreover, individual differences can amplify these risks—some users may exhibit higher sensitivity to electrical stimulation and experience discomfort even at low intensities. Consequently, future EMS systems must include adaptive safety mechanisms, such as upper limits on stimulation intensity, automatic rest intervals, and real-time monitoring of skin–electrode contact conditions.

In summary, while this dissertation demonstrates the feasibility of EMS for human augmentation, several challenges persist in terms of sample representativeness, technical stability, user experience, dependency, and long-term safety. These limitations not only clarify the scope of the current findings but also offer valuable insights for future research aimed at improving the reliability, safety, and inclusivity of EMS-based Augmented HCI.

8.3 Individual Differences and Adaptation Mechanisms

The effectiveness of EMS depends not only on stimulation parameters and device design but also on significant individual physiological and psychological differences. Users vary in skin impedance, muscle thickness, neural sensitivity, and subjective tolerance to electrical stimulation, making it difficult for a single parameter configuration to provide consistent enhancement effects for everyone. Therefore, research on EMS-based augmented human–computer interaction must carefully account for these individual differences and develop effective adaptive mechanisms.

From a physiological perspective, skin impedance and tissue conductivity vary widely among individuals and can dynamically change with external factors such as humidity and temperature. The same current intensity may induce a noticeable muscle contraction in one user but have little effect in another. Moreover, differences in muscle thickness and distribution affect the spread of current within tissues, influencing both the amplitude of motion and the perceived comfort. These physiological variations highlight the need for EMS systems to incorporate personalized parameter adjustment to ensure that stimulation achieves the intended effect without causing discomfort.

From a psychological standpoint, users exhibit substantial differences in their subjective acceptance and comfort toward electrical stimulation. Some may find mild stimulation novel and engaging, whereas others may experience tension or resistance, making adaptation difficult. These psychological differences not only affect users' willingness to use EMS but also influence learning outcomes and interaction performance. Accordingly, EMS system design should prioritize controllability and transparency—for instance, by allowing users to manually adjust stimulation intensity or frequency, or to deactivate stimulation when needed—to foster trust and acceptance.

To address these individual differences, this study emphasizes the necessity of adaptive mechanisms. First, individualized parameter calibration serves as a fundamental step. Before experiments or use, stimulation intensity should be gradually increased to determine each user's sensory and contraction thresholds, which then inform a personalized parameter range. Second, adaptive control mechanisms can improve continuity and safety by monitoring electrode contact and skin impedance in real time and automatically adjusting stimulation intensity to maintain stable effects. Third, advancements in smart electrodes and wearable design offer new possibilities for adaptation. The use of conductive fabrics or flexible electrodes can enhance comfort and stability while reducing issues such as electrode displacement or poor contact.

In summary, individual differences are an unavoidable yet critical factor in EMS-based augmented human-computer interaction. Only through individualized calibration, adaptive adjustment, and intelligent electrode design can users consistently achieve safe, comfortable, and stable enhancement effects. These adaptive mechanisms not only improve the generalizability of the technology but also provide essential conditions for the practical deployment of EMS systems.

8.4 Theoretical and Interdisciplinary Implications

Beyond verifying the feasibility of EMS in Augmented HCI, this research also revealed several findings of theoretical and interdisciplinary significance. These findings not only expand the boundaries of HCI research but also offer new perspectives for related fields such as neuroscience, motor learning, and emotional regulation.

First, the results suggest a potential role of EMS in facilitating neural plasticity. In the sensorimotor and coordination experiments, participants retained part of their learning effects even after EMS was removed, indicating that the combination of external stimulation and voluntary motor intention may accelerate the internalization of motor patterns through synaptic plasticity mechanisms. This phenomenon aligns with Hebbian learning theory [239] and the principles of spike-timing-dependent plasticity (STDP) [156], suggesting that EMS may enhance the encoding of correct motor patterns in the central nervous system by providing additional neural input at critical moments.

These insights not only offer a new pathway for motor learning intervention but also provide empirical support for understanding learning mechanisms in human–technology coupling.

Second, this research highlights the potential of multimodal augmentation. As a modality that acts directly on muscles, EMS provides more immediate and less ignorable feedback compared to visual or auditory cues. When integrated with multimodal signals such as heart rate, eye movement, or acceleration, EMS can form a closed-loop augmentation system. For example, in the stress regulation experiment, heart rate data triggered EMS to guide breathing, enabling real-time physiological intervention through biofeedback. Such cross-modal integration represents a promising direction for future augmented interaction systems—achieving synergistic enhancement across perception, movement, and emotional regulation through complementary modalities.

Third, the findings contribute to the theoretical development of “Embodied HCI” [240]. Traditional interaction design has largely focused on cognitive and informational interfaces, whereas EMS directly intervenes in bodily movement and physiological rhythms, making the human body an active component—and even the core—of interaction. In both the finger control and breathing regulation experiments, users experienced external intervention at the bodily level and a reshaping of their learning process. This form of “technological embodiment” expands the paradigm of HCI, shifting attention from perception and cognition toward deeper coupling between the body and technology.

Finally, this research underscores the interdisciplinary potential of HCI. By introducing EMS technology from medical and rehabilitative contexts and integrating it with behavioral science frameworks of skill learning and emotional regulation, this dissertation demonstrates the necessity of interdisciplinary collaboration in addressing complex research problems. The study of EMS requires not only the engineering foundations of hardware design and signal control but also the physiological insights of neuroscience and the theoretical models of psychology. Consequently, this research contributes not only to HCI but also to the broader interdisciplinary exploration of human augmentation technologies.

In summary, the theoretical and interdisciplinary implications of this dissertation can be summarized at three levels: (1) EMS may facilitate skill learning through mechanisms

of neural plasticity; (2) EMS can be integrated with other modalities to form closed-loop augmentation systems; and (3) EMS provides new perspectives for embodied interaction and interdisciplinary integration in HCI. Together, these insights establish a solid theoretical and practical foundation for the future development of augmented interaction research.

8.5 Design Implications and Future Application Prospects

Through multiple empirical studies, this dissertation has demonstrated the feasibility of EMS in Augmented HCI. These findings not only hold academic significance but also provide valuable insights for the design and application of future interactive systems.

First, the experiments presented in this dissertation demonstrate that EMS can function both as an immediate cue and as an actuation mechanism, and thus its use should be flexibly adapted to the task context. During the early stages of skill learning, EMS can serve as a strong guidance signal to help users quickly establish correct movement patterns. In later consolidation stages, however, the intensity of stimulation should be gradually reduced, transitioning to lighter cues to prevent overreliance on external assistance. Designers should carefully balance this “augmentation–transition–autonomy” process to ensure that users maintain agency and self-control while benefiting from enhancement.

Second, in terms of system design principles, this research highlights the importance of adaptive parameter control and safety protection. Because individual differences in skin impedance, muscle sensitivity, and current tolerance vary widely, fixed parameters cannot guarantee an optimal experience. Future EMS systems should incorporate real-time monitoring and adaptive adjustment functions, automatically tuning stimulation parameters based on user feedback or physiological signals. Additionally, multi-layered safety mechanisms are essential, including electrode contact detection, automatic current cutoff in case of anomalies, and user-controlled emergency stop functions, ensuring safety and reliability during long-term use.

Third, regarding application potential, EMS demonstrates strong value across multiple domains. In education and training, EMS can accelerate skill acquisition in areas

such as musical performance, manual craftsmanship, or sports. In competitive sports learning and training, many disciplines, including e-sports, fencing, basketball, and table tennis, demand exceptional reaction speed, hand-eye coordination, and rhythm control. Traditional training typically relies on prolonged repetitive practice and experience accumulation, whereas EMS can provide immediate motion cues at critical moments, accelerating the formation of correct motor patterns and potentially improving skill retention and transfer across tasks.

In remote instruction and education, EMS can be integrated with wearable devices and network communication technologies to enable the transmission of motor guidance beyond visual and auditory channels. In the context of music learning, for instance, an instructor could remotely send EMS signals to guide learners to perform specific movements at appropriate moments, thus shortening the adaptation period during early training. In professional skill development, EMS can also serve as an assistive tool to help trainees master fine-motor operations more efficiently. This combination of remote communication and embodied feedback introduces new possibilities for future remote education and distributed training systems.

