From Perception To Action: Understanding The Role Of Electrical Muscle Stimulation In Influencing The Human

Dissertation

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ABSTRACT

Due to recent technological advancements, wearable computing has gained considerable attention. With it, users can interact with computers on the go, resulting in multiple new application scenarios that improve everyday life. The close proximity to the user´s body enables researchers to envision novel input and output techniques. While current research mainly focuses on novel sensing that assesses, for example, the physiological states of users, the output side also provides novel interaction opportunities. One promising wearable output technology is Electrical Muscle Stimulation (EMS). EMS is an actuating technology that utilizes the proximity to the body to actively take over control of the user's body by actuating muscles. This enables control over the user's actions (e.g., movements of the limbs) as well as perceptions of the environment (e.g., weight perception while lifting objects).

In this dissertation, we investigate how EMS can benefit humans in executing everyday life activities and how EMS systems should be designed in order to reach their full potential. We employ empirical research methods that are commonly used in human-computer interaction. In the beginning, we explain the interaction nature of EMS and the difference from other output technologies by extending fundamental interaction models.

Based on a structured literature review, we chart a taxonomy consisting of two main dimensions. The first dimension describes the purpose of the application. This is either to augment the human's abilities in executing a certain task or to introduce the user to a new action or perception, which we refer to as induction. The second dimension classifies EMS applications from action to perception. The outcome of these two dimensions is four potential use case categories. Hence, we investigate scenarios from each category as well as mixed scenarios along the second dimension (i.e., action and perception). We explore these scenarios using six research probes.

Based on these research probes, we distill a set of recommendations and highlight the main challenges facing EMS-based systems. These findings provide a better understanding of the design requirements needed for systems using EMS. Our findings are centered around two main aspects: general research implications and implications linked to our proposed categories. Our work serves as a base for researchers and practitioners that are interested in exploring the opportunities of EMS as a wearable output technology.

ZUSAMMENFASSUNG

Mit den jüngsten technologischen Fortschritten gewinnt das Wearable Computing erheblich an Aufmerksamkeit. Benutzende können unterwegs mit Computern interagieren, was zu zahlreichen neuen Anwendungsszenarien führt, die das alltägliche Leben verbessern.

Die unmittelbare Nähe zum Körper der Benutzenden ermöglicht es Forschenden, neue Ein- und Ausgabemethoden zu entwickeln. Während sich die derzeitige Forschung vor allem auf neuartige Sensorik konzentriert, die beispielsweise den physiologischen Zustand der Benutzenden erfasst, bietet auch die Ausgabeseite neuartige Interaktionsmöglichkeiten. Eine der aufstrebenden, tragbaren Ausgabetechnologien ist die Elektrische Muskel Stimulation (EMS). Bei EMS handelt es sich um eine Technologie, die die Nähe zum Körper nutzt, um die Steuerung von Muskeln aktiv zu übernehmen. Dadurch können sowohl die Handlungen der Benutzenden (z.B. die Bewegungen der Gliedmaßen) als auch die Wahrnehmung der Umgebung (z.B. Gewichtswahrnehmung beim Heben von Gegenständen) beeinflusst werden.

Diese Dissertation untersucht, wie EMS den Menschen bei der Ausführung von Aktivitäten des täglichen Lebens unterstützen kann und wie solche EMS-Systeme gestaltet sein sollten, um ihr volles Potenzial zu entfalten. Dabei wurden empirische Forschungsmethoden eingesetzt, die in der Mensch-Computer Interaktion üblich sind. Zu Beginn erklären wir den Interaktionscharakter von EMS und den Unterschied zu anderen Output-Technologien, indem wir grundlegende Interaktionsmodelle erweitern.

Auf der Grundlage einer strukturierten Literaturanalyse erstellen wir eine Taxonomie, die aus zwei hauptsächlichen Dimensionen besteht. Die erste Dimension beschreibt den Zweck der Anwendung. Dieser besteht entweder darin, die menschlichen Fähigkeiten bei der Ausführung einer bestimmten Aufgabe zu erweitern oder den Benutzenden eine neue Handlung oder Wahrnehmung zu vermitteln, die wir als Induktion bezeichnen. Die zweite Dimension klassifiziert EMS-Anwendungen von der Aktion bis zur Wahrnehmung. Das Ergebnis beider Dimensionen sind vier potenzielle Kategorien von Anwendungsfällen. Daher untersuchen wir Szenarien aus jeder Kategorie, sowie gemischte Szenarien entlang der zweiten Dimension (d. h. Aktion und Wahrnehmung). Wir untersuchen diese Szenarien mit Hilfe von sechs Forschungsprojekten.

Auf der Grundlage dieser Forschungen definieren wir eine Reihe von Empfehlungen und heben die wichtigsten Herausforderungen hervor, denen sich EMS stellen muss. All diese Erkenntnisse ermöglichen ein besseres Ver-

ständnis der Anforderungen an die Gestaltung von Systemen, die EMS als Bestandteil verwenden. Unsere Ergebnisse konzentrieren sich auf zwei hauptsächliche Aspekte, nämlich erstens, die allgemeinen Forschungsimplikationen und zweitens, die Implikationen in Verbindung mit den von uns vorgeschlagenen Kategorien. Unsere Arbeit dient als Grundlage für Forschende und Anwendende gleichermaßen, die an der Erforschung der Möglichkeiten von EMS als tragbare Ausgabetechnologie interessiert sind.

Preface

This dissertation is the result of the research I carried out at the University of Duisburg-Essen from 2018 to 2022. Every decision that I made for the research mentioned here is an outcome of fruitful discussions with my colleagues from different universities and research institutes. Within the context of this work, I also supervised several bachelor's and master's students, who supported me in realizing my ideas. These collaborations resulted in publications that are a core part of this dissertation. The contributing authors (i.e., co-authors of papers) are clearly stated at the beginning of each chapter together with the reference to the publication when applicable. To emphasize these collaborations, I use the scientific plural ("we") throughout this dissertation.

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First and foremost, I would like to thank God for blessing me with this amazing opportunity. At the top of my list, I am genuinely grateful to Professor Stefan Schneegass for granting me this chance, and for his open-door policy and support, which made it easy for me to seek guidance and direction. I am indebted to many people who have supported me from the beginning to the end of this journey. My sincere gratitude goes to Lewis Chuang, without whom I would not have had the chance to first encounter the HCI community in Germany. I would also like to thank Mariam Hassib, Max Pfeiffer, Yomna Abdelrahman, and Florian Alt for their unwavering support, especially during my early days in research.

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Introduction and Background

Chapter 1

Introduction

"But O alas, so long, so far,
Our bodies why do we forbear?
They are ours, though they are not we; we are
The intelligences, they the spheres.
We owe them thanks, because they thus
Did us, to us, at first convey,
Yielded their senses' force to us,
Nor are dross to us, but allay."

– John Donne, The Ecstasy

The 21st century has thus far been a prosperous era for many new technologies that have become part of our daily lives (e.g., mobile or wearable computing). Devices build with such technologies moved from the user's desks closer to the human bodies. Due to this proximity, novel opportunities arose that consider the entire body (e.g., physiological information) of the user to improve the interaction. Consequently, the need for multidisciplinary research has arisen, as both technical knowledge and an understanding of human nature are required to develop a human-centered system. Furthermore, the user's role has shifted from being only an external operator in the interaction process to be interwoven with it. Hence, the user both influences and is influenced by the technology. Most of the existing technological advancements, however, still target human perception and interpretation of provided feedback. Furthermore, optimization approaches have been focusing on how to adapt the existing modalities so that they are better perceived by humans (e.g., audio, visual, and vibrotactile feedback).

A fundamentally new approach is to use *actuating technologies*, which aim to directly control human actions. Such technologies have the potential to change the way we interact. For conventional modalities, the user is the master of their own actions. Actuating technologies, however, directly stimulate the user to perform actions. In this dissertation, we define actuating technologies as any technology that directly influences the movement of the human body. One of the most promising actuating technologies is Electrical Muscle Stimulation (EMS). Conceptually, using EMS involves externally actuating the human muscles to induce a movement [330], which is an artificial imitation of the natural process of movement initiation in the human body [57]. Researchers have been exploring the use of EMS to induce movements [394], communicate feedback in virtual environments [255], or manipulate perception [17].

With research focused mainly on the use cases, little is known about the influence of the actuating technologies on the user in general or in comparison to other known modalities (e.g., auditory, visual, and vibrotactile feedback). We explore this aspect through two main steps. The first step is understanding the user's side. Therefore, we first reflect on the nature of the interaction, where we explore how interaction using EMS differs from traditional interaction. At the start of the 21st century, Dix et al. provided an early definition of Human-Computer Interaction (HCI) as *"a communication between a user and a computer, be it direct or indirect"* [66]. The brilliancy of this definition is becoming more apparent over time. Back then, however, the computing technology was still in its infancy compared to today's standards. Nevertheless, the breadth that it covers still includes the most advanced technologies that exist in the present-day, such as EMS. While conventional output methods only allow for a direct form of interaction (i.e., system output technology is perceived), EMS utilizes indirect form of interaction (i.e., the body's movement as a result of actuation is the output itself and can additionally be perceived by the human). To get more insights into the EMS technology, we conduct a structured literature review of relevant previous work that was done in the HCI field. By scrutinizing each work, we position EMS along with the other technologies to provide a better understanding of the technological capabilities of each. This results in a taxonomy that provides a better understanding of the interaction nature, challenges, and future work. With a clear overview of the technology's nature, we start to explore the users' requirements and expectations for such technology. Given that EMS is a new technology that directly influences the human body, it faces more challenges in being adopted by users. Previous work has focused on defining the basic requirements for designing applications with this technology [214]. However, user acceptance of this technology is seldom explored [369, 370].

As a second step, we assess the users' performances in six scenarios when using EMS. Since EMS creates a new dimension of computer output that does not completely rely on human perception, but rather directly influences actions, we explore the potential suitability of this new technology for these scenarios. Thereby, we compare the performance of using EMS as output to using traditional output modalities or other baselines. Moreover, we investigate how we can use EMS for augmenting the user or inducing feedback to the user. This dissertation investigates how applications can utilize EMS in a human-centered way. Through the explorations of the user´s perspective and the six application scenarios, we gain insights on how EMS can be used in a beneficial way. We derive research implications that help researchers and practitioners utilizing the potential of EMS.

1.1 Research Questions

Electrical muscle stimulation is a rising technology that directly influences the human body. In this dissertation, we provide a better understanding of the technology's nature by expanding existing theories and proposing new ones. Furthermore, we investigate the opportunities as well as challenges of using such technology in various scenarios. For this purpose, several research questions are investigated (cf., Table 1.1).

To begin, we explore the properties of actuating technologies. There are many theories and models that ought to explain the interaction cycle between a human and a computer. However, since EMS is designed to directly control human movement, the nature of EMS differs from the other commonly used feedback technologies (e.g., auditory). Therefore, it is important to understand the difference in the interactive nature of actuating technologies in comparison to the conventional ones (i.e., audio, visual, and tactile) **(RQ1)**. We proceed by examining the users' needs and concerns about using EMS. This, in turn, strongly highlights the gap between the technology's potential and users' requirements **(RQ2)**.

With a clearer understanding of the interactive nature of EMS, we go on to investigate the impact of using this technology in various use cases. Our aim is not only to reflect on the feasibility of using such technology, but also to extend it to provide insight into the potential as well as challenges of using EMS within a specific context. Thus, we first explore the use of such technology to augment humans. The nature of EMS allows the computer to influence and, in some cases, even control human movement. For this purpose and over the course of three studies, we explore how EMS can be used to manipulate human perception **(RQ3)**, improve motor skill execution **(RQ4)**, and enhance motor skill acquisition **(RQ3** & **RQ4)**.

One of the major research directions in HCI focuses on comparing the efficiency of the different existing interaction modalities in communicating notifications to users. As EMS allows electrical signals to flow into the users' muscles, unexpected muscle stimulation can also serve as a notification method. This feedback, depending on the targeted muscle and use case, could influence both human perception and action. Therefore, we proceed by exploring the different scenarios in which EMS could be used to notify users by inducing action or perception. Specifically, we explore scenarios in which EMS could be used to communicate notifications requiring different levels of decision-making. The decision-making levels vary from leaving the action execution completely up to the human and only nudging them upon need **(RQ5)**, to executing the action on behalf of the human **(RQ6)** and to nudging the human to execute an action by initiating it **(RQ5** & **RQ6)**. By answering the previous research questions, we highlight the potential as well as novel challenges of EMS technology.