In gaming and entertainment, EMS can enhance immersion and expressivity. In e-sports or immersive gaming environments, EMS can not only help players improve control accuracy and reaction speed but also act as a novel feedback channel that complements visual and auditory stimuli with bodily sensations. For example, in rhythm-based games, EMS can synchronize with musical beats to produce tactile feedback consistent with the sound and visual rhythm, thereby intensifying the sense of immersion. For entertainment applications, the immediacy and intuitiveness of EMS open new opportunities for creating innovative gameplay and interactive experiences.

In mental health and stress management, EMS demonstrates unique advantages when combined with physiological signals. The experiments in this dissertation have verified that when users experience stress, EMS can act on respiratory-related muscles to guide breathing rhythms, thereby reducing heart rate and tension levels. Building on this, EMS could evolve into a physiological-level emotion-regulation tool that provides real-time stress management solutions for high-pressure professions such as surgery, aviation, or competitive performance. Unlike traditional meditation or cognitive approaches, EMS

can directly and immediately influence physiological rhythms, enabling rapid and effective emotional stabilization.

With the continued advancement of wearable devices and intelligent sensing systems, EMS can be integrated with visual, auditory, and haptic feedback to form multimodal closed-loop systems, further improving the naturalness and effectiveness of interaction. In multi-user or social contexts, EMS could be employed to support collaborative activities or shared experiences, extending its applications in education, entertainment, and social interaction. These prospects suggest that designers and researchers should increasingly focus on multimodal integration and collective interaction scenarios in future developments.

In summary, the findings of this dissertation provide both theoretical grounding and practical guidance for the design and application of EMS-based interactive systems. From interaction principles to system architecture and application potential, EMS demonstrates its unique value as a key technology for Augmented Human–Computer Interaction.

8.6 Ethics and Social Responsibility

As EMS gradually transitions from laboratory research to real-world applications, issues of ethics and social responsibility have become increasingly prominent. As a technology that acts directly on the human body, EMS raises not only the conventional concerns of usability and user experience in human–computer interaction but also deeper questions of autonomy, safety, fairness, and sustainability. Therefore, alongside technical advancement, researchers and designers must give thorough consideration to the ethical and societal implications of EMS.

At the research ethics level, ensuring participant safety and rights is paramount. Because EMS involves direct bodily stimulation, experimental design must strictly adhere to the principle of informed consent, ensuring that participants fully understand the stimulation intensity, potential discomfort, and emergency-stop mechanisms. Researchers must also implement rigorous safety measures—such as setting upper limits for stimulation intensity, monitoring device output in real time, and providing an emer-

gency stop button—to minimize risks. In addition, potential psychological effects should be taken into account; participants may experience discomfort or distress related to the sense of “being controlled,” which should be carefully mitigated.

At the technological ethics level, the augmentative capability of EMS may risk diminishing user autonomy and sense of control. When the system enforces involuntary movements at critical moments, users may perceive a loss of agency or even a feeling of manipulation—raising questions about freedom and control in interaction. If system design neglects this balance, it could foster dependency or psychological resistance. Therefore, designers must adhere to the principle of augmentation rather than replacement, ensuring that EMS functions only as an assistive mechanism, not as a means of complete control. Moreover, EMS must not be misused for manipulative or coercive purposes, such as delivering stimulation without explicit consent, as this would violate ethical boundaries concerning human rights and privacy.

At the societal responsibility level, the development of EMS should emphasize fairness and accessibility. If enhancement technologies are available only to limited or privileged groups, they may exacerbate social inequalities—for instance, creating divisions between “technologically enhanced” and “naturally capable” individuals in competitive domains. Long-term use may also pose new health or psychological dependency risks, requiring the establishment of ethical review processes and usage guidelines to prevent misuse. More broadly, HCI researchers must take on anticipatory responsibility when addressing enhancement technologies—considering not only performance improvements but also the long-term societal, cultural, and ethical implications of their deployment.

In summary, the advancement and application of EMS must be grounded in ethical and social responsibility. From safety assurance in research, to the preservation of user autonomy in system design, and to fairness and regulation in social deployment, ethical considerations permeate the entire lifecycle of EMS. Only by achieving a balance between technological innovation and ethical constraint can EMS serve as a meaningful form of augmented human–computer interaction—one that truly enhances human ability while contributing to social well-being.

8.7 Chapter Summary

This chapter provided an integrated discussion of the research findings on EMS within the context of Augmented Human–Computer Interaction and examined their implications for applications, user experience, and ethics. From an overall feasibility perspective, the empirical studies verified the effectiveness of EMS across three enhancement dimensions—sensorimotor control, coordination, and physiological–emotional regulation—demonstrating its distinctive potential as an augmentation technology.

At the same time, the chapter identified several constraints, including limited sample size, individual variability, technical stability, user experience, dependency, and issues related to long-term use, risk, and ethics. These factors serve as valuable references for future refinement and broader application of EMS-based systems. The discussion of theoretical and interdisciplinary implications highlighted the intrinsic connections between EMS, neural plasticity, embodied interaction, and multimodal integration, underscoring its interdisciplinary value and theoretical contributions.

Furthermore, this chapter outlined design principles and application prospects spanning education and training, competitive sports, remote instruction, gaming and entertainment, and psychological intervention and stress management, providing a practical roadmap for implementing EMS in real-world contexts. Finally, it emphasized the importance of ethics and social responsibility, calling for careful consideration of autonomy, fairness, and sustainability in the development and deployment of EMS technologies.

Overall, this chapter reaffirmed the academic significance and practical potential of EMS in Augmented HCI while emphasizing the challenges and risks that accompany its development. Building on these discussions, the concluding chapter will summarize the main contributions of this dissertation and present future research directions, including multimodal integration, multi-user interaction, and long-term adaptive interventions.

Chapter 9

Conclusion and Future Work

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9.1 Summary of Research Contributions

Building on the integrated discussion in the previous chapter, this chapter concludes the dissertation by summarizing its main contributions and outlining future research directions. The overarching goal of this dissertation was to explore the role and potential of EMS in Augmented HCI and to propose a paradigm of EMS-based augmented interactive systems. Through the integration of theoretical analysis, system design, and empirical validation, this research makes contributions across three primary dimensions: technical implementation, empirical investigation, and conceptual development.

At the technical level, this study developed multiple EMS-based interactive systems encompassing hardware architecture, electrode design, and signal control mechanisms. It summarized the fundamental principles and parameter adjustment methods of EMS and proposed a modeling framework for stimulation efficiency, explaining variations in EMS effects from the perspectives of energy transmission and individual adaptation.

These technical explorations established a robust foundation for subsequent empirical studies and provided methodological references for ensuring the scalability and safety of EMS systems.

At the empirical level, a series of user studies systematically validated the effects of EMS across three augmentation dimensions. First, in sensorimotor augmentation, EMS was shown to improve users' timing control and finger precision, shortening learning curves and enhancing retention. Second, in coordination augmentation, results demonstrated that EMS facilitated the formation of efficient action mappings in hand-eye coordination and musical instrument learning tasks, reducing learning costs and improving multi-limb coordination efficiency. Third, in affective and physiological augmentation, experiments verified the feasibility of integrating EMS with physiological signals such as heart rate and breathing rhythm, showing that EMS can help users maintain stable physiological and psychological states under stress. Together, these studies demonstrate the broad applicability of EMS across diverse tasks and human capabilities.

At the conceptual level, this research articulated EMS-based Augmented HCI as a paradigm that positions EMS as a direct interaction channel intervening in bodily movement and physiological processes. Unlike traditional interaction modalities that rely primarily on sensory feedback, EMS operates at the bodily level, providing direct enhancement and thereby extending the boundaries of HCI research. This framework offers a systematic rationale for applying EMS within HCI and lays conceptual groundwork for future studies exploring deeper coupling between the human body and interactive technologies.

In summary, the contributions of this dissertation can be categorized into three aspects: (1) **Technical Contribution**: a systematic EMS system architecture and stimulation efficiency modeling framework; (2) **Empirical Contribution**: experimental validation of EMS effectiveness across sensorimotor, coordination, and affective-physiological dimensions; (3) **Conceptual Contribution**: the articulation of an EMS-based paradigm for augmented interaction.