1.2 Methodology

Researching interactive systems that use EMS for everyday applications is relatively new and has only flourished in the last decade. Before that, EMS was commonly used in medicine [140] and sports [106]. Nowadays, most evaluation methodologies focus on showing the feasibility of this novel technology. Examples include integrating the technology with other technologies, such as virtual reality [255], or communicating certain emotions through different actuation levels [146]. With the main research focus being the technology's capabilities, less attention is paid to the users. Therefore, we expand the existing body of research exploring the potential of electrical muscle stimulation while focusing more on the user side. In this section, we provide an introduction to the research methodology applied in this dissertation. In general, our

Research Question	No.	Chapter
I. EMS Application Fundamentals		
How can one model human-computer interaction through EMS?	RQ1	3
What are the users' requirements for using EMS?	RQ2	4
II. Human Augmentation Applications		
How can one augment user perception?	RQ3	5 & 7
How can one augment users' motor skills?	RQ4	6 & 7
III. Human Induction Applications		
To what extent can we nudge the user?	RQ5	8 & 10
How much control can we take over from the user?	RQ6	9 & 10

Table 1.1: Summary of the research questions addressed in this dissertation.

research is based on human-centered design methods [232] and corresponding human-centered evaluations [104]. We iteratively design systems tackling a specific application scenario, design the actuation using EMS, compare EMS actuation in a user study to other feedback modalities, and derive insights and novel knowledge from the recorded subjective and objective data.

1.2.1 Designing EMS Actuation

Over the course of this work, several artifacts were developed to answer our research questions. As EMS feedback was directly communicated to actuate human muscles, each system design and development went through three stages. The first stage is the ideation of the system architecture. In this stage, we focused on the hardware and system design. Since the EMS electrodes were always wired, we needed to make sure that the presented connections did not impede the users from performing the targeted motion. Moreover, in the scenarios in which communication of the signals was time-sensitive or the action had to be accurate, a suitable tracking system was deployed. The second stage was the calibration stage. By calibration, we mean the process of achieving the targeted movement by actuating the corresponding muscles (e.g., by determining the level of stimulation intensity that could lead to the targeted movement in the user). This stage depended on the use case: for fine-grained motion, we deployed a semi-automatic calibration approach, but otherwise manual calibration was applied. For the semi-automatic calibration, we adjusted the maximum intensity for each participant as well as the pad position. Using an algorithm, we calibrated parts of the signal attributes, such as the signal duration and intensity, to achieve the fine-grained motion that we aimed for (cf., Chapter 6). For the manual calibration, we verified the end movements visually in a trial-and-error approach (e.g., Chapters 9 and 10). The third and final stage of our implementation was the iterative approach for optimization, as we started by testing the prototype in pilot studies and adjusting the design accordingly. In this dissertation, we report on the final prototypes.

1.2.2 Evaluation

The nature of the feedback communicated through EMS differs from other technologies. Therefore, it was important to gather the users' feedback in order to understand their behavior while experiencing the technology, to determine their requirements to accept such technology, and to measure any observed interaction effects. We focused on collecting quantitative as well as qualitative feedback to gain better insights into both the system's performance and the users' thoughts and reasons behind their performance. In the scenarios in which the users' EMS-induced movements were the target, we tracked the movements of the targeted limbs, logged them, and analyzed them (cf., Chapter 7). As the experience may greatly differ between users, especially in the case of EMS feedback, we conducted questionnaires and semi-structured interviews. The questionnaires mainly consisted of Likert items and open-ended questions. For the interviews, we conducted both online as well as in-person interviews that were audio or video recorded with the consent of the interviewee. Since our application scenarios involved specific domains, we involved experts in either the data collection or the evaluation of participant performance (cf., Chapters 4 and 7).

1.2.3 Study Guidelines & Ethics

To ensure the quality and replicability of our studies, we developed study guideline templates. We adapted each template's context before the start of each study. The guidelines consisted of a general description of the study procedure for both the experimenter and the participant. The participant's guidelines presented a textual overview of the study, a general consent form, and a consent form for photos and/or audio and video recordings taken during the study. Furthermore, to ensure safety, we provided a list of medical issues that could make EMS dangerous or harmful. Each participant read the list and confirmed that none of the conditions applied to them. After the consent forms were signed, we collected demographic data. In some studies, both the pre- and post-questionnaires were attached to the guidelines. For the experimenter, it was the same study description along with the table of conditions applied and, if applicable, the interview questions template. A sample of the adopted study description and guidelines can be found in the Appendix (cf., Appendix B).

1.3 Research Contribution

In answering our overarching question of the potential of using EMS within HCI, this dissertation makes contributions in three main established areas [427]. First, we had to understand the interactive nature of EMS and the differences to the existing modalities, which led to the proposition of a new theoretical relation linked to the previously proposed HCI models. Second, this dissertation contributes several research artifacts that cover different contexts and scenarios for exploring the opportunities to use EMS as actuating feedback. Additionally, to evaluate the influence of these artifacts, we conducted user studies that contribute empirical evidence to our hypotheses. Finally, this dissertation contributes a set of challenges and recommendations for building EMS systems that are based on observations from our research as well as previous work targeting EMS studies in HCI fields.

1.3.1 Survey Contribution

We started our research by conducting a structured literature review to understand the opportunities and challenges of EMS research. The research included in our survey represented the work targeting EMS in the HCI field, which expanded over the course of this dissertation. The results of this survey also served as the base for our theoretical as well as empirical contributions.

1.3.2 Theoretical Contribution

Our first theoretical contribution is highlighted in proposing a new relation to Schomaker's model that presents a simple overview of how the interaction between the human and the computer is carried out. This proposition depended on reviewing similar models, reflecting on the existing interaction modalities, and discussing the difference to the interactive nature of EMS. Furthermore, based on our research and the analysis of previous EMS research, we propose a taxonomy that categorizes EMS applications with respect to the sense of agency, ethics, and design challenges.

1.3.3 Artifacts & Empirical Contribution

Over the course of this dissertation, we developed a set of research artifacts with the goal of exploring application scenarios that benefit from EMS-based feedback. Throughout the implementation, we focused on communicating EMS, either as a standalone modality or in comparison to other feedback modalities (cf., Table 1.2).

1.4 Research Context

This dissertation was completed over the course of nearly five years at the University of Duisburg-Essen under the supervision of Prof.Dr.Stefan Schneegass. It has been shaped over time as a result of many collaborations. Besides the research presented in this dissertation, I also worked on the following research projects, which resulted in multiple collaborations and joint publications. While this research is not included in my dissertation, it shaped my understanding of research in human-computer interaction.

DAAD: Computing for Intercultural Competences (ComIC)
The aim of the project was to promote intercultural dialogue between Islamic and European countries using "computing" and "research" as the common language to tackle emerging challenges. Within the frame of this project, we collaborated with the German University in Cairo (GUC), with which we cooperated to organize several events, including student exchange between the countries. The collaboration with the GUC resulted in several joint publications that form the first half of the research conducted in this dissertation [356, 87, 90, 93, 96, 88].

BMBF: IoTAssist
The second half of the research included in this dissertation is supported by the IotAssist project. IotAssist focuses on the development of a platform that enables interoperability between devices and services in the IoT and wearable areas and, based on this, makes the implementation of intelligent assistance

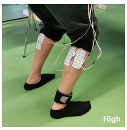
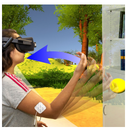
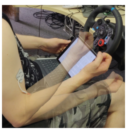
Prototype	Description	Ch.
	**Give Weight to VR:** we created the illusion of changing weight in VR by actuating different muscles. The signal initiation and duration were then determined by an Optitrack tracking system that communicates the coordinates of the real-life weight in relevance to the user's position.	5
	**GeniePutt:** In the golf putting scenario, we implemented a system that would fine-tune the user's arms rotation degree so the center of the golf putt is aligned to the center of the goal. To determine the correct rotational degree we deployed a machine learning approach, which determines the EMS signal intensity and duration.	6
	**Sign Me Up:** The Sign Me Up system actuates the users to perform certain signs retrieved from the American Sign Language. We targeted four signs that could be actuated by one or a combination out of six muscles to realize a novel sign learning scenario.	7
	**EMStriker:** this prototype communicates an EMS signal to assist the crossminton players to adjust their postures prior to serving the ball. The EMS pads target the calf muscle and are proposed for integration into regular sports socks.	8
	**SaVR:** using a leap motion mounted on an Oculus Quest virtual reality headset we tracked the user's hand position using Leap motion. Whenever the user's hand would approach an obstacle in the real world. An EMS signal would be induced to pull back the user's arms preventing the user from any potential harm.	9
	**TOR using EMS:** in this system, we actuated the users' arms would to communicate a take-over request. The arms of the users would be directed towards the driving wheel, however, no specific command would be communicated to the users. The decision of how the overtaking maneuver should look like is the users' decision.	10

Table 1.2: Research artifacts developed within the course of this dissertation, including a brief description of each one and the chapters where they are presented.

systems easy and intuitive. This project is conducted in cooperation with the German Research Center for Artificial Intelligence (DFKI), the Technical University of Ingolstadt, Centigrade, Eyeled, ThingOS and the German University for Prevention and Health Management (DHfPG). Within the context of this project, several research papers have been published [91, 85, 92].

Further Collaborations
Over the course of this dissertation, multiple collaboration projects were realized in cooperation with the Bundeswehr university in Munich, Ludwig Maximilian University in Munich, Darmstadt University, TU Chemnitz, Augsburg University, Ulm University, Seoul National University, Seoul, Heilbronn University, Siegen University, and Ruhr West University of Applied Sciences. These collaborations resulted in multiple publications [86, 61, 93, 94, 90, 89, 92, 85].

1.5 Dissertation Outline

This dissertation is made up of twelve chapters divided into five parts. Figure 1.1 depicts the interplay between the different parts of this dissertation.

Part I: Introduction and Background

Chapter 1 - Introduction
We introduce this dissertation's topic in the first chapter. It also includes a description of the study methodology used and the research context. Finally, the dissertation's contribution and a brief overview are given.

Chapter 2 - Background & related work
In this chapter, we provide an overview of the basics of electrical muscle stimulation. We start by explaining the physiology of human bodies, then move on to discuss perception of haptics and action execution. We proceed by presenting an overview of the history of electrical muscle stimulation and how it influences the human body.

Part II:EMS Application Fundamentals

Chapter 3 - Understanding Interaction Nature
Human-computer interaction models deliver a conceptual overview of the fundamental communication processes between a computer and a human. The

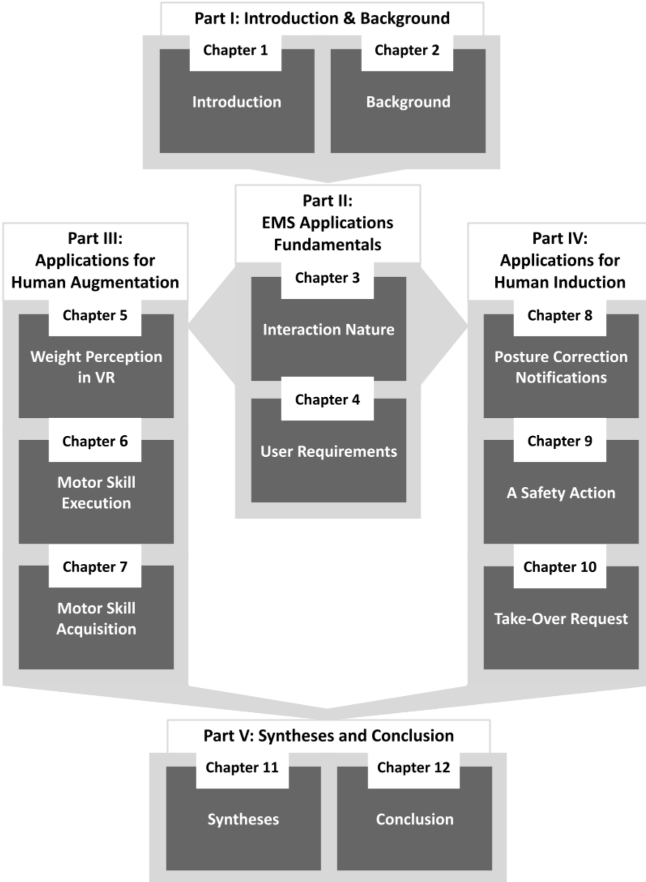


Figure 1.1: Outline of this dissertation with the interplay between the different chapters and parts.

aim of these models is to provide a basic understanding of the interaction on a meta level. Existing HCI models cover most of the actual interaction modalities. New and arising technologies such as EMS provide the possibility of directly manipulating human action through direct actuation. Such interaction, however, is not covered by classical models. In this chapter, we discuss how the interactive nature of EMS differs from other modalities. We further propose additional relations extending current HCI models to include novel interactions using human actuation. We proceed by checking potential actuation challenges in a user study in which we applied different actuation techniques. Furthermore, by conducting a structured literature review, we propose an EMS application taxonomy that reflects the related work from the HCI field. Thus, the contribution of this chapter lays the foundation for our research.

Chapter 4 - Understanding User Requirements
There is a wide range of EMS applications and there are more scenarios being explored. In this chapter, we bridge the gap between understanding the technology and the users' expectations for EMS-integrated systems. EMS has a wide range of applications within the human-computer interaction (HCI) field. It has unique capabilities that can manipulate users' actions or perceptions (e.g., by actuating user movement while the user is walking). These applications point to a bright future for EMS, but they do not always account for user acceptance. To investigate the users' acceptance and requirements for using an EMS system, we conducted an online survey. In this chapter, we present the results of this research to outline the challenges and potential of EMS with respect to social and technological acceptance.

Part III: Applications for Human Augmentation

Throughout this dissertation, we investigated six different applications with relevance to the previously proposed taxonomy. We divided these applications into two groups. The first group includes the applications that augment human action and perception. In this part, we investigate multiple scenarios that assist the human in perceiving feedback, executing an action, or both.

Chapter 5 - Weight Perception in Virtual Reality
EMS allows us to directly influence human action, which reflects on human perception. However, little is known about perception manipulation using EMS. In this chapter, we explore the effect of various arm placements of EMS pads on the users' perceptions of weight.

Chapter 6 - Motor Skill Execution
The ability to directly move a limb is a major advantage of using EMS. In this chapter, we explore using EMS to improve the execution of a fine movement. We implement a system that can automatically calibrate the right intensities and signal durations for certain hand rotational angles. We then use this algorithm to examine golf putting.

Chapter 7 - Motor Skill Acquisition
We explore the learning effect of using EMS on new movements. For that, we use EMS to teach American Sign Language signs. Conventional teaching methods depend on visual or auditory inputs. Therefore, in this chapter, we explore the benefits of each modality. We compare these three modalities in terms of long-term learning effects, where EMS influences both the users' perception and actions.

Part IV: Applications for Human Induction

We proceed in this part by reflecting on applications that induce new actions or perceptions in the user. Similar to the previous part, we investigate an application that induces a new action, a new perception, or both.

Chapter 8 - Posture Correction Notifications
The nature of the haptic feedback communicated through EMS differs from the conventional ones (e.g., vibration), as it is more of an in-body feedback. In this chapter, we explore the use of EMS feedback to communicate ready posture-correction notifications during a game of crossminton. Here, the user is expected to act upon receiving the input.

Chapter 9 - A Safety Action
Here, we proceed from leaving the action-execution decision completely or partially up to the user to taking full control. In this chapter, we explore executing a safety action on behalf of the user. In a virtual reality scenario, we use EMS to actuate the participants' muscles to pull their arms backward, preventing them from hitting a real-world object while immersed in VR. Here, the action initiation and execution depended completely on the EMS.

Chapter 10 - Take-over Request
Along the same lines, we explored initiating a take-over request using EMS. Unlike the previous scenario, instead of just depending only on the user to react to the perceived feedback, we initiate the action by actuating the user's arms. In this scenario, however, the decision of how the action should be continued (and therefore the action consequence) is up to the user.

Part V: Syntheses and Conclusion

Chapter 11 - Syntheses

Our work contributes to the knowledge of EMS in a wide pool of research. As a rising technology, EMS should be extensively researched and must overcome many challenges before making its way into our everyday lives. In this chapter, we place our work among the existing research on EMS in HCI to provide research implications as well as outline the challenges of having EMS seamlessly integrated into everyday life.

Chapter 12 - Conclusion and Future Work

This chapter summarizes the dissertation's contribution and refers back to our primary research questions. It also highlights open questions that should be addressed in the future.

Chapter 2

Background

In this chapter, we provide background about the human body, where we discuss some important aspects that would form a base for this dissertation. Specifically, we focus on the human body physiology and how that is used for haptics in general and Electrical Muscle Stimulation (EMS) in particular. EMS use external electrical signals, imitating our brain, to cause muscle contraction and consequently a movement. We proceed then by presenting the history of EMS.

2.1 Understanding the Human Body

In our research, we focus on using an actuating technology that directly goes into our bodies. However, in order to understand how this works, we need to understand the very basic physiology of our bodies. Thus, understanding the nervous system would establish the base of why and how as humans we are the way we are.

2.1.1 Brain and Nervous System

Our body is composed of organs, which are all working under the guidance of our brain. While our brain controls how we think, feel, learn, and in general behave, it also coordinates the functionality of our organs that we are not aware of, like our heart beating. In a simplified description of what is a brain,

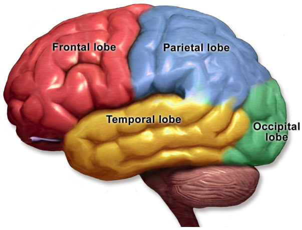


Figure 2.1: The brain four main lobes (Source: Blausen.com staff (2014). WikiJournal of Medicine 1).

Larissa Hirsch described it as *"a central computer that controls all the body's functions. The rest of the nervous system is like a network that relays messages back and forth from the brain to different parts of the body"* [1].

Types of nervous systems The nervous system is composed of two main parts. Together, they act as a huge network, reaching to each part of our bodies [52].

Central Nervous System It consists of the brain and the spinal cord. It is like the headquarters of the nervous system. The brain is the manager, coordinating and sending signals directing the human body. The brain has four main lobes[2] (cf., Figure 2.1):

1. **The frontal lobe**, which controls mainly speech and movement as it contains the motor cortex.
2. **The temporal lobe**, which is linked to memory, hearing, speech, and language.
3. **The parietal lobe**, which is relevant to taste, touch, temperature and pain, numbers processing, body awareness, and feeling of space.
4. **The occipital lobe**, which is important to have clear vision.

The spinal cord is then the first secretary managing the reception and the out-sent signals from the brain to the rest of the body.

Peripheral Nervous System It represents all the nerves branching out from the spinal cord and reaching the different parts of the body. It is then divided into the somatic and autonomic nervous systems [3]. The somatic is

[1] https://kidshealth.org/

[2] https://www.uq.edu.au/, https://www.nichd.nih.gov/

[3] https://training.seer.cancer.gov/

responsible for transmitting signals and controlling any conscious activities like movements. The autonomic is then responsible for any subconscious activities like digestion and heart beating.

Nerves and Neurons The communication between the brain and the rest of the body is done through the nervous system. The nervous system is composed of neurons and nerves. Both of them contribute to the process of sending and receiving electrochemical signals to and from the brain. The neuron is composed of dendrites, cell body, and axon and it is the functional unit in both the CNS and PNS nervous system [4]. The nerves, however, are a bundle of axons that only exist in the PNS.

Once a signal is generated by a certain neuron in the brain it gets transmitted via the neuron axon to the neighboring neurons. When the dendrites of the neighboring neurons receive this signal, it transmits it to the neuron body and down to the axons. The axons then transmit it to the next neighbor through a chemical process known as synapse communication. The electrical signal transmissions resemble the domino effect. Once it is generated, it doesn't stop till it reaches the targeted destination.

2.1.2 Action and Perception in HCI

Research has long investigated how we execute our actions. In a simplified way, we can think of our actions as a consequence of different phases. The first phase is the motivation, or the urge to execute an action. This occurs in one of two cases. The first case is a response to a will or a desire that comes from within. A simple example is feeling thirsty and going to drink. The desire in this case is your motivation to move to drink. The second case is a response to an external event that provokes our desire to execute an action. For example, extending hands for a shake as we see friends. In this case, the hand extension is a response to the event of meeting a friend.

In our brain, once we have identified the motivation to execute the action, we design how the action would look like. This is known as the intended action. Once we decide the suited action for the event, which is till this point just an abstract thought, our brain starts sending these actions to our body for execution. Our action then leads to change or an effect, which we again perceive through our senses. Our perception is then the key factor in the action planning for the upcoming response.

[4] https://qbi.uq.edu.au/

To be able to show how technology influences human action, we have to go one level higher and define how humans in general could be influenced. In checking the origin of the word perception, the oxford dictionary provides its definition based on the Latin origin as *"the action of taking possession, apprehension with the mind or senses"* [63]. That is to say, that perception is the gate to the human body and soul as earlier indicated by Aristotle. So, what does this mean in real life? It simply implies that the different stimuli that we experience influence our way of thinking, and this precise point forms the base of HCI. Throughout the history of HCI, researchers have been trying to speculate the different approaches to affect the human perception of certain artifacts or situations while interacting with their systems. Furthermore, models like Schomaker [365] and Norman's seven stages of action [302] tried to explain how this interaction process is carried out aiming to provide a better understanding of the connection between humans and computers.

For a long time, since Aristotle, our understanding of human perception has been linked to the known five senses (i.e. seeing, hearing, tasting, smelling, and touching). In fact, most of the technologies in our current day focus on one of that senses. Nonetheless, these are not the only senses the human body possesses. There are some less-appreciated invisible senses like vestibular (i.e., sense of balance), proprioception (i.e., sense of limbs positions in the world), thermoception (i.e., sense of heat), and nociception (i.e., sense of pain)[228]. While research in HCI might not be able to explore all the invisible senses' potentials, recent systems have been developed to make use of both proprioception (e.g., Lopes et al. [249]) and thermoception (e.g., Ozcelik, and Becerik-Gerber [307]). In this work, we focus on the effect of influencing proprioception.

2.1.3 Proprioception

In the 19th century, the words "sixth sense" were used by sir Charles Bill to describe the limbs' sense of position and movement [158]. Later, at the beginning of the 20th century, the word proprioception was introduced by Sherrington [373]. The origin of the word proprioception is extracted from the Latin *proprius* which means *"one's own"*. It is then used to reflect on the perception of one's own self [158]. Proprioception could be defined as the perception of stimuli resulting from proprioceptors or proprioceptive tissues that provide information regarding the body position and movement within the space[270, 336]. Often proprioception is interchanged with kinesthetic sense [336, 158], which stands for *the sense that provides the brain with information* *concerning the contracting and stretching of our muscles.* [5]. To sum the difference up, on one side proprioception could be thought of as the cognitive awareness of our body position in the 3D world [112]. On the other side, kinesthetic sense is the behavioral awareness of our body movements[346].

Given the wide pool of definitions of proprioception, we stick to the proprioception understanding mentioned by Lopes et al. [249], defining proprioception as *"the users' sense of the relative position of neighboring limbs of the body."*

Due to the complexity of neurophysiological processes involved in proprioception, there is no direct way of measuring [158]. However, there are some clear aspects and measures that could aid in assessing proprioception. In a literature survey of the existing proprioception assessing tools, Hillier et al. [158] analyzed 57 works. While many approaches exist, in the absence of empirical data comparing all of them, it remains challenging to determine which approach is the most accurate one [138]. However, the researchers highlighted four main factors linked to the proprioception assessment. Two of these aspects are linked to the availability of tools and the difference linked to the various population (e.g., old vs. younger participants). The other factors are what concern humans. The first factor is the type of movement which indicates whether it is a passive or an active movement as they are linked to the muscles' afferent and efferent. The second factor is measurements linked to the joints as angles and displacements of limbs could be used to assess the perception. In our research, we focus on passive movements resulting from the EMS actuation.

2.1.4 Haptic sensation

Throughout our research, we would be considering the EMS as haptic feedback, therefore it is crucial to understand what is defined as haptic feedback.

The origin of the word haptics extends back to the Greek word *haptesthai*, which means related to the sense of touch. Unlike all the other senses, the haptic sense is not linked to only one organ and extends throughout the body with the peripheral nervous system reaching the skin, muscles, tendons, joints, and internal organs [401]. Furthermore, the haptic sense doesn't cover only one sense, however, it could be influenced by addressing the user's proprioception, thermoception, and touch sense. This comes as a result of retrieving the sensory information through either the kinesthetic or cutaneous receptors. The

[5] https://psychologydictionary.org/kinesthetic-sense-movement-sense/

difference between these two types of receptors is the key to what we know as tactile feedback and force or position feedback [141].