Collectively, these contributions enrich the theoretical and methodological foundations of Augmented HCI and provide a novel interdisciplinary pathway for exploring human ability enhancement through technology.

9.2 A New Paradigm of EMS-Based Augmented HCI

Building on the preceding findings, this dissertation proposes a paradigm of EMS-based Augmented HCI that moves beyond traditional interaction frameworks relying solely on visual, auditory, and tactile cues. Instead, it extends the scope of interaction to the human muscular and physiological systems, enabling augmentation at a more fundamental bodily level.

Conventional HCI research has primarily focused on improving the efficiency of information transmission and the usability of interfaces—optimizing visual displays, refining input devices, or introducing virtual and augmented reality to enhance perception and cognition. However, these approaches largely operate at the sensory level and lack the ability to directly intervene in users’ motor execution or physiological states. In contrast, EMS can act directly on muscles through externally applied electrical currents, guiding or assisting users in performing specific movements. Moreover, by influencing physiological processes such as breathing and heart rate, EMS can contribute to the regulation of emotions and stress. This distinctive capability positions EMS as a unique medium of interaction—one that translates technological signals into immediate, embodied feedback and intervention.

The proposed paradigm features three core characteristics. (1) **Embodied interactivity**: EMS not only provides external cues but can also physically alter a user’s movement state, delivering real-time motor assistance during interaction. (2) **Augmentation rather than substitution**: EMS is not intended to take control of the user’s actions but to serve as an assistive mechanism that accelerates learning and improves performance while maintaining user autonomy. (3) **Cross-modal and cross-domain extensibility**: EMS can be integrated with visual, auditory, and haptic feedback to form closed-loop multimodal systems, while its applications can extend beyond gaming and education to athletic training, psychological intervention, and collaborative or social interaction contexts.

Compared with other augmentation technologies, EMS-based systems offer distinct advantages. Brain–Computer Interfaces (BCIs) can directly read neural activity but are often limited by invasiveness and technical complexity. Exoskeletons and robotic systems

provide physical augmentation but are typically bulky and lack flexibility. In contrast, EMS devices are lightweight, non-invasive, and highly portable, making them easy to deploy in both everyday and experimental settings. These characteristics make EMS a practical and scalable pathway for achieving augmented human–computer interaction.

In summary, the proposed paradigm of EMS-based augmented interaction systems broadens the conceptual scope of HCI and establishes a theoretical foundation for future research into the deep integration of technology and the human body. By extending interaction to the muscular and physiological domains, this framework opens a body-centric pathway for augmentation and lays the groundwork for future explorations of multimodal integration, multi-user collaboration, and long-term adaptive intervention in augmented interactive systems.

9.3 Future Research Directions

Although this dissertation has verified the feasibility of EMS in Augmented HCI from multiple perspectives, its full potential has yet to be realized. Future research should aim to expand the application boundaries of EMS and address the challenges that arise in complex and realistic scenarios. This section outlines three promising directions for further exploration: multimodal integration, multi-user and social interaction, and long-term intervention and behavioral shaping.

9.3.1 Multimodal Integration

Current studies have primarily focused on single-modal or limited-modal applications of EMS, such as combinations with visual tasks or heart rate feedback. However, in real-world interactive environments, users typically rely on the integrated processing of multiple sensory modalities. Future research could investigate how EMS can be combined with visual, auditory, and haptic feedback to form a closed-loop interactive system. For example, in rhythm-based games or physical training, the system could present visual targets, deliver auditory rhythm cues, and employ EMS to guide motor execution, thereby achieving cross-modal synergy. Moreover, with advances in artificial intelligence and sensing technologies, it is possible to construct adaptive multimodal frameworks that dynamically allocate the contribution of each modality based on real-time user states,

enhancing both the efficiency and naturalness of augmentation.

9.3.2 Multi-User and Social Interaction

The experiments conducted in this dissertation primarily addressed single-user scenarios, yet many real-world tasks require group collaboration and social engagement. Future studies could explore the role of EMS in multi-user interactions. For instance, synchronized stimulation could be used to enhance motor coordination among team members during cooperative sports training, or EMS could enable bodily-level guidance between instructors and learners in remote education contexts. Beyond functional training, EMS could also facilitate shared bodily experiences—for example, generating synchronized sensations in multi-user virtual environments to promote a sense of connection and collective immersion. This line of research not only broadens the scope of EMS applications but also introduces new challenges, such as maintaining individual adaptability while ensuring fairness and synchronization at the group level.

9.3.3 Long-Term Interventions and Behavior Shaping

The studies in this dissertation primarily focused on short-term experiments and training sessions, leaving the long-term effects and risks of EMS largely unexplored. Future research should examine the impact of prolonged EMS use on skill transfer, retention, and habit formation. For example, in music learning or athletic training, it is worth investigating whether continuous EMS intervention over weeks or months can significantly enhance learning efficiency and sustain performance even after the stimulation is removed. At the same time, potential negative outcomes—such as muscle dependence, psychological resistance, or reduced autonomy—must be carefully assessed. Furthermore, EMS could serve as a tool for behavioral shaping, helping users develop consistent breathing rhythms or eliminate maladaptive movement patterns. This direction entails not only verifying the long-term technical efficacy of EMS but also addressing ethical and sustainability concerns associated with its extended use.

9.4 Chapter Summary

This dissertation has systematically explored the potential and value of EMS within the framework of Augmented HCI. From theoretical foundations and system construction to multiple empirical studies, it has demonstrated the feasibility of EMS in three dimensions of augmentation: sensorimotor enhancement, coordination enhancement, and affective and physiological regulation enhancement. The results indicate that EMS can significantly improve user performance across different tasks and contexts, facilitate skill acquisition, and, to some extent, contribute to physiological and psychological stabilization. These findings provide empirical support for integrating EMS into HCI and offer new perspectives for expanding the conceptual boundaries of human–computer interaction.

Building upon these results, this dissertation proposed a paradigm of EMS-based Augmented HCI, emphasizing the extension of interaction from perceptual and cognitive layers to bodily and physiological layers. Through direct engagement with the human body, EMS enables deeper forms of human capability enhancement. The establishment of this paradigm enriches the theoretical framework of HCI and opens an interdisciplinary perspective that bridges computer science, neuroscience, motor learning, and psychology.

At the same time, this work identified several practical challenges associated with EMS, including individual variability, long-term usage risks, user agency preservation, and ethical as well as social responsibility. These issues highlight the need for future research on personalized adaptation, adaptive control, and the integration of multimodal and multi-user scenarios, ensuring a balance between augmentation effectiveness and user experience.

Looking ahead, the application of EMS in Augmented HCI holds vast potential. Whether in competitive training, education, entertainment, or psychological intervention and stress management, EMS has the capacity to serve as a key medium for embodied interaction. With ongoing advances in sensing technologies, artificial intelligence, and wearable systems, EMS may evolve toward tighter integration with multimodal interfaces, creating more natural, efficient, and sustainable augmentation systems.

In summary, this dissertation provides a systematic justification and theoretical

framework for the use of EMS in HCI and lays a foundation for future exploration of human capability enhancement. By jointly advancing technological innovation and ethical responsibility, EMS has the potential to become a cornerstone of Augmented HCI—propelling the field from a focus on interface optimization and information exchange toward a broader vision of capability augmentation and human–technology co-evolution.

Acknowledgements

It is my great honor to have completed my PhD at Kyoto Sangyo University. I would like to express my sincere and deepest gratitude to my principal supervisor, Professor Norihisa Segawa of the Faculty of Information Science and Engineering, Kyoto Sangyo University. I have been a member of the Segawa Laboratory since my undergraduate studies, and under his continuous guidance and support, I was able to progress through my master's and doctoral programs. Without his long-term mentorship, encouragement, and patience, this dissertation would not have been possible. Professor Segawa provided invaluable guidance not only in my research but also in my academic life more broadly. Through his supervision, I learned how to think independently as a researcher and developed the fundamental skills and attitudes necessary for conducting rigorous scientific research. His mentorship has had a profound and lasting impact on my academic development.

I would also like to sincerely thank the members of my doctoral examination committee, Professor Mitsuru Minakuchi and Professor Nagisa Munekata, as well as all other faculty members who participated in the examination process, for their valuable advice and constructive feedback throughout my graduate studies. Their guidance greatly contributed to shaping my research direction and improving the rigor and clarity of my work.

I am especially grateful to Mr. Masato Yazawa of the Mathematical Assist Design Laboratory for his extensive support during my graduate studies. His practical advice across various projects, as well as his generous financial assistance, enabled me to actively engage in international academic exchanges and disseminate my research through overseas conferences and publications.

I would like to extend my gratitude to all faculty members who have guided me

throughout my academic journey, my co-authors for their collaboration on this dissertation, all members of the Segawa Laboratory, and the many mentors, colleagues, and friends who have supported me from my undergraduate years through my graduate studies. Their encouragement, discussions, and companionship have been invaluable.

This work was supported in part by JSPS KAKENHI Grant Numbers 20K11780 and 25K15200, and by JST SPRING, Japan Grant Number JPMJSP2157. I gratefully acknowledge this financial support.

Finally, I would like to express my heartfelt gratitude to my family for their unwavering support over many years. I am deeply thankful for their encouragement in my education and for the immense emotional and financial support they have provided throughout my long journey as an international student. I cannot imagine having reached this point without their constant understanding and support.

In an era in which technologies are increasingly integrated and interdisciplinary research continues to rapidly expand, I strongly believe that research in the field of Human–Computer Interaction holds significant potential for shaping future human behavior and interaction paradigms. In particular, I consider Augmented HCI to be a promising and important research direction that may fundamentally influence how people learn, work, play, and live. Motivated by this perspective, I intend to continue pursuing research in Augmented HCI, including but not limited to approaches based on EMS technologies, as well as other emerging interactive and augmentation technologies.

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Appendix A

Sensorimotor Augmentation Implementation

A.1 FPS Game Source Code

Listing A.1: FPS game implementation used in the experiment

```
1
2 from ursina import *
3 from ursina.prefabs.first_person_controller import FirstPersonController
4 from ursina.shaders import lit_with_shadows_shader
5 import random
6 import serial
7 import time
8 from concurrent.futures import ThreadPoolExecutor
9
10 count = 0
11 def input(key):
12     if key == 'left mouse down':
13         global count
14         count = count + 1
15         for enemy in enemys:
16             if enemy.hovered:
17                 destroy(enemy)
18     if key == 'c':
19         acc = num / count
20         print(count)
21         print(acc)
22
23
24 ems_on = 1
```



```

25
26 def input_once():
27     if ems_on == 1:
28         ser.write("1".encode())
29
30
31 class Enemy(Button):
32     def __init__(self, x, y, z):
33         super().__init__()
34         self.parent = shootables_parent
35         self.model = 'cube'
36         self.scale = 1.39
37         self.position = (x, y, z)
38         self.rotation = (0, 0, 0)
39         self.collider = 'box'
40         self.color = color.white
41
42 ser = serial.Serial("COM3", 115200)
43
44 app = Ursina()
45
46 random.seed(0)
47 Entity.default_shader = lit_with_shadows_shader
48
49 ground = Entity(model='plane', collider='box', scale=128, texture='grass',
50                 , texture_scale=(4,4))
51
52 wall_1 = Entity(model='cube', collider='box', position=(0, 0, 0), scale
53               =(32, 32, 1), rotation=(0, 0, 0), texture='brick', texture_scale=(1,2)
54               , color=color.orange)
55 wall_2 = Entity(model='cube', collider='box', position=(-12, 0, -10),
56               scale=(12, 25, 1), rotation=(0, 0, 0), texture='brick', texture_scale
57               =(1,2), color=color.white)
58 wall_3 = Entity(model='cube', collider='box', position=(6, 0, -10), scale
59               =(16, 25, 1), rotation=(0, 0, 0), texture='brick', texture_scale=(1,2)
60               , color=color.white)
61
62 editor_camera = EditorCamera(enabled=False, ignore_paused=True)
63 player = FirstPersonController(model='cube', x=-4, z=-30, color=color.
64                               orange, origin_y=-.5, speed=8)
65 player.collider = BoxCollider(player, Vec3(0,1,0), Vec3(1,2,1))
66
67 gun_texture = Texture('gun1.png')
68 gun = Entity(model='quad', parent=camera, position=(.3,-.25,.25), scale
69             =(1,.4,1), origin_z=-.5, texture=gun_texture, on_cooldown=False)

```

```
61 gun.muzzle_flash = Entity(parent=gun, z=1, world_scale=.5, model='quad',
    color=color.yellow, enabled=False)
62
63 shootables_parent = Entity()
64 mouse.traverse_target = shootables_parent
65
66 num = 5 #enemy number
67 enemys = [None]*num
68 for i in range(num):
69     ex = random.uniform(-20, -8)
70     ey = random.uniform(1, 15)
71     ez = -2
72     enemys[i] = Enemy(ex, ey, ez)
73     enemys[i].on_mouse_enter = input_once
74     enemys[i].animate_x(ex + 30, duration = random.uniform(3.5, 4), loop=
        True) #enemy movement
75
76 def pause_input(key):
77     if key == 'tab': # press tab to toggle edit/play mode
78         editor_camera.enabled = not editor_camera.enabled
79
80         player.visible_self = editor_camera.enabled
81         player.cursor.enabled = not editor_camera.enabled
82         gun.enabled = not editor_camera.enabled
83         mouse.locked = not editor_camera.enabled
84         editor_camera.position = player.position
85
86         application.paused = editor_camera.enabled
87
88 pause_handler = Entity(ignore_paused=True, input=pause_input)
89
90
91 sun = DirectionalLight()
92 sun.look_at(Vec3(1,-1,1))
93 Sky()
94
95 app.run()
96 ser.close()
```

A.2 Finger Training Source Code

Listing A.2: Finger training implementation used in the experiment

```
1
2 import pygame
3 import random
4 import serial
5
6 ser = serial.Serial("COM3", 115200)
7
8 pygame.init()
9
10 screen_width = 1366
11 screen_height = 768
12 screen = pygame.display.set_mode((screen_width, screen_height))
13 pygame.display.set_caption("Mouse Click Training Game")
14
15 WHITE = (255, 255, 255)
16 BLACK = (0, 0, 0)
17 RED = (30, 144, 255)
18
19 pygame.mouse.set_visible(False)
20
21 TARGET_RADIUS = 120
22 NUM_TARGETS = 5
23
24 destroyed_targets = 0
25 click_count = 0
26 correct_clicks = 0
27
28 possible_click_counts = [5, 10, 15, 20, 25, 30]
29
30 def spawn_target():
31     x = random.randint(TARGET_RADIUS, screen_width - TARGET_RADIUS)
32     y = random.randint(TARGET_RADIUS, screen_height - TARGET_RADIUS)
33     needed_clicks = random.choice(possible_click_counts)
34     return [x, y, needed_clicks]
35
36 current_target = spawn_target()
37
38 start_ticks = pygame.time.get_ticks()
39
40 running = True
```

```

41 while running:
42     screen.fill(WHITE)
43
44     mouse_x, mouse_y = pygame.mouse.get_pos()
45     mouse_buttons = pygame.mouse.get_pressed()
46
47     for event in pygame.event.get():
48         if event.type == pygame.QUIT:
49             running = False
50         elif event.type == pygame.MOUSEBUTTONDOWN:
51             click_count += 1
52
53
54             dist_sq = (mouse_x - current_target[0]) ** 2 + (mouse_y -
55                 current_target[1]) ** 2
56             if dist_sq <= TARGET_RADIUS ** 2:
57                 if current_target[2] > 0:
58                     current_target[2] -= 1
59                     correct_clicks += 1
60                     ser.write(b'1')
61
62                 if current_target[2] == 0:
63                     destroyed_targets += 1
64                     if destroyed_targets < NUM_TARGETS:
65                         current_target = spawn_target()
66                     else:
67                         running = False
68             else:
69                 pass
70         else:
71             pass
72
73     if destroyed_targets < NUM_TARGETS:
74         pygame.draw.circle(screen, RED, (current_target[0],
75             current_target[1]), TARGET_RADIUS)
76         font = pygame.font.SysFont(None, 120)
77         text_surf = font.render(str(current_target[2]), True, BLACK)
78         text_rect = text_surf.get_rect(center=(current_target[0],
79             current_target[1]))
80         screen.blit(text_surf, text_rect)
81
82     pygame.draw.line(screen, BLACK, (mouse_x - 15, mouse_y), (mouse_x +
83         15, mouse_y), 2)
84     pygame.draw.line(screen, BLACK, (mouse_x, mouse_y - 15), (mouse_x,
85         mouse_y + 15), 2)