Tactile feedback The tactile sense is represented by the information derived from the cutaneous receptors, which consist of thermoreceptors, nociceptive, and mechanoreceptors receptors [333]. Cutaneous receptors could be only found in the Epidermis (most outer) and Dermis (middle) skin layers [233]. For the skin thermoreceptors, they communicate the change of temperature [233]. For the nociceptive receptors, they detect any *"noxious stimuli"* [241]. The third and most relevant part of the receptors to this research is the mechanoreceptors. In the skin, the mechanoreceptors include [103]:

- Pacinian corpuscles: receptors detect vibration or a quick touch.
- Merkel's discs: receptors that detect constant deformation or touch.
- Meissner's corpuscles: receptors that detect a moving touch.
- Ruffini endings: receptors that detect a fixed pressure as a result of a touch

The number of receptors affects resolution and sensitivity. When compared to the back, upper leg, or upper arm, the tongue, lips, and fingertips are extremely sensitive. According to Hick [157], the resolution is the smallest difference detectable distance between two stimuli. For an adult, the average resolution at the tongue tip is 1-2 mm and 55-75 mm towards the rear.

kinesthetic and proprioception receptors As previously mentioned, kinesthetic sense and proprioception are sometimes used interchangeably. One main reason is that they use almost the same receptors, which are found in muscles, tendons, and joints [233]. All receptors in the muscles, tendons, and joints, except for the vestibular inputs, are shared by both senses [346]. These receptors are:

- Muscle spindles: They are stretch receptors that exist in the muscles. They detect the variations of the muscle length and are contained within a separate capsule that runs parallel to the main muscle and stretches according to the muscle movement [381].
- Golgi tendon organs: they can be found in tendons' collagen fibers and joint capsules. In contrast to the parallel distribution of the muscle fibers, they are usually found in series with the muscle. As a result, tendons stretch reflects the total force applied to the tendon by all of the muscles, and their firing rate encodes muscle force rather than stretch, despite the fact that it senses stretch [101].

- Fibrous capsule: It is a dense fibrous connective tissue that is attached to the bones at the ends of each involved bone via specific attachment zones. It offers active stability by sealing the joint area, therefore limiting movements [32].

2.2 Understanding Electrical Muscle Stimulation

There are a lot of technologies that can influence our haptic sense, each tackles a certain set of receptors (e.g., exoskeletons and vibrotactile motors). In this dissertation, we focus on an uprising haptic feedback-inducing technology known as electrical muscle stimulation (EMS). Our brain controls our body movements via electrical signals. These electrical signals are initiated by motor neurons existing in neural cells [377], which are controlled by a part of our brain known as the motor cortex [57, 395]. These electrical signals get to be transmitted throughout the body (i.e., to the peripheral nerves) via the spinal cord [377]. Whenever an electrical signal reaches a muscle, the muscle contracts leading to a targeted movement. The muscle force could be then manipulated by varying the intensities of the electrical signals [57]. While the limbs' movements are usually initiated by the brain, externally actuating the muscles is also possible. While the interest in exploring the benefits of using electricity extends all the way back to the pharaoh's time as they used electrically emitting fish for medical treatment purposes [191]. It wasn't until 1748 that Jean Jallabert discovered that electricity has an influence on the muscle tissue [176]. Later in 1756 in Bologna, Leopoldo Marco Antonio Caldani and Felice Fontana made their breakthrough by discovering the influence of electrical stimulation on muscle movement [352]. Their approach was based on inserting electrical rods into frogs' legs and observing the muscle contractions. Expanding their research later in the 18th century, Luigi Galvani succeeded, in creating a closed circuit between the muscle and the nerve via a metal connection in what is known as the frog leg experiment [314, 330]. The original aim of this study was to investigate the atmospheric electricity on a skinless frog leg that is to release what he believed to be in-body electricity [6]. However, after publishing his results Alessandro Volta cited the observed effect to be a result of the two presented metals (i.e., the copper hook and iron gate to which the hook is hung) [165]. Nevertheless,

[6] retreived on June 23. https://www.encyclopedia.com/people/medicine/medicine-biographies/luigi-galvani

and with the existence of different opinions regarding the explanation behind how it happened, the scientists agreed then that Galvani's discovery shows the influence of electricity on muscle movements.

Galvani's work was then continued by his nephew Giovanni Aldini, who explored more animal parts and exposed his work not only in Italy but also England and France [8]. This discovery of the electrical muscle stimulation concept was later connected to the imitation of the electrical signals from the brain using external electric current on the skin (e.g., surface electrodes). Although the brain's signals may seem complex, the muscles can be easily stimulated as they cannot differentiate between externally induced or brain-generated signals. The intensity and frequency of the externally induced signals then influence the muscle spindles and consequently influence the joints and tendons. EMS is thus different compared to other actuation technologies such as exoskeletons since it generates the feedback using the human body itself (i.e., user´s muscles) rather than generating it externally (i.e., through robotics).

While the main exploration for the use of EMS was in the medical field and especially with paralyzed patients [229], the 19th century also witnessed some exploratory studies with EMS. In the mid of 19th century, Guillaume-Benjamin Duchenne known as Duchenne de Boulogne, a french neurologist, conducted a series of studies to actuate the human face to induce several emotions (e.g., happiness, sadness, surprise, etc. – cf., Figure 2.2). Research with EMS continued from this point on only in the medical field. It wasn't until the mid-20th century, that researchers incorporate technology into sports. In the 1960s, EMS was used to train the Russian Olympic team by strengthening their muscles [416]. The effect of EMS on muscle mass was further explored in several studies [105, 6]. In medicine, EMS broke through and was used for both rehabilitation after strokes [277] and maintaining the muscle mass of critically ill patients [432, 183]. At the same time, EMS while scarcely being investigated for general use and with the absence of human-computer interaction as we know it today, researchers investigated using it for taste manipulation by placing the electrodes directly on the tongue papillae affecting sweetness and bitterness perception [27].

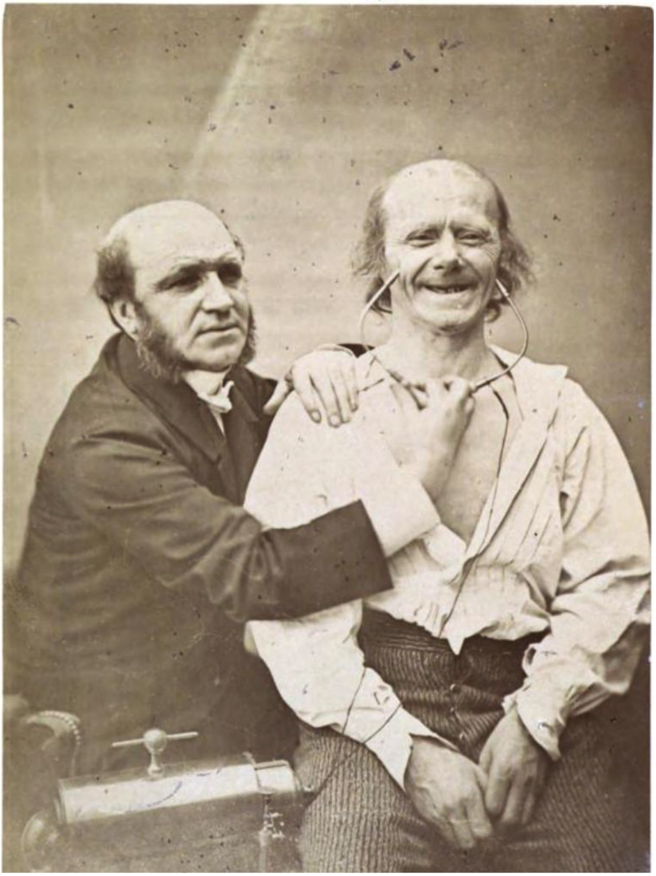


Figure 2.2: The french neurologist Duchenne de Boulogne testing EMS on a skinny man to induce a smile. The photo is taken from the front pages of his later introduced book, where he provides more details regarding his approach [68].

II

Human Centered

Overview

In this part, we place the base for this dissertation. We started with understanding the difference between EMS and the other conventional interaction modalities (e.g., visual, auditory, and haptic) by extending Schomaker's HCI model and proposing new relations. In Schomaker's interaction model, the human perceives the computer's feedback and acts accordingly. However, in our proposed relations we focus on the interaction that happens as a result of the system actuating the human.

We proceeded by conducting a structured literature survey, linking previous work to our proposed relation. Our literature survey resulted in a taxonomy of EMS applications that would serve as a structural base for this dissertation.

We conclude this part with a chapter investigating the user acceptance of EMS applications Through an online survey along with interviews with both experienced and inexperienced participants, we highlight the major challenges facing EMS technology acceptance.

Chapter 3

Understanding Interaction Nature

This chapter is based on the following publications:

- Faltaous, S., & Schneegass, S. (2020, November). HCI Model: A Proposed Extension to Human-Actuation Technologies. In 19th International Conference on Mobile and Ubiquitous Multimedia.
- Faltaous,S., Koelle, M., & Schneegass, S. (2022, November). From Perception to Action: A Review and Taxonomy on Electrical Muscle Stimulation in HCI. 21st International Conference on Mobile and Ubiquitous Multimedia.

The interaction between humans and computers has been modeled in various ways. Up till now, these models depict the human and the computer as two entities in a closed loop each with an input and an output, with only one relation linking the system output with the human input. That is to say that human only reacts to the system output. While this approach could be generalized to cover most of the interaction techniques, it does not cover, from our perspective, the *human actuation technologies*. Human actuation technologies allow the computer to control the movement of the human (e.g., exoskeleton and electrical muscle stimulation). Hence, the human is not

Figure 3.1: Examples of Electrical Muscle Stimulation for human actuation. The user‘s leg is actuated to change the walking path [319] or the arm is actuated to communicate emotions [146], prevent hitting physical objects while in virtual reality [95], and to communicate take-over request in autonomous vehicles [97] (left to right).

only reacting to the system's feedback but is then controlled by the system. Perceiving this change could also alter human perception according to the communicated feedback. Since the previous HCI models describe the human output as a consequence of perceiving the system´s output (i.e., seeing a button and clicking on it), new links that would further extend the basic HCI models to adapt to the new-offered technologies are then required. Therefore, in this work, we discuss a new relation to the existing models that would depict the change in human action and perception as a result of being actuated by the computer.

3.1 Human Actuation Technologies

We define human actuation technologies as the technologies that enable the computer or a system to directly manipulate human action. While research is still in an early stage for some technologies in this field (e.g., implantable chips), it has been focusing on developing and testing others. One example of such technology are exoskeletons, which are robot-like skeletons that human can put on. A computing system could then be used to control the movement of the exoskeleton and thus the human body. The use cases of this technology include human-limbs support [315], gait rehabilitation [130, 411], human performance augmentation [334, 414, 198] and virtual reality feedback-communication [110].

Another example is the electrical muscle stimulation (EMS - cf. Figure 8.1). This technology mimics brain-muscle communication, but with an external signal. In the human body, the brain sends electrical signals that cause certain muscles to contract and therefore result in a movement. A similar effect could be reached by externally inducing electrical signals. Applications of EMS include physiotherapy [140], fitness training [106], and HCI applications where the human could be actuated to execute a certain action [74, 185, 319].

3.2 HCI Models

The main aim of these models is to provide an easy understanding of a given system, by providing an overview of the system's behaviour regardless of the scenario it is used in. These existing models vary in terms of focus, representation of entities, and depicted relations. One example is the *seven stages of action model* [302]. This model could be used to highlight while designing a system, the challenges that hinder the users from achieving their goal [302] or those of the computer to process the input [1]. Other models that reflect more details in the interaction loop have also been suggested [184, 342, 238]. One of the most fundamental models is the model proposed by Schomaker [365]. According to this model, there are six main entities and processes. The main entities are the *human*, also referred to in similar models as intention [239], and the *computer*, also referred to as digital interface [310] or state [239]. The computer input process is represented by the computer input modalities which are the sensors [310] that could detect multi-modal input [184]. The computer feedback process is communicated through the computer output modalities which are the displays [310] to convey feedback [239] to the user. The human input process is the human input modality that senses [310] the input information and transfers it to the perception channels [184, 425, 239]. The human feedback process is the human body output [310], which is presented by the effectors [425, 239] generated from the information expression channels [184].