```

```
81
82     elapsed_time = (pygame.time.get_ticks() - start_ticks) / 1000.0
83
84     if click_count > 0:
85         accuracy = (correct_clicks / click_count) * 100
86     else:
87         accuracy = 100
88
89     font_info = pygame.font.SysFont(None, 40)
90     time_surf = font_info.render(f"Time: {elapsed_time:.2f}s", True,
91                                 BLACK)
92     acc_surf = font_info.render(f"Accuracy: {accuracy:.2f}%", True, BLACK
93                               )
94
95     screen.blit(time_surf, (10, 10))
96     screen.blit(acc_surf, (10, 50))
97
98     pygame.display.update()
99
100 screen.fill(WHITE)
101 end_font = pygame.font.SysFont("comicsansms", 60)
102 end_text = end_font.render("Game Over", True, BLACK)
103 time_text = end_font.render(f"Time: {elapsed_time:.2f}s", True, RED)
104 acc_text = end_font.render(f"Accuracy: {accuracy:.2f}%", True, RED)
105
106 screen.blit(end_text, (screen_width / 4, screen_height / 3))
107 screen.blit(time_text, (screen_width / 4, screen_height / 2))
108 screen.blit(acc_text, (screen_width / 4, screen_height / 2 + 70))
109 pygame.display.update()
110
111 pygame.time.wait(5000)
112 pygame.quit()
```

Appendix B

Coordination Augmentation Implementation

B.1 Hand-Eye Coordination Training System

B.1.1 Eye tracking Source Code

Listing B.1: Eye tracking implementation used in the experiment

```
1
2 import cv2
3 import dlib
4 import numpy as np
5
6 def find_pupil(eye):
7     gray_eye = cv2.cvtColor(eye, cv2.COLOR_BGR2GRAY)
8     blurred_eye = cv2.GaussianBlur(gray_eye, (7, 7), 0)
9     _, threshold_eye = cv2.threshold(blurred_eye, 30, 255, cv2.
    THRESH_BINARY_INV)
10    contours, _ = cv2.findContours(threshold_eye, cv2.RETR_TREE, cv2.
    CHAIN_APPROX_SIMPLE)
11    contours = sorted(contours, key=lambda x: cv2.contourArea(x), reverse
    =True)
12    for cnt in contours:
13        (x, y, w, h) = cv2.boundingRect(cnt)
14        return x + w // 2, y + h // 2
15    return None
16
17 def get_eye_direction(eye_center, pupil_position):
18     if pupil_position:
19         dx = abs(pupil_position[0] - eye_center[0])
```

```
20     threshold = 8
21
22     if dx < threshold:
23         return "Center"
24     elif pupil_position[0] < eye_center[0]:
25         return "Left"
26     else:
27         return "Right"
28     return "Center"
29
30 cap = cv2.VideoCapture(0)
31
32 detector = dlib.get_frontal_face_detector()
33 predictor = dlib.shape_predictor("shape_predictor_68_face_landmarks.dat")
34
35 left_eye_points = []
36 right_eye_points = []
37
38 left_text_position = (600, 200)
39 right_text_position = (600, 200)
40
41 left_text_color = (255, 0, 0)
42 right_text_color = (0, 0, 255)
43
44 while True:
45     _, frame = cap.read()
46     frame = cv2.flip(frame, 1)
47     gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
48     faces = detector(gray)
49
50     for face in faces:
51         landmarks = predictor(gray, face)
52         left_eye = frame[landmarks.part(37).y:landmarks.part(41).y,
53                          landmarks.part(36).x:landmarks.part(39).x]
54         right_eye = frame[landmarks.part(43).y:landmarks.part(47).y,
55                           landmarks.part(42).x:landmarks.part(45).x]
56
57         left_pupil = find_pupil(left_eye)
58         right_pupil = find_pupil(right_eye)
59
60         if left_pupil:
61             left_eye_center = (left_eye.shape[1] // 2, left_eye.shape[0]
62                               // 2)
63             left_eye_direction = get_eye_direction(left_eye_center,
64                                                    left_pupil)
```

```

61         cv2.circle(left_eye, left_pupil, 3, (0, 255, 0), -1)
62         left_eye_points.append(left_pupil)
63         cv2.putText(frame, left_eye_direction, (landmarks.part(36).x
64             - 10, landmarks.part(37).y - 10),
65             cv2.FONT_HERSHEY_SIMPLEX, 1.0, (0, 255, 0), 2)
66
67     if right_pupil:
68         right_eye_center = (right_eye.shape[1] // 2, right_eye.shape
69             [0] // 2)
70         right_eye_direction = get_eye_direction(right_eye_center,
71             right_pupil)
72         cv2.circle(right_eye, right_pupil, 3, (0, 255, 0), -1)
73         right_eye_points.append(right_pupil)
74         cv2.putText(frame, right_eye_direction, (landmarks.part(42).x
75             - 10, landmarks.part(43).y - 10),
76             cv2.FONT_HERSHEY_SIMPLEX, 1.0, (0, 255, 0), 2)
77
78     key = cv2.waitKey(1) & 0xFF
79     key = cv2.waitKey(1) & 0xFF
80     if key == ord('l'):
81         cv2.putText(frame, "Left", left_text_position, cv2.
82             FONT_HERSHEY_SIMPLEX, 1.0, left_text_color, 2)
83     elif key == ord('r'):
84         cv2.putText(frame, "Right", right_text_position, cv2.
85             FONT_HERSHEY_SIMPLEX, 1.0, right_text_color, 2)
86
87     cv2.imshow("Frame", frame)
88
89     if cv2.waitKey(1) & 0xFF == ord('q'):
90         break
91
92 cap.release()
93 cv2.destroyAllWindows()