3.3 Proposed Relation

Although the previously referenced models use different names, they are based on a similar concept, which is a closed loop between the human and the computer. For each of them, there is an input and an output channel defining the interaction. In the existing HCI interaction models, the human has to execute an action upon which the system reacts and displays the feedback. The human then processes the communicated feedback and decides accordingly to modify the executed action. For example, clicking on an icon to start an application or entering a room to switch on the light implicitly.

While this interaction loop is valid for classical HCI scenarios, it does not properly match the usage with actuation technology as output. When an exoskeleton or EMS device lets you perform a certain movement, the user performs the action immediately without the necessity of cognitively processing a command. Thus, this interaction does not follow the entire loop but skips the *Senses* and *Human* part (cf., Figure 3.2). This action, however, is similar to the action a user would do when receiving classical feedback (i.e., the human is in the same state afterward). In return, the user can sense this change and the circle can be completed (i.e., through proprioception). This might not be done when the attention of the user is shifted (e.g., using electrical muscle stimulation to change the walking direction while being immersed in virtual reality [17]).

To model such interactions, we added two relations to the model (cf., Figure 3.2). First, we add one relation between the computer output and the human's action. (i.e., Display → Action). In these cases, the human's action is directly manipulated by the computer. Thus, the human is not only acting upon the perceived feedback from the system but is rather moved by the system to execute a certain task. In this case, depending only on the existing relation between the display and the senses would not allow modeling the interaction accurately. Therefore, adding this relation highlights the direct manipulation of the human's actions by the system. This relation would not only be detected by the computer or the system but also perceived by the human. Thus, we propose another relation between the human output and the human perception (Action → Perception). For example, Hassib et al. [146] used electrical muscle stimulation to let the user perform a gesture describing the feeling of a remote partner. This movement then is perceived and interpreted by the user to understand the partner´s feelings. In another example, Faltaous et al. [97] use electrical muscle stimulation to raise the hand towards the steering wheel to communicate a takeover request in autonomous cars. Users perceive

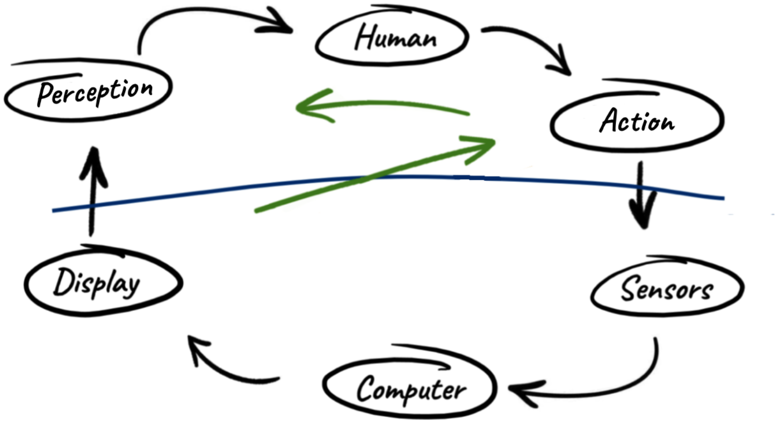


Figure 3.2: HCI model, based on Schomaker's model [365]. In this adaptation, we propose adding a new relation between the system's displayed feedback and human action as well as the senses. In actuating technologies where the system is controlling human action. The relation between the display and the action is not only through senses but rather a direct influence that would also impact the human senses & perception.

this movement and know that they should grasp the steering wheel to gain control. Furthermore, Lopes et al. [250] proposed a system reminding the user to execute a certain action to do a task correctly. Although the system only reminds the user to execute a certain action, the user has to perceive the reminder and process which action is needed to complete the task (e.g., shaking the user's hands before using a spray can).

3.4 Literature Survey Methodology

To this extent, we established how to target and influence humans. Especially given that any interaction design takes into consideration the users' abilities and skills [386]. This raises another question, whether all EMS applications targeting perception or action have a similar approach. To get a better understanding of the EMS applications design, we had to explore the related work within the HCI field.

We conducted a systematic literature analysis on research focusing on electrical muscle stimulation. We followed established procedures for systematically retrieving and analyzing literature [405], where we utilized a digital library to find all the relevant work. For our initial outlet we used *Scopus*, an online citations and abstract database initiated in 2004 [7]. Our choice is based on previous research showing that Scopus resulted in the maximum coverage in comparison to other digital libraries [23].

3.4.1 Search and Paper Extraction

Scopus resulted in $9,114$ hits as we looked for *"Electrical Muscle Stimulation"* or its synonyms *"Electric Muscle Stimulation"* or *"electromyostimulation"* OR *"neuromuscular electrical stimulation"* OR *"Functional electrical stimulation"*. As our main focus is to find out EMS research that doesn't target only the medical field and health applications, we limited our search to Computer Science, Multidisciplinary, social sciences, engineering, and psychology. This resulted in $3,419$ hits.

3.4.2 Exclusion and Inclusion Criteria

We included all papers that are (1) peer-reviewed, original work (e.g., conference paper), or juried content (e.g., workshop proposals) & (2) written in the English language. To focus our analysis on EMS applications that are related to HCI, we excluded any works that reported on using EMS solely for medical purposes. Our applied criteria resulted in a primary set of $N = 121$ relevant papers. We further checked manually the references of the relevant papers (i.e., backward chaining) to reduce systematic bias caused by the choice of initial outlet. Our iteration resulted in $N = 30$ additional publications that are relevant to the scope of our work resulting in a final set of $N = 151$ papers.

3.4.3 Analysis and Coding

We coded each research publication according to its primary research contribution. Two researchers went through the papers and classified them into three main types of contribution (cf., Figure 11.1). First type is *Systems* ($N = 44$). It includes the research done in implementing EMS artifacts and toolkits or novel calibration techniques *without* integrating or testing it in a specific application scenario context. The second type is *Theory* ($N = 21$) referring to the work that focuses on providing *theoretical* contribution either by reflecting the users'

[7] https://www.scopus.com/

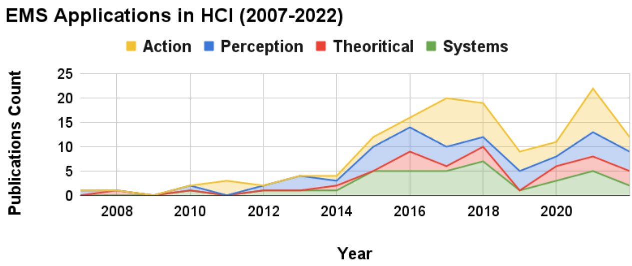


Figure 3.3: Research count, across the past 15 years, showing the increase of interest of EMS applications in the HCI field.

requirements, design requirements, or discussing theoretical constructs. The third type is *Application Scenarios* ($N = 86$), where the research focuses on a certain application scenario that utilizes EMS. For these papers, we further extracted (1) the keywords, (2) time points where EMS feedback is initiated (e.g., based on a user action, based on an environment change), (3) actuated limbs & muscles, (4) number of electrodes, (5) type of users studies (i.e. lab or field study), (6) type of results (qualitative or quantitative), the (7) calibration method, and (8) publishing venue.

3.5 Literature Survey Results

Overall, we analyzed 151 publications from 62 different venues. In our search, we did not include research applied for only medical and health-related purposes as they mostly focus on certain health aspects and/or specific age groups, which could not be generalized. Nevertheless, the resulting literature covers multiple fields that are not only confined to computer science but also electrical engineering, and medical engineering among others. In the following, we present the results of our literature survey with regard to the used terminologies, targeted research scenarios, electrode positioning, and calibration, as well as the evaluation methods.

3.5.1 EMS Synonyms

In our search, we used *electrical muscle stimulation*, *electromyostimulation*, *neuromuscular electrical stimulation*, or *functional electrical stimulation*.

While 94% of the literature used either electrical muscle stimulation ($N = 106$), electrical stimulation ($N = 20$), and functional electrical stimulation ($N = 16$), others used various synonyms like electrical body manipulation, electric muscle stimulation, electro-muscle stimulation, electro physiologic, electrical muscle signaling, transcutaneous electrical stimulation and neuromuscular electrical stimulation. Moreover, three research publications appeared in our search targeting tendon electrical stimulation, however by referring back to the human anatomy we excluded them as it targets a different approach to body actuation that is out of our focus.

3.5.2 Research Contribution

Our literature results ($N = 151$) show that the literature covers three main contribution types. The first one is *Systems* ($N = 44$), where research focuses purely on presenting actuating systems and approaches without focusing on a specific scenario or a use case (e.g., [245]). The second contribution type is *Theory* ($N = 21$), where research discusses and presents some theoretical foundation for designing and evaluating EMS applications. The third contribution type is evaluating EMS *Applications Scenario* ($N = 86$) within specific contexts and use cases.

Systems

One of the very first devices used in EMS is a double current Volta Faraday device used by the french neurologist Duchenne de Boulogne in the mid of the 19th century [68] (cf., Figure 3.4). More than a hundred years passed till the researchers developed a more complex system that uses multiple channels for leg muscle stimulation (e.g., 6 channels in [384], 4 channels in [272] and 8 channels in [76]). Researchers further compared the quality of actuation using different platinum-coated wires vs foil electrodes and ordinary ECG electrodes [169] or further develop new electrodes [445, 29, 21] or even proposing wireless implantable stimulating microchips [350]. Research further focused on obtaining more accurate actuation by applying automatic calibration that would communicate the electrodes' targeted position [187, 122, 22] or the signal parameters and stimulation [160, 289, 332, 213, 24, 439, 351, 263, 151]. Jungeun Lee et al. [234] took one step further and started bridging the gap between medical applications and HCI, where they developed and tested a mathematical model of force feedback from medicine to haptics by manipulating the amplitude and frequency. Furthermore, researchers started shedding more light on the technology potentials [252, 251], providing systems

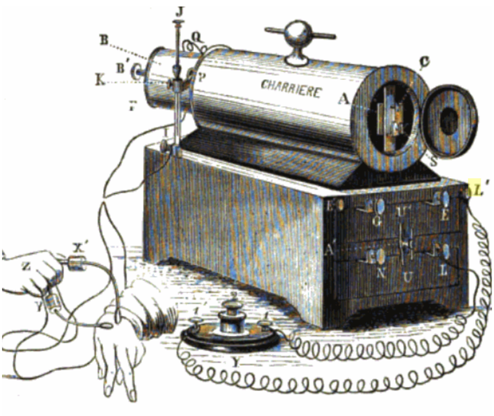


Figure 3.4: Dual current Volta-Faraday device used for muscle actuation by the french neurologist Duchenne de Boulogne in the mid-19th century [68].

and toolkits that facilitates the developing of EMS applications [317, 245, 211, 397, 53].

In 2016, Pfeiffer et al. presented a toolkit that allows controlling EMS devices via mobile phone [318]. The toolkit includes a microcontroller that is connected to a mobile phone via Bluetooth and controls the intensity of a signal generator. Following similar steps, Lopes presented Open EMS Stim that uses the same components but provides different user interfaces[8]. Aiming at generating a smooth movement like the one generated by the brain, other systems focused on the calibration process. Duente et al. [70] presented a twenty-channels EMS system designed for fine-grained movements. Further research deployed automatic calibration process in their work either by adjusting the current intensity or configuring the placements, however, their research tends to focus on a specific scenario [84, 131, 46, 396, 395]. Other research focused on the targeted muscles, as it is challenging to reach deep muscles since the EMS is usually communicated through non-invasive methods. Akifumi et al. proposed a different layout for finger muscle actuation by placing the electrodes at the back of the hand [391, 392]. Ohara and Hasegawa [304] presented a system that could reach pronation arm movement by comparing the arm motion behavior experiencing six electrical signals waves forms. Other

[8] Open EMS Stim. 2016. URL: `https://github.com/PedroLopes/openEMSstim`

systems focused on generating gestures by dividing each complex one into a controllable sequence of movements [320].

Theory

We grouped theoretical contribution work under three main groups. The first group provides use case suggestions where EMS could be integrated as Schneegass and Rzayev suggest using EMS as a notification modality for mobile devices [363]. Other work proposed the idea of using EMS for interpersonal communication instead of visual or audio icons [65].

Another group of research focuses on providing design guidelines for EMS systems. Research in this group includes providing design challenges in general regarding physiological interaction systems [202], establishing quantitative measures for tactile display [147], design aspects for systems that use electricity and the safety measures, and ethical considerations that should be made [215, 69, 325]. Other research focused on the hardware design of wearable interactive devices that could communicate proprioceptive feedback [243, 192]. Furthermore, researchers investigated the user experience while using varying different attributes of the signal (e.g., frequency) [205]. The users' side, was further explored by Shahu et al. as they inspected the different factors affecting the user acceptance of the technology [370, 369].

The last group targets the understanding of the interactive nature of EMS. As work in this group provided an overview of EMS technology [77] and proposed new relations to explain the interaction between the human and computer in case of being externally actuated by EMS [96]. Research further examined the perceptual simultaneity of an executed movement and an intended one as a result of EMS actuation [265, 116] as well as the relation between specific muscle and the change of intensity and voltage EMS (e.g., calf muscle [387]).

Application Scenarios

Most of the retrieved research ($N = 86$) contributes an application scenario of using EMS for non-medical purposes. First, we analyze how the muscles are actuated, calibrated, and how the overall application is evaluated. Next, we categorized the applications and provide a taxonomy.

Electrodes and Actuation Overall, the authors suggested placing electrodes on 12 different body locations (cf., Figure 3.5). Out of the 114 reported placements (note that some approaches used multiple locations), the lower arms were used most (55 times), followed by upper arms (21 times) and lower leg (10 times). These spots are easily accessible and provide a movement applicable to multiple application scenarios. To actuate the user, researchers

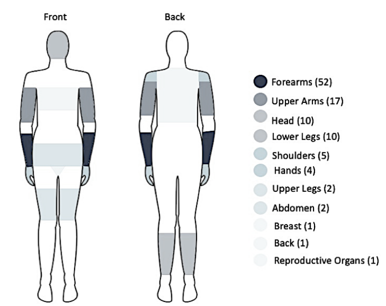


Figure 3.5: EMS electrodes positioning research count, grouped per body part. It shows that most of the studies placed electrodes on the forearm.

used between 2 and 20 electrodes ($M = 4.9$, $SD = 4.1$). Out of the selected 86 papers, only 43 papers present the precise name of the muscle actuated (e.g., *flexor carpi radialis*). The other 43 papers describe the location (e.g., *lower arm*) or present images of the electrode placement (e.g., photos of participants equipped with electrodes or schematics of the human anatomy).

Calibrating EMS For calibration, in most of the application scenarios (68 out of 86) researchers calibrated the EMS system manually and only 6 times automatically. We considered automatic calibration as that of automatically allocating the electrodes' position or signal attributes (i.e., intensity and frequency) (e.g., [394]). In 3 cases, the EMS system is not calibrated to the users (e.g., [12]), and in 9 more the calibration method is unclear. In contrast, 8 papers out of the 44 system papers report on automatic calibration methods that can be used to improve the calibration process. They use, for example, a sleeve-like system with 60 electrodes [207].

Evaluating EMS On one hand, researchers evaluated 68 application scenarios through user studies. On the other hand, researchers presented 18 application scenarios without an evaluation involving users. Studies invited on average 12 participants ($SD = 9.7$, $Min = 1$, $Max = 62$). Most of the studies were conducted in the lab ($N = 65$) whereas only 2 studies focused solely on the field [144, 415] and one work backed up the findings from a lab study in an outdoor setting [319]. The majority of studies produce quantitative data on the performance of the system ($N = 43$) followed by a mix of quantitative and qualitative data ($N = 17$), or only qualitative data ($N = 5$). Three papers didn't reflect on the studies' results.

3.6 EMS Applications Taxonomy

The majority of research work focuses on application scenarios. Thus, we analyzed the application scenarios in further detail. In an iterative approach, we identified two dimensions on which we categorized the application scenarios, namely (1) action – perception and (2) augmentation – induction.

3.6.1 Action – Perception

The first dimension describes the target of the application scenario whether it targets the *Action* or *Perception* of the user. This is based on basic models of interaction in which the interface between human and computer is either on the input (i.e., users' action) or output (i.e., users' perception) side [365]. Traditionally, the input channel is used to transfer information from the human to the computer – in EMS research, however, this channel might also be used to transfer the computer information to the human via users' own body [96] (e.g., communicating affordance [250]). Application scenarios targeting *action* are those taking-over the human movements. Users share their bodies and allow the computer to manipulate their actions. For example, action application scenarios use the EMS system to shift walking direction [319] or assist in learning new musical instruments [74]. Perception-targeting applications are those utilizing EMS to generate a certain change in the perception of the user. This is primarily not focused on generating a movement but on the effects associated with the EMS signal. Note that a body movement is triggered to achieve perception manipulation but it is not the goal of such application scenarios. Examples of perception applications include weight perception [200] and food texture manipulation [291].

3.6.2 Augmentation – Induction

The second dimension describes the integration in the interaction between the human and a computer or object. Application scenarios either *augment* such an interaction or initialize a new interaction by *inducing* a stimulus. *Augmentation* application scenarios improve the users' skills, for example, while doing sports (i.e., the accuracy while golfing [84]) and the *induction* application scenarios, for example, provide feedback to the user by using EMS as a form of notification [188].

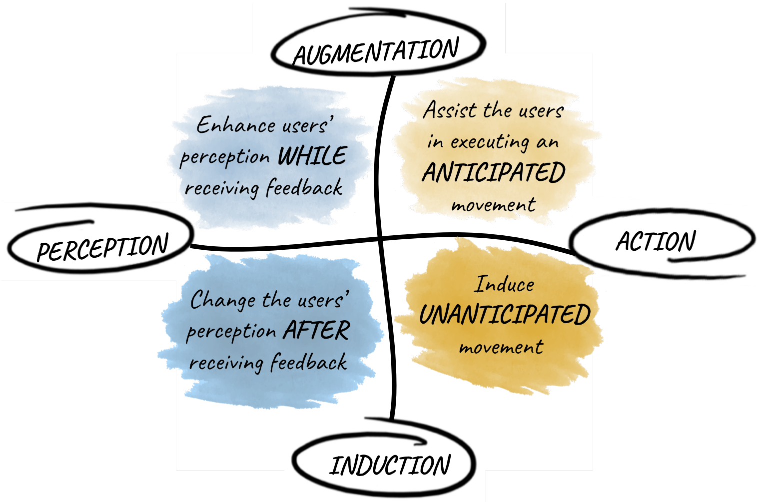


Figure 3.6: EMS applications taxonomy deduced from our literature review. The first dimension presents the aim of the application, whether it is targeting a perception manipulation or action execution. The second dimension describes the integration of the interaction between the human and a computer or object, where the system could either augment the human or induce new action or perception.

3.6.3 EMS Applications Classification

Since both dimensions are orthogonal to each other, the application scenarios can be grouped into four categories (cf., Figure 3.6). Following, we discuss the four categories and present examples of the work falling into each category.

Perception Augmentation

Applications in this category enhance the users' perception while receiving feedback (independently from the use case; $N = 35$). This means that the EMS feedback has to be synchronized with an external application or tracking system so that the signal is activated simultaneously. Any haste or delay in communicating the feedback would result in a completely different user experience. It represents most of the retrieved application scenarios done targeting *Perception* ($N = 40$).

We observe this type of application in interacting in VR or XR. One of the very first applications was communicating feedback in a 3D environment while playing a desktop game [221]. Yuichi et al. and yem et al. showed the plausibility of manipulating different levels of hardness, softness, and stickiness while interacting with virtual objects [440, 223]. Other applications made use of this concept and tested it in VR applications. Lopes et al. [254], showed a system that communicates different stiffness perceptions as per interacting with various VR objects (e.g., walls, gates, sliders, boxes, and projectiles). Further research has integrated EMS with physical tools to amplify the haptic sense of force feedback. As researchers integrated a solenoid with EMS to achieve the sensation of being hit in VR [248] or used a hanger reflex along with EMS in implementing a wrist-mounted haptic feedback device [357]. In Both cases, the proposed gadgets improved the immersion and realism in VR. Similarly, researchers have integrated EMS to XR games to either create the illusion of interacting with completely virtual objects, manipulating the environment perception of interacting with real ones [256] or communicating live feedback on the users' arms while playing tennis [99]. Following similar steps, Jinwook, Seonghyeo, and Jeongmi made use of EMS in manipulating the weight perception by communicating different levels of force feedback on the engaged arm [200]. Other applications investigated increasing immersion in VR by actuating the users' body to react to virtual events as if they were the avatars [197] or changing the heat perception of surfaces [108].

Other applications in this category focus on interacting in real life while creating the perception. In a general approach, Takaya and Satoshi [173] changed the EMS wavelength to manipulate the discomfort, electrical, and pain sensation. In a more focused scenario, Asada et al. [14, 15] communicated the menstrual pain level. Gomes & Wu [129] further explored transferring the sexual intercourse feeling through EMS for long-distance relationships. Also, applications used the EMS sensation to create the illusion of virtual bumps [174] or to communicate feedback while interacting with mobile devices [246, 247]. Moreover, researchers have tried to integrate this feedback into exer games either by communicating the different feelings of touch, grasp, or punch [326] or by investigating the influence of actuating antagonists muscles in increasing the motivation for exerting more physical effort while playing [40]. Research in this regard further investigated the use of EMS in augmenting the selection process while interacting with a UI or generally interacting with public display [324], showing that providing haptic feedback is better than the conventional visual one [328, 327]. Pfeiffer et al. [322] also extended this idea to include interaction with drones. While most of the research done within this category focus on the body muscles underneath the neck. Another direction of research focuses on the muscles present in either the neck or head. As researchers examined deploying EMS to change the texture of food while chewing as it targets the masseter muscle to increase the stiffness of the perceived chewing [291, 292, 288]. In a similar approach, researchers have been trying to manipulate the taste of different food by inducing electrical current to different positions in the mouth [285, 343] based on early studies of a similar aim [27, 331]. , For example, Yukika and Takafumi implemented a spoon that once touched the tongue would create a circle that could induce a metal taste or changes a soup's saltiness, sourness, and bitterness [12]. While for the taste changing normally the taste buds are the ones responsible for the taste acquisition, research has shown that manipulating the tongue muscle could also be of influence [235], consequently, we didn't exclude research targeting taste change using electrical stimulation.

Perception Induction

This category includes application scenarios that change the users' perception *after* receiving the EMS signal ($N = 5$). The timing of communicating the EMS feedback shows that applications could be processed and reasoned at a later time point than that from receiving the feedback. Unlike the *Perception Augmentation* applications, the influence of the EMS applications is not time critical and could need some time to be processed by the users. Most of the application scenarios in this category have been used for posture correction. Masato et al. [375] used EMS to communicate feedback to the fingertips to help avoid postural sway while standing on one leg. Other research used it in sports to communicate fatigue or pre-cramps warnings while running [257] and ready posture correction signal in crossminton [91]. Kattoju et al. [188] further used it in correcting slouching sitting posture by integrating it into a system that uses an inertial measurement unit (IMU) for posture detection. Another type of application depends on the EMS signals' nature as they flow into the muscles to create massage-like sensations. Wang [415] used that to elevate the drivers' fatigue by providing EMS signals to the thumb and leg biceps when the drivers' physiological measures indicating fatigue exceed a certain threshold.

Action Augmentation

Applications in this category assist the users in executing an *anticipated* movement ($N = 25$). That means that the users know when the system would actuate them and what the actuation consequence would be. In this category, we found research that focuses on four groups. The first group consists of teaching-oriented applications. In early work, Tamaki, Miyaki, and Rekimoto [396, 395, 396] presented a system that could actuate the users' 16 arm joints through 14 EMS pads based on a computerized output. They further proposed this system for teaching musical instruments. Later many studies were conducted to facilitate the teaching process of linking music rhythms to movements. Ebisu et al realized that system for playing percussions using EMS, where the users' arms and legs would be actuated to communicate a certain rhythm that is communicated via the computer [74]. Other research proposed a system to move the arms and wrists of certain performers while holding musical instruments or nudging a dancer to communicate the rhythm and melody of a displayed music/tone [279]. Along the same line, Pffeifer et al. [321] suggested using VR to train remote workers. For that, they implemented a system where a finger of a user is either driven to or pulled away from pushing a certain button.

The second group of research focused more on applications that can assist human performance. This includes applications that aim at reducing muscle activity by assisting the users to shift and rotate their wrist while playing the piano [294, 295]. Following a similar approach, the researchers further inspected stimulating different various pinch forces to assist the execution of voluntary pinches [290]. In a different use case, Lopes et al. [253] presented a system that could act as both input and output for the computer through handwriting (e.g., a user writes an equation, and the computer plots it via actuating the users' hands). Other work focused more on experimenting with the right time when a signal should be communicated to assist the users while not compromising their sense of agency [186]. In a more comparative approach, Korres et al. [217] examined the different reaction times resulting from communicating either a visual, vibrotactile or EMS to touch their face, showing that EMS is more convenient where there is no room for errors.