```


B.1.2 Custom Hand-Eye Coordination Game Source Code

Listing B.2: Custom game implementation used in the experiment

```
1
2 import pygame
3 import random
4 import string
5 import serial
6
7 ser =serial.Serial("COM3", 115200)
8
9 pygame.init()
10
11 screen_width = 800
12 screen_height = 600
13 screen = pygame.display.set_mode((screen_width, screen_height))
14
15 black = (0, 0, 0)
16 white = (255, 255, 255)
17 red = (255, 0, 0)
18 blue = (0, 0, 255)
19
20 block_size = 50
21
22 score = 0
23
24 pygame.display.set_caption('Enhanced Moving Target Game')
25
26 game_over = False
27 game_end = False
28
29 block_x = screen_width / 2
30 block_y = screen_height / 2
31
32 def rand_target_position_type_and_speed():
33     has_letter = random.choice([True, False])
34     if has_letter:
35         letter = random.choice("qweasdzxc")
36         text = letter
37         color = red
38         ser.write(b'0')
39     else:
40         letter = None
41         text = random.choice(["Left", "Right"])
```

```
42         color = blue
43         ser.write(b'1')
44
45         x = random.randrange(0, screen_width - block_size)
46         y = random.randrange(0, screen_height - block_size)
47         speed_x = random.randint(-1, 1)
48         speed_y = random.randint(-1, 1)
49         return x, y, letter, text, color, speed_x, speed_y
50
51 target_x, target_y, target_letter, target_text, target_color,
    target_speed_x, target_speed_y = rand_target_position_type_and_speed()
52
53 current_key = None
54
55 penalty_applied = False
56
57 start_ticks = pygame.time.get_ticks()
58
59 while not game_over:
60     for event in pygame.event.get():
61         if event.type == pygame.QUIT:
62             game_over = True
63         elif event.type == pygame.KEYDOWN:
64             current_key = event.unicode
65
66     seconds = (pygame.time.get_ticks() - start_ticks) / 1000
67     countdown = max(60 - seconds, 0)
68
69     if countdown <= 0:
70         game_end = True
71         game_over = True
72
73     target_x += target_speed_x
74     target_y += target_speed_y
75
76     if target_x < 0 or target_x > screen_width - block_size:
77         target_speed_x *= -1
78     if target_y < 0 or target_y > screen_height - block_size:
79         target_speed_y *= -1
80
81     mouse_pressed = pygame.mouse.get_pressed()
82     block_x, block_y = pygame.mouse.get_pos()
83     block_x -= block_size / 2
84     block_y -= block_size / 2
85
```

```

86     if target_x < block_x < target_x + block_size and target_y < block_y
87         < target_y + block_size:
88         if target_color == red:
89             if current_key == target_letter:
90                 if mouse_pressed[0] or mouse_pressed[2]:
91                     score -= 20
92                     penalty_applied = True
93             else:
94                 target_x, target_y, target_letter, target_text,
95                 target_color, target_speed_x, target_speed_y =
96                 rand_target_position_type_and_speed()
97                 score += 10
98                 penalty_applied = False
99         elif not penalty_applied:
100             score -= 20
101             penalty_applied = True
102         elif target_color == blue:
103             if (target_text == "Left" and mouse_pressed[0]) or (
104                 target_text == "Right" and mouse_pressed[2]):
105                 target_x, target_y, target_letter, target_text,
106                 target_color, target_speed_x, target_speed_y =
107                 rand_target_position_type_and_speed()
108                 score += 10
109                 penalty_applied = False
110             elif not penalty_applied:
111                 score -= 20
112                 penalty_applied = True
113         current_key = None
114
115     screen.fill(white)
116
117     pygame.draw.rect(screen, black, [block_x, block_y, block_size,
118         block_size])
119
120     pygame.draw.rect(screen, target_color, [target_x, target_y,
121         block_size, block_size])
122
123     font = pygame.font.SysFont(None, 55)
124     text = font.render(target_text.upper(), True, black)
125     text_rect = text.get_rect(center=(target_x + block_size / 2, target_y
126         + block_size / 2))
127     screen.blit(text, text_rect)
128
129     score_font = pygame.font.SysFont(None, 35)
130     score_text = score_font.render("Score: " + str(score), True, black)

```

```
122     screen.blit(score_text, [0, 0])
123
124     countdown_font = pygame.font.SysFont(None, 35)
125     countdown_text = countdown_font.render(f"Time: {int(countdown)}",
126     True, black)
127     screen.blit(countdown_text, [screen_width - 150, 10])
128
129     pygame.display.update()
130
131 if game_end:
132     screen.fill(white)
133     end_font = pygame.font.SysFont("comicsansms", 60)
134     end_text = end_font.render("Game Over", True, black)
135     score_text = end_font.render("Final Score: " + str(score), True, red)
136     screen.blit(end_text, [screen_width / 4, screen_height / 3])
137     screen.blit(score_text, [screen_width / 4, screen_height / 2])
138     pygame.display.update()
139     pygame.time.wait(5000)
140
141 pygame.quit()
```

B.2 EMS-Based Drum Learning System

B.2.1 Hand Motion Detection Code

Listing B.3: Right-hand motion detection using IMU

```
1  #include <LSM6DS3.h>
2  #include <Wire.h>
3  #include <MadgwickAHRS.h>
4
5  #define MEASURING_FREQ 1660
6
7  LSM6DS3 IMU(I2C_MODE, 0x6A);
8
9  typedef struct {
10     float x;
11     float y;
12     float z;
13     float a;
14 } pos3d_t;
15
16 pos3d_t acc_;
17 double mes_time_ = 1.0 / MEASURING_FREQ * 1000.0;
18
19 void setup() {
20     Serial.begin(115200);
21     IMU.settings.gyroRange = 2000;
22     IMU.settings.accelRange = 4;
23     IMU.begin();
24 }
25
26 void loop() {
27     acc_.x = IMU.readFloatAccelX();
28     acc_.y = IMU.readFloatAccelY();
29     acc_.z = IMU.readFloatAccelZ();
30     acc_.a = acc_.x*acc_.x + acc_.y*acc_.y + acc_.z*acc_.z;
31     Serial.println(acc_.a);
32     delay(mes_time_);
33 }
```

B.2.2 Foot Pedal Detection Code

Listing B.4: Foot pedal detection using pressure sensor

```
1  const int pressureSensorPin = A0;
2  const int interruptPin = 2;
3
4  int threshold = 300;
5  int resetThreshold = 100;
6  bool hitDetected = false;
7
8  void setup() {
9      Serial.begin(115200);
10     pinMode(interruptPin, OUTPUT);
11 }
12
13 void loop() {
14     int value = analogRead(pressureSensorPin);
15     if (value > threshold && !hitDetected) {
16         digitalWrite(interruptPin, HIGH);
17         delay(10);
18         digitalWrite(interruptPin, LOW);
19         hitDetected = true;
20     } else if (value < resetThreshold) {
21         hitDetected = false;
22     }
23     Serial.println(value);
24     delay(10);
25 }
```

B.2.3 EMS Output Control Code

Listing B.5: EMS relay control on ESP32

```
1  int pinRight = 2;
2  int pinLeft  = 14;
3  int pinFoot  = 5;
4
5  void setup() {
6      pinMode(pinRight, OUTPUT);
7      pinMode(pinLeft, OUTPUT);
8      pinMode(pinFoot, OUTPUT);
9      Serial.begin(115200);
10 }
11
12 void loop() {
13     if (Serial.available()) {
14         char cmd = Serial.read();
15         if (cmd == '1') {
16             digitalWrite(pinRight, HIGH);
17             delay(30);
18             digitalWrite(pinRight, LOW);
19         } else if (cmd == '2') {
20             digitalWrite(pinLeft, HIGH);
21             delay(30);
22             digitalWrite(pinLeft, LOW);
23         } else if (cmd == '3') {
24             digitalWrite(pinFoot, HIGH);
25             delay(30);
26             digitalWrite(pinFoot, LOW);
27         }
28     }
29 }
```

B.2.4 Host-Side Signal Processing

Listing B.6: Python-based strike detection and EMS control

```
1 import serial
2 import threading
3
4 THRESHOLD = 37
5 RESET_THRESHOLD = 15
6
7 ser_right = serial.Serial('/dev/ttyUSB0', 115200)
8 ems = serial.Serial('/dev/ttyUSB3', 115200)
9
10 def process_data():
11     while True:
12         data = ser_right.readline().decode().strip()
13         try:
14             value = float(data)
15             if value > THRESHOLD:
16                 ems.write(b'1')
17         except:
18             pass
19
20 threading.Thread(target=process_data).start()
```