Another group of applications relates more to orientation guiding in 3D space. Pfeiffer et al. explored actuating the users' leg to guide them while walking [319]. In a similar approach, and to avoid the limited room space, Auda et al. [17]proposed a system that would do the same just in VR while shifting also the visual feedback to create the illusion of walking straight in VR. The last group of this category focuses on presenting sports training scenarios. Examples include adjusting the feet posture while running [58, 422], adjusting the angle of the wrist to enable the users to learn how to execute a certain movement in bowling swing [399] or golf putting [84].

Action Induction

This category of applications reflects the scenarios where EMS intervention results in an unanticipated action (i.e., similar to notifications; $N = 21$).

Application scenarios use EMS to communicate notifications, warnings, and other information to the users [95]. This also includes application scenarios in which an audience actuates a painter‘s hands by drawing on a tablet [54] or having a system that guides the users’ index finger to point in 2D space [190]. Further application targeted communicating take over request using EMS [97]. Another direction aims at creating communication and collaboration between either two persons or an input system and a person. These application scenarios mainly aim at passing the movements of one person to another [46, 300, 299, 154, 139, 273, 298]. This might, for example, also be used to identify users [48]Lopes et al. proposed a system that would indicate how a gadget could be used if at all by actuating the users’ arms to execute the right movements [250]. Other research focused on creating a system’s interaction cycle by actuating the user’s hand in case of output and detecting the user’s hand movements and muscle activation in case of input [71]. Additionally, researchers investigated the potential of using EMS to increase safety in VR environments by actively pulling the user’s arms in case of a potential collision with real-world objects [95]. This category also includes research that generates emotions as a result of a physical movement [62] induced by EMS. Research done within this type focuses on applications that target emotion induction based on the James-Lange theory that emotions are the result of physical changes [62]. In 1862, Duchenne reported on the studies that he conducted from 1852 to 1856 the actuation of the facial muscles to induce different emotions [68]. Similarly, researchers actuate the *masseter muscles* to imitate a smile [441] or frown [131] or sign language gestures to induce linked emotions [146]. Further application scenarios focused on fear and pain forcing eye closure to introduce fear [212].

3.7 Conclusion

In this chapter, we explored the interaction nature of EMS. We first proposed new relations based on Shomaker’s foundational model describing the human-computer interaction. Our suggestion focuses on providing a clear understanding of using human-actuation technologies, in which human actions are controlled by the computer. We proceeded by reviewing research papers on EMS ($N = 151$). Based on the literature, we propose a taxonomy for categorizing EMS application scenarios using two dimensions (1) action – perception and (2) augmentation – induction. We base this dissertation on the proposed taxonomy. Therefore, this chapter lies the foundation for our research.

EMS Research Type		Paper Reference
Theoretical Work		[244, 387, 147, 363, 243, 65, 215, 205, 265, 96, 202, 186, 390, 173, 370, 369, 69, 325, 192, 77, 116]
Systems		[394, 318, 242, 70, 358, 245, 320, 301, 391, 392, 304, 213, 211, 332, 22, 289, 245, 251, 317, 252, 122, 187, 160, 169, 384, 117, 206, 207, 393, 272, 76, 24, 397, 445, 403, 350, 439, 351, 263, 234, 53, 29, 151, 21]
Application Scenarios	Perception Augmentation	[99, 246, 247, 324, 326, 248, 12, 328, 291, 291, 288, 223, 254, 108, 256, 440, 322, 197, 357, 40, 174, 14, 15, 129, 200, 343, 327, 285, 221, 172, 175, 143, 367, 115, 341]
	Perception Induction	[415, 257, 375, 188, 91]
	Action Augmentation	[395, 396, 319, 253, 399, 74, 422, 144, 421, 296, 73, 185, 17, 321, 311, 281, 84, 280, 295, 294, 290, 217, 98, 279, 113, 408]
	Action Induction	[107, 46, 250, 190, 146, 441, 298, 139, 54, 71, 212, 300, 131, 97, 273, 95, 47, 48, 154, 299, 68]

Table 3.1: Overview of all the retrieved research work in our survey and their categorization. Overall, we analyzed 151 research work and categorized them into either *Theoretical Work* ($N = 21$), *Systems* ($N = 44$) and *Application Scenarios* ($N = 86$).

Chapter 4

Understanding User Requirements

This chapter is based on the following publications: Faltaous, S., Williamson, J R., Koelle, M., Pfeiffer, M., Keppel, J., and Stefan Schneegass . An Online Survey on Understanding User Acceptance of Electrical Muscle Stimulation in Human-Computer Interaction. Under review in **International Journal of Human-Computer Interaction**

EMS radically deviates from how human-computer interfaces traditionally implement system feedback because *EMS appropriates the human body to stimulate movement*. It enables system feedback that is displayed through a motion of the user's own body, which appeals to the user's proprioception [364]. Therefore it was important to understand which factors would influence the users' acceptance of this technology. Prior EMS applications have made use of EMS to manipulate a user's walking direction [319], change their perception of foods' texture, namely elasticity and hardness [293], and speed up their reaction times [185]. EMS has the ability to actuate the human body, which has also been taken advantage of in the medical [119, 267, 385, 83, 335] and fitness [106, 6] domains. To this end, an EMS system conveys electrical impulses imitating a signal sent by the human brain via electrodes into the

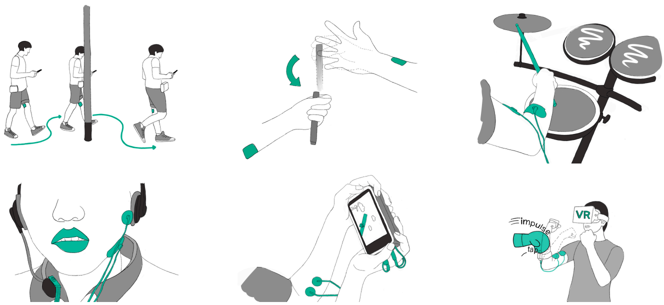


Figure 4.1: Electrical Muscle Stimulation has been used to realize multiple application scenarios. The illustrations from left to right in the top row display EMS systems that direct users while walking [319], accelerate a user's reaction time [185] or aid percussion learning [73]. In the bottom row, the illustrations display EMS systems that: change chewing food texture [293], enhance interaction experience by adding haptic feedback in mobile games [246] or realistic haptic sense of being hit in VR [248].

user's body, where the EMS system can elicit muscle contraction. Henceforth, bodily motion is subject to *external actuation*, which makes the user no longer the sole initiator of action. As a result, systems involving EMS have the potential to violate the user's internal locus of control [376] and may cause concerns over pain and loss of bodily control, as well as the social factors of on-body electrodes.

EMS applications are quite well established in the research community [319, 185, 73, 293, 246, 248, 75, 146]. Even though a number of applications, predominantly from the health[9] and fitness domains[10,11], have already found their way into consumer markets, the precise nature of concerns triggered by EMS is so-far underexplored. With EMS substantially changing the dynamics between user and system (i.e., the user's actions being altered instead of the user altering the system's state) and, consequentially, the user's perception of it [96], an in-depth understanding is of utmost importance for future system design. Most significantly, concerns and reservations towards EMS might

9 https://www.physiosupplies.de

10 https://www.compex.com

11 https://visionbody.shop

even prevent prospective users from trying out EMS in the first place. Hence, negative attitudes towards EMS paired with a lack of insight into the nature of those concerns may pose a significant entry hurdle for the adoption, acceptance, and applicability of EMS technology as a feedback paradigm – or, as put by Knibbe et al.: EMS might be *"too awful to ever be an acceptable paradigm for HCI"* [205].

Building upon this strand of work, this chapter explores user attitudes, expectations, and concerns towards EMS. In particular, we complement work on experiential aspects of EMS [205] by focusing on *user acceptance*. To this end, we make use of Davis' *technology acceptance model (TAM)* [59] as a theoretical foundation. The aim of this well-established model is to *predict* the adoption and use of technology by individuals [164]. TAM and its expansions [412, 438, 150] share that they aim to explore an individual's willingness to start using a specific technology before having gained actual experience with it [20]. In this chapter, we account for this goal, as well as for EMS often being poorly understood [205], by including two different perspectives: prospective users of EMS without prior exposure, as well as more experienced users with some first-hand EMS exposure. This choice of theoretical foundation is well suited for the topic of investigation due to the novelty of EMS as a feedback paradigm and the high entry hurdle caused by concerns and reservations towards EMS. Notably, TAM and related models differ significantly from *user experience* models. User experience models (e.g., as proposed by Hassenzahl and Tractinsky [145]) aims to understand the experiential and hedonic aspects of technology use [164] after the user has come in contact with the technology. As a result, the question answered by the present work is orthogonal to prior insights into experience [205]: *What are the precise factors that contribute to users refraining from using EMS?*

To address this question, we follow a two-step approach. First, we conduct an in-depth analysis of the user's acceptance of EMS using an online survey ($N = 101$) that explored eight existing EMS applications. Aiming to explore the opportunities as well as the challenges facing the use of EMS for HCI, we carefully selected those applications, portrayed as videos, to cover the fields of HCI, sports, and the medical domain. Extracting constructs from previous work [59, 412, 438, 150], thoughtfully examining overlaps, and filtering for relevance, we tailored a questionnaire that assesses nine different aspects influencing user acceptance. As the online survey's results pinpointed the influence of prior experience with EMS, we followed up with in-depth semi-structured interviews ($N = 10$, $mean = 1{:}15 hrs$) with a subset of respondents, balanced with and without prior EMS experience. This gave us further qualitative insights into the reasoning behind their answers. From an in-depth analysis of survey and interview data, we distill key potentials and challenges for the application of EMS in human-computer interfaces. Reflecting on the role of use-case, social factors, anxiety, safety, agency, and trust, we outline how future EMS applications might be designed to achieve a higher level of user acceptance.

Contribution We present (1) a detailed analysis of the interplay of factors shaping the user's willingness to adopt and accept EMS. Most significantly, our results show that the purpose and necessity of EMS use in a specific application scenario is a deciding factor for user acceptance. (2) We contribute an in-depth understanding of the reasons behind the responses from the online survey based on semi-structured interviews, and consequently, (3) we derive design recommendations addressing the high entry hurdle to using EMS, by taking into account a combination of social values, safety concerns, and fear of control loss that result from a lack of exposure to EMS.

4.1 User Acceptance and Technology Acceptance Models

"User acceptance", according to Dillon [64], is the *"demonstrable willingness within a user group to employ information technology for the tasks it is designed to support"*.

There are multiple theories and models that have been developed to provide a better understanding of the factors influencing user acceptance (e.g., [38, 60]). These models do not only reflect on the actual status of technology but also project the challenges as well as the opportunities that the technology stands in the long run.

User experience and user acceptance are two approaches used to define how a user would adopt a new technology [164]. One can think of them as related constructs. However, each of them provides insights obtained from two different points in time. On one side, user acceptance targets the user's expectation from the system, on the other side the user experience targets the users' opinion based on actual interaction with the system.

As the first step in our research, we needed a base for the potential constructs that we can use in our work. For that, we reviewed existing technology and acceptability models. Various models have been constructed to reflect user acceptance with respect to specific technologies (e.g., robots [149]) or with respect to specific age groups (e.g., elderly users [150]). Such models focus on providing the general constructs influencing the functional evaluation [59], while others are more focused on social aspects [412]. However, exploring the users' acceptance of new arising technologies may not always depend on the existing technology acceptance models and may require a modified and adapted version. While there is no model that reflects directly on the usage and deployment of EMS across the different fields, it was necessary to refer back to the existing models and adapt our research questions to reflect on the relevant constructs.