Appendix C

Affective and Physiological State Augmentation Implementation

C.1 Heart Rate Sensor-Based Training

Listing C.1: Heart Rate Sensor-Based FPS game implementation used in the experiment

```
1
2 from ursina import *
3 from ursina.prefabs.first_person_controller import FirstPersonController
4 from ursina.shaders import lit_with_shadows_shader
5 import time
6 from ursina import Texture
7 import serial
8
9 class ArduinoReader:
10     def __init__(self, port, baudrate=115200):
11         self.ser = serial.Serial(port, baudrate)
12         self.current_heart_rate = 0
13
14     def read_data(self):
15         while self.ser.in_waiting > 0:
16             line = self.ser.readline().decode('utf-8').strip()
17             try:
18                 self.current_heart_rate = int(line)
19             except ValueError:
20                 print(f"Received invalid data: {line}")
21
22 app = Ursina()
23
24 random.seed(0)
```

```
25 Entity.default_shader = lit_with_shadows_shader
26
27 heart_rate_text = Text(anchor=(0, 0), position=(-.5, -.45), color=color.
    white)
28
29 ground = Entity(model='plane', collider='box', scale=64, texture='grass',
    texture_scale=(4,4))
30
31 editor_camera = EditorCamera(enabled=False, ignore_paused=True)
32 player = FirstPersonController(model='cube', z=-10, color=color.orange,
    origin_y=-.5, speed=8)
33 player.collider = BoxCollider(player, Vec3(0,1,0), Vec3(1,2,1))
34
35 gun_texture = Texture('gun1.png')
36 gun = Entity(model='quad', parent=camera, position=(.3,-.25,.25), scale
    =(.5,.4,1), origin_z=-.5, texture=gun_texture, on_cooldown=False)
37 gun.muzzle_flash = Entity(parent=gun, z=1, world_scale=.5, model='quad',
    color=color.yellow, enabled=False)
38
39 shootables_parent = Entity()
40 mouse.traverse_target = shootables_parent
41
42 crosshair_texture = Texture('shoot.png')
43 crosshair = Entity(parent=camera.ui, model='quad', texture=
    crosshair_texture, scale=.08 )
44
45 wall = Entity(model='cube', scale=(35, 10, 2), texture='brick',
    texture_scale=(15,5), x=0, y=5, z=20, collider='box', color=color.
    white)
46 wall = Entity(model='cube', scale=(15, 10, 2), texture='brick',
    texture_scale=(15,5), x=20, y=5, z=12, collider='box', color=color.
    white)
47 wall = Entity(model='cube', scale=(15, 10, 2), texture='brick',
    texture_scale=(15,5), x=-20, y=5, z=12, collider='box', color=color.
    white)
48 def update():
49     if held_keys['left mouse']:
50         shoot()
51
52 def shoot():
53     if not gun.on_cooldown:
54         gun.on_cooldown = True
55         gun.muzzle_flash.enabled=True
56         from ursina.prefabs.ursfx import ursfx
```

```

57         ursfx([(0.0, 0.0), (0.1, 0.9), (0.15, 0.75), (0.3, 0.14), (0.6,
           0.0)], volume=0.5, wave='noise', pitch=random.uniform(-13,-12)
           , pitch_change=-12, speed=3.0)
58     invoke(gun.muzzle_flash.disable, delay=.05)
59     invoke(setattr, gun, 'on_cooldown', False, delay=.15)
60     if mouse.hovered_entity and hasattr(mouse.hovered_entity, 'hp'):
61         mouse.hovered_entity.hp -= 10
62         mouse.hovered_entity.blink(color.red)
63
64     class Bullet(Entity):
65         def __init__(self, position, direction, speed, **kwargs):
66             super().__init__(**kwargs)
67
68             self.speed = 30
69             self.direction = direction
70             self.position = position
71
72             self.model = 'sphere'
73             self.scale = (0.2, 0.2, 0.2)
74             self.collider = 'sphere'
75             self.color = color.white
76
77         def update(self):
78             self.position += self.direction * self.speed * time.dt
79
80     class Enemy(Entity):
81         def __init__(self, speed=5, **kwargs):
82             super().__init__(parent=shootables_parent, model='cube', scale_y
              =2, origin_y=-.5, color=color.blue, collider='box', **kwargs)
83             self.health_bar = Entity(parent=self, y=1.2, model='cube', color=
              color.red, world_scale=(1.5,.1,.1))
84             self.max_hp = 100
85             self.hp = self.max_hp
86             self.timer = 0
87             self.start_time = time.time()
88             self.arduino_reader = ArduinoReader('COM3')
89             self.shoot_timer = 0
90             self.speed = speed
91
92         def update(self):
93             self.arduino_reader.read_data()
94             heart_rate_text.text = f"Heart Rate: {self.arduino_reader.
              current_heart_rate}"
95             speed = (self.arduino_reader.current_heart_rate-50)*1.5
96             self.timer += time.dt

```

```

97         self.x += math.sin(self.timer) * speed * time.dt
98         self.x = max(min(self.x, 16), -16)
99         self.shoot_timer += time.dt
100         if self.shoot_timer >= 1:
101             self.shoot()
102             self.shoot_timer = 0
103
104     def shoot(self):
105         direction = (player.position - self.position).normalized()
106         Bullet(self.position, direction, self.speed, parent=
            shootables_parent)
107
108     @property
109     def hp(self):
110         return self._hp
111
112     @hp.setter
113     def hp(self, value):
114         self._hp = value
115         if value <= 0:
116             self.end_time = time.time()
117             self.game_time = self.end_time - self.start_time
118             destroy(self)
119             show_game_end_screen(str(round(self.game_time, 2)))
120             return
121
122         self.health_bar.world_scale_x = self.hp / self.max_hp * 1.5
123         self.health_bar.alpha = 1
124
125 enemy = Enemy(x=0, z=15, speed=10)
126
127 def pause_input(key):
128     if key == 'tab':
129         editor_camera.enabled = not editor_camera.enabled
130
131         player.visible_self = editor_camera.enabled
132         player.cursor.enabled = not editor_camera.enabled
133         gun.enabled = not editor_camera.enabled
134         mouse.locked = not editor_camera.enabled
135         editor_camera.position = player.position
136
137         application.paused = editor_camera.enabled
138
139 pause_handler = Entity(ignore_paused=True, input=pause_input)
140

```

```
141 def show_game_end_screen(game_time):
142     end_screen = Entity(parent=camera.ui)
143     Text(parent=end_screen, text='You Win!', origin=(0,0), position=(0,
144         .1))
145     Text(parent=end_screen, text=f'Time: {game_time} seconds', origin
146         =(0,0))
147
148 sun = DirectionalLight()
149 sun.look_at(Vec3(1,-1,1))
150 Sky()
151
152 app.run()
```

C.2 EMS-Based Breathing Control System

C.2.1 Heart Rate Sensor Code

Listing C.2: PulseSensor

```
1
2  const int PulseSensorPin = 1;
3  const int RelayPin = 2;
4  int Signal;
5  int Threshold = 550;
6
7  boolean Pulse = false;
8  int BPM;
9  int IBI = 600;
10 unsigned long SampleCounter = 0;
11 unsigned long LastBeatTime = 0;
12 int rate[10];
13 int P = 512;
14 int T = 512;
15 int amp = 100;
16 boolean firstBeat = true;
17 boolean secondBeat = false;
18
19 unsigned long aboveThresholdStartTime = 0;
20 bool relayOn = false;
21 const int BPM_THRESHOLD = 85;
22 const unsigned long REQUIRED_DURATION = 3000;
23
24 unsigned long lastPrintTime = 0;
25
26 void setup() {
27     Serial.begin(115200);
28     analogReadResolution(10);
29     pinMode(RelayPin, OUTPUT);
30     digitalWrite(RelayPin, LOW);
31 }
32
33 void loop() {
34     Signal = analogRead(PulseSensorPin);
35     SampleCounter += 2;
36     int N = SampleCounter - LastBeatTime;
37
38     if (Signal < Threshold && N > (IBI / 5) * 3) {
```

```
39     if (Signal < T) T = Signal;
40 }
41
42 if (Signal > Threshold && Signal > P) {
43     P = Signal;
44 }
45
46 if (N > 250) {
47     if ((Signal > Threshold) && (Pulse == false) && (N > (IBI / 5) * 3))
48     {
49         Pulse = true;
50         IBI = SampleCounter - LastBeatTime;
51         LastBeatTime = SampleCounter;
52
53         if (firstBeat) {
54             firstBeat = false;
55             secondBeat = true;
56             return;
57         }
58
59         if (secondBeat) {
60             secondBeat = false;
61             for (int i = 0; i < 10; i++) rate[i] = IBI;
62         }
63
64         long runningTotal = 0;
65         for (int i = 0; i < 9; i++) {
66             rate[i] = rate[i + 1];
67             runningTotal += rate[i];
68         }
69         rate[9] = IBI;
70         runningTotal += rate[9];
71         runningTotal /= 10;
72         BPM = 60000 / runningTotal;
73
74         unsigned long currentTime = millis();
75         if (BPM > BPM_THRESHOLD) {
76             if (aboveThresholdStartTime == 0) {
77                 aboveThresholdStartTime = currentTime;
78             } else if ((currentTime - aboveThresholdStartTime) >=
79                 REQUIRED_DURATION) {
80                 if (!relayOn) {
81                     relayOn = true;
82                     digitalWrite(RelayPin, HIGH);
83                 }
84             }
85         }
86     }
87 }
```

```
82     }
83   } else {
84     aboveThresholdStartTime = 0;
85     if (relayOn) {
86       relayOn = false;
87       digitalWrite(RelayPin, LOW);
88     }
89   }
90 }
91 }
92
93 if ((Signal < Threshold) && (Pulse == true)) {
94   Pulse = false;
95   amp = P - T;
96   Threshold = amp / 2 + T;
97   P = Threshold;
98   T = Threshold;
99 }
100
101 if (N > 2500) {
102   Threshold = 512;
103   P = 512;
104   T = 512;
105   LastBeatTime = SampleCounter;
106   firstBeat = true;
107   secondBeat = false;
108 }
109
110 unsigned long now = millis();
111 if (now - lastPrintTime >= 1000) {
112   lastPrintTime = now;
113   Serial.println(BPM);
114 }
115
116 delay(2);
117 }
```