We based our design on four main technology acceptance models; technology acceptance model (TAM) [59], unified theory of acceptance and use of technology (UTAUT) [412], User acceptance of wearable devices (UAWD) [438] and Almere model [150]. We started by taking TAM as the base for the model that we would apply to our research, extending it with the above-mentioned three additional models. After combining overlapping constructs, we filtered out all the non-relevant constructs that could not be applied at this early stage of the EMS technology (e.g., brand name) and that could not be generalized to every use-case (e.g., visual attractiveness). This approach leads to nine main constructs affecting the user acceptability of EMS on which we base the online survey (cf., Section 4.3) and the interview questions:

- **Social Value** is defined in previous work as the user's perception of how people who are important to the user think about the user using the system [150] and based on the UTAUT model [412]. This definition complies with Montero's explanation of the user's social acceptance as the users' feelings resulting from using the technology among other people (e.g., feeling embarrassed) [282]. Previous literature categorized social acceptability into two types, the user's and the spectator's [209]. While the first reflects the user's impression regarding the interaction with a specific technology, the latter reflects the spectator's impression of the user using the technology. We focus on the user's impression itself. In our work, the *Social Value* reflects the self-perceived image while using EMS within a group of people.

- **Perceived Usefulness** is defined as the degree to which an individual believes that using a particular system would enhance their job performance [59]. It is based on several motivation theories [171], which all argue that if the outcome is encouraging enough, the person would be willing to exert the effort [264, 155]. We base our definition along the same lines. Hence, we define *Perceived Usefulness* as the extent to which the users believe that the EMS technology could enhance their performance.

- **Perceived Enjoyment** is defined as the extent to which using a wearable system is perceived as enjoyable in its own right apart from any performance consequence that might be anticipated [438]. One can think of it as intrinsic motivation [171] based on the self-measure of fun doing a certain task. Therefore, we define the *Perceived Enjoyment* as the level of enjoyment while using EMS devices.

- **Anxiety** is defined as the induced anxious or emotional reactions when it comes to using the system [150]. While it was not presented in the early technology acceptance models (e.g.,[59]), it was recommended to be explored in any future study [389]. Furthermore, research linked *Anxiety* to negative beliefs affecting the *Perceived Usefulness* [171]. Thus, we define the *Anxiety* as the arising negative emotional reactions while using EMS.

- **Trust** is defined as the belief that the system performs with personal integrity and reliability [150]. According to Lankton [227], to trust technology is to believe that the technology has credible attributes, namely; reliability, functionality, and helpfulness. Other studies described *Trust* as a fundamental construct [237] and an attitude [28] carried out by the user towards a system that reflects the user's perception of a technology [237]. Based on that we define the *Trust* construct as the belief that EMS is reliable to confirm a user's certain needs.

- **Intention of Use** is defined as the individual's subjective probability to use the system [59]. Research has often regarded this construct as a general measure of the technology's perceived value (i.e., hedonic and pragmatic values [438, 417]). In our work, based on that, we define the *Intention of Use* as the individual's subjective probability of using EMS in the near future.

- **Functionality** is defined as the set of potential benefits that the users could have [344, 447]. The set of functionalities is then adaptive to each use case (e.g., hardware or software [438]). In our work, we define *Functionality* as the potential benefits resulting from using EMS.

- **Compatibility** is defined as the measure of compatibility level to existing systems [438, 34]. Other research focuses on compatibility form, business requirements, and personal lifestyles [55, 45]. In our work, we define *Compatibility* as the ability to integrate EMS technology in daily life tasks.

- **Attitude** is defined as a positive or negative feeling about the appliance of technology [150]. Research further divided the *Attitude* into cognitive (i.e., related to a belief) and affective attitude (i.e., related to a feeling) [437]. Therefore, in our work, we define the *Attitude* as the positive and negative feelings and beliefs about the appliance of EMS. Unlike the *Intention of Use*, this construct reflects generally technology usage.

4.2 EMS in the Context of HCI Models

To better understand the fundamentals of EMS in HCI, we explored the existing models describing the interaction between humans and computers. Based on Schomaker's [365] HCI model, there are six main entities and processes. The main entities are the *human*, sometimes referred to as intention [240], and the *computer*, sometimes referred to as digital interface [310] or state [240]. The computer input process is represented by the computer input modalities which are the sensors [310] that detect multi-modal input [184]. The computer feedback process is communicated through the computer output modalities which are the displays [310] to convey feedback [240] to the user. The human input process is the human input modality that senses [310] the input information and transfers it to the perception channels [184, 425, 240]. The human feedback process is the human body output [310] that is presented by the effectors [425, 240] generated from the information expression channels [184].

Other research proposes adding a new relationship in the case of human actuating technologies (e.g., EMS and Exoskeletons) connecting the computer output directly to the human effectors (i.e., output actions) turning the human body into a display [96].

EMS does not only affect the perception channels of humans but also actuates the human to execute certain actions (e.g., moving the arms). This proposed connection should also be extended to reach the human entity on the model as well as the effectors since it would become a new part of the loop and human intention. Based on these two relations, we group the EMS literature into EMS systems focusing on manipulating the action and focusing on manipulating the perception of users.

4.2.1 Application Scenarios of EMS

While applications of EMS already exist in fields such as fitness training (e.g., strengthening the muscles [106]) or health (e.g., overcoming certain health conditions [140]), it was not until recently that the HCI field started to explore this technology [394]. Over the last decade, within HCI, research has started to look into different use cases where EMS could be integrated [364]. To have an overview of the existing application scenarios that have been developed using EMS, we used Scopus[12], where we used *"electrical muscle stimulation"* as a search term to look for relevant literature. For the search criteria, we selected *computer science* as a field, and the time range from 2010 till 2021. We filtered the results and ended up with 67 papers in the field of HCI related to electrical muscle stimulation. Examples using electrical stimulation for non-muscle parts were excluded as out of the scope of our research (e.g., [13]). The retrieved results present different EMS systems and technologies [318, 70, 213] and present guidelines for developing EMS applications [205, 216]. Based on the HCI models, we found two directions in which EMS is applied in HCI.

- Action manipulation: the users are actuated to carry out certain movements depending on the application scenario (24 papers).
- Perception manipulation: feedback is communicated to users to convey a certain feeling (26 papers).

Electrical Muscle Stimulation for Action Manipulation A large set of research papers introduce scenarios that use EMS to manipulate the actions of users to improve or augment their skills. This could be achieved by using EMS to teach the users how to use certain objects [250] or to accomplish a certain task [358]. EMS could also teach them how to learn a certain skill in sports [399, 144, 296, 84] or improve using musical instruments [395, 75, 294]. Studies explored the possibility of directing the users while walking in real-world settings [319] or in virtual realities [17], as well as pointing at a target by actuating their arms' muscles [394, 190]. The use cases also included examples where gestures were not necessarily generated by a system, but could also be mapped between two different users [46, 300]. Further, the actions of users are manipulated to convey a certain notification as a system output [363]. Examples included actuating the human to express a certain emotion [146, 65], react faster to a certain event [185, 298], act as output notifications [71, 243, 244], or actuate the hand muscles to plot or draw a certain output [253, 54].

[12] https://www.scopus.com

Also, research focused on specific environments such as autonomous vehicles to take over the system [97] or to lessen the driving fatigue [415].

Electrical Muscle Stimulation for Perception Manipulation EMS can also be used to manipulate users' perceptions. Examples of this include gaming-feedback in mobile devices [246], in real life (i.e., exergames [40]), or in mixed reality applications [100, 256]. EMS can have an interesting role in virtual reality applications, where users receive EMS feedback when they interact with virtual objects [321, 328] or virtual characters [248].

Other examples use EMS to change the way users perceive the texture of certain objects in virtual reality (e.g., object stiffness and hardness [440]) or in real life (e.g., food texture while chewing [288, 293]). EMS can also be used to manipulate temperature sensing [108]. Another application is to create or enhance emotions by actuating the facial muscles. This can either be used to create positive emotions [132, 441] or fear [212].

Summary Overall, EMS applications are being used in the health and fitness fields as well as in HCI research. In HCI research, EMS focuses mainly on building novel application scenarios that manipulate the action or perception of the user. While research also started looking into how EMS systems can be designed to be more acceptable [206, 323], investigations on the general acceptability are still missing. However, understanding what factors influence users' willingness to adopt and accept EMS is crucial to make the step from a research technology to the market. Thus, it is important to explore the design requirements that would bridge the gap between user needs and technology opportunities.

4.2.2 Online Survey of Users' Acceptance

This chapter aims at exploring the attitudes, expectations, and concerns of users toward EMS. Thus, we made use of TAM [59] as a theoretical basis, which allows for predictions about how users in the future will adopt and use EMS technology. Most importantly, to make such predictions, a reliable way of measuring users' *attitudes and perceptions* is needed. Surveys, which have been extensively used in prior work around TAM [61, 153, 309], is a reliable way of providing such metrics [284]. Surveys were used in the past to assess user acceptance (e.g., data glasses [210] or smart kitchens [268]). It provides the advantage of high experimental control, while capturing misconceptions about a novel technology, and allows for the inclusion of a broad range of scenarios and diverse respondents. At the same time, this breadth also comes at the cost of the participants not gaining actual experience with the technology (here: EMS) during the study. This is because EMS, being haptic and unfamiliar to many participants, cannot be fully experienced in a video. A key reason for this is that EMS is fundamentally different compared to other haptic feedback methods. Thus, inferring from a known feedback method such as vibrotactile feedback to EMS is more challenging compared to related work (e.g., classical displays to data glasses [210]). Bodily impressions, for example, that are unique to EMS cannot be gained through a survey. On the other hand, expectations of how EMS might be seen from a bystander perspective (relating to its social value) can be adequately evaluated; potential misperceptions (e.g., about how the technology works [205]) can be captured. However, in the context of a survey on attitudes and expectations, this limited exposure is also a benefit: it allows to showcase the to-be-evaluated scenarios in a manner approximating market entry when prospective users get first in contact with technology via media reports, advertisements, and accounts of peers.

4.3 Online Survey

To understand users' current acceptance of EMS technologies, we conducted an online survey using eight existing EMS scenarios. Our results explore how nine factors, drawn from technology acceptance models, influence user acceptance when considering the unique constraints of EMS.

4.3.1 Scenario Selection

In the first step, we selected scenarios from existing EMS applications across HCI, health, and sports. In particular, we selected ten out of the most-cited[13] research articles from our literature review, which implies an interest in future work as indicated by the number of citations. We further selected two baseline scenarios, showcasing products available on the market for application in the medical or sports domain. Thus, both scenarios do not show research prototypes but actual applications of EMS which might already be known to users. The first scenario is a commercial fitness application, where EMS is used to strengthen muscles. The second scenario is a rehabilitation scenario, where EMS is used to aid the treatment of a stroke patient who has difficulty walk-

[13] We used the citation count on Google Scholar in June 2020.

ing. Both baseline scenarios describe applications in which EMS is currently successfully applied on the market in contrast to the research prototypes.

We analyzed these potential scenarios by conducting a pre-test to assess their suitability for the online survey format. For this, we prepared a 30 seconds video and a brief textual description for each scenario. The video and textual description both present the goal of each project and show the benefits of the EMS technology in each scenario. We based our videos on videos uploaded to YouTube and other video platforms and changed the length to 30 seconds to have a comparable level of detail. We showed the potential videos in combination with the textual description to 3 pilot participants. These participants had no prior experience with EMS. After each participant, we iteratively improved the descriptions and videos to make sure that the overall concepts and benefits could be understood by survey respondents. This resulted in six scenarios focusing on EMS research in HCI (cf., Table 4.1). Three are covering applications in which EMS changes the *action* and three additional scenarios covering the *perception* part.

4.3.2 Question Design

We base our research on nine different constructs related to user acceptance of EMS. For each of them, we derive questions from different questionnaires which is a common approach in HCI [209]. Table 4.2 lists the constructs and questions. Each question is formulated as a statement and uses a 7-point Likert item stating to which degree the respondent agrees or disagrees.

4.3.3 Survey Protocol

The online survey is structured as follows. First, we collected demographic data (age, gender, country), tech-savviness, and prior experience with EMS applications. We next introduce the basic principles of EMS using a short video and textual description. Afterward, we provided each respondent with all 8 scenarios (6 HCI-related scenarios, a sports scenario, and a health scenario) one after the other. The order of presentation is randomized to prevent confounding effects from boredom or fatigue. We used a single page per scenario. For each scenario, we presented the textual description and the video and asked all 14 questions (cf., Table 4.2) using 7-point Likert items. At the end of the questionnaire, we asked for participants' emails in case they were willing to participate in follow-up interviews or the voucher raffle. We implemented the survey using the Limesurvey platform[14].

4.3.4 Respondents

We recruited respondents through mailing lists and social media. Participation was incentivized with ten Amazon vouchers of 25 €, which were raffled to respondents after the survey closed. Overall, 101 respondents filled in the questionnaire completely (mean time 29.58 mins). Respondents self-identified gender