C.2.2 EMS-based Breathing Control

Listing C.3: EMS-based breathing control implementation used in the experiment

```
1
2 import serial
3 import serial.tools.list_ports
4 import time
5 import pandas as pd
6 import os
7 from datetime import datetime
8 import threading
9 import tkinter as tk
10 from tkinter import messagebox
11 import subprocess
12 import matplotlib.pyplot as plt
13 from matplotlib.backends.backend_tkagg import FigureCanvasTkAgg
14
15 BAUD_RATE = 115200
16 LOG_INTERVAL_SECONDS = 1
17 FILE_ROTATION_INTERVAL = 300
18 MAX_PLOT_POINTS = 60
19
20 possible_paths = [
21     os.path.join(os.path.expanduser("~"), "Desktop"),
22     os.path.join(os.path.expanduser("~"), "OneDrive", "Desktop"),
23 ]
24 for path in possible_paths:
25     if os.path.exists(path):
26         SAVE_DIR = path
27         break
28 else:
29     SAVE_DIR = "."
30
31 ser = None
32 data = []
33 recording = False
34 start_time = None
35 latest_bpm = 0
36 last_saved_filename = None
37 SERIAL_PORT = None
38 live_monitoring = False
39
40 bpm_times = []
41 bpm_values = []
```

```

42
43
44 def get_serial_ports():
45     ports = serial.tools.list_ports.comports()
46     return [port.device for port in ports]
47
48
49 root = tk.Tk()
50 root.title("BPM Recorder with Real-time Chart")
51 root.geometry("600x600")
52
53 tk.Label(root, text="Select Serial Port:", font=("Arial", 12)).pack()
54 port_var = tk.StringVar()
55 port_list = get_serial_ports()
56 port_menu = tk.OptionMenu(root, port_var, *port_list)
57 port_menu.pack(pady=5)
58
59 label_time = tk.Label(root, text="Time: --:--:--", font=("Arial", 14))
60 label_time.pack(pady=5)
61
62 label_bpm = tk.Label(root, text="BPM: --", font=("Arial", 14), fg="blue")
63 label_bpm.pack(pady=5)
64
65 fig, ax = plt.subplots(figsize=(5, 2.5))
66 ax.set_title("Real-time BPM")
67 ax.set_xlabel("Time")
68 ax.set_ylabel("BPM")
69 (line,) = ax.plot([], [], color="blue")
70 canvas = FigureCanvasTkAgg(fig, master=root)
71 canvas.get_tk_widget().pack(pady=5)
72
73
74 def update_plot():
75     if bpm_times and bpm_values:
76         line.set_data(bpm_times, bpm_values)
77         ax.relim()
78         ax.autoscale_view()
79         canvas.draw()
80     root.after(1000, update_plot)
81
82
83 def update_time():
84     now = datetime.now().strftime("%H:%M:%S")
85     label_time.config(text=f"Time: {now}")

```

```

86     label_bpm.config(text=f"BPM: {latest_bpm}" if latest_bpm else "BPM:
      --")
87     root.after(1000, update_time)
88
89
90 def save_data(manual=False):
91     global data, last_saved_filename
92     if data:
93         df = pd.DataFrame(data, columns=["Time", "BPM"])
94         suffix = "_manual" if manual else ""
95         filename = os.path.join(
96             SAVE_DIR,
97             f"bpm_record_{datetime.now().strftime('%Y%m%d_%H%M%S')}-{
              suffix}.xlsx",
98         )
99         df.to_excel(filename, index=False)
100        last_saved_filename = filename
101        print(f"Saved Excel: {filename}")
102        data = []
103
104
105 def record_loop():
106     global recording, data, start_time
107     start_time = time.time()
108     print("Recording started...")
109
110     while recording:
111         try:
112             now = time.time()
113             s = ser.readline().decode("utf-8", errors="ignore").strip()
114             if s.isdigit():
115                 bpm_value = int(s)
116                 timestamp = datetime.now().strftime("%H:%M:%S")
117                 data.append([timestamp, bpm_value])
118                 print(f"[{timestamp}] BPM: {bpm_value}")
119
120                 if (now - start_time) >= FILE_ROTATION_INTERVAL:
121                     save_data(manual=False)
122                     start_time = now
123         except Exception as e:
124             print("record_loop error:", e)
125             break
126         time.sleep(LOG_INTERVAL_SECONDS)
127
128

```

```

129 def live_monitor_loop():
130     global ser, live_monitoring, latest_bpm, bpm_times, bpm_values
131     print("Live monitoring started...")
132
133     while live_monitoring:
134         try:
135             s = ser.readline().decode("utf-8", errors="ignore").strip()
136             if s.isdigit():
137                 latest_bpm = int(s)
138                 bpm_times.append(len(bpm_times))
139                 bpm_values.append(latest_bpm)
140
141                 if len(bpm_times) > MAX_PLOT_POINTS:
142                     bpm_times = bpm_times[-MAX_PLOT_POINTS:]
143                     bpm_values = bpm_values[-MAX_PLOT_POINTS:]
144         except Exception as e:
145             print("live_monitor error:", e)
146             break
147         time.sleep(LOG_INTERVAL_SECONDS)
148
149
150 def on_port_selected(*args):
151     global ser, SERIAL_PORT, live_monitoring
152     selected_port = port_var.get()
153     if not selected_port:
154         return
155
156     SERIAL_PORT = selected_port
157     try:
158         ser = serial.Serial(SERIAL_PORT, BAUD_RATE, timeout=1)
159         time.sleep(2)
160         live_monitoring = True
161         threading.Thread(target=live_monitor_loop, daemon=True).start()
162     except Exception as e:
163         messagebox.showerror("Serial Error", f"Cannot open serial: {
164             SERIAL_PORT}\n{e}")
165
166
167 def start_recording():
168     global recording
169     if not ser or not ser.is_open:
170         messagebox.showwarning("Warning", "Please select a serial port
171             first.")
172     return

```

```

172     if not recording:
173         recording = True
174         threading.Thread(target=record_loop, daemon=True).start()
175
176
177 def stop_recording():
178     global recording
179     if recording:
180         recording = False
181         save_data(manual=True)
182         messagebox.showinfo("Saved", f"Data saved:\n{last_saved_filename}"
183                               ")
184
185 def open_folder():
186     # NOTE: This uses Windows explorer. If you run on macOS/Linux,
187     # replace accordingly.
188     if last_saved_filename:
189         folder = os.path.dirname(last_saved_filename)
190         subprocess.Popen(f'explorer "{folder}"')
191     else:
192         subprocess.Popen(f'explorer "{SAVE_DIR}"')
193
194 def on_close():
195     global live_monitoring, recording
196     live_monitoring = False
197     recording = False
198     if ser and ser.is_open:
199         ser.close()
200     root.destroy()
201
202
203 port_var.trace_add("write", on_port_selected)
204
205 btn_start = tk.Button(root, text="Start Recording", width=25, command=
206     start_recording)
207 btn_start.pack(pady=5)
208
209 btn_stop = tk.Button(root, text="Stop", width=25, command=stop_recording)
210 btn_stop.pack(pady=5)
211
212 btn_open = tk.Button(root, text="Open File", width=25, command=
213     open_folder)
214 btn_open.pack(pady=5)

```

```
213  
214 btn_exit = tk.Button(root, text="Exit", width=25, command=on_close)  
215 btn_exit.pack(pady=10)  
216  
217 update_time()  
218 update_plot()  
219 root.protocol("WM_DELETE_WINDOW", on_close)  
220 root.mainloop()
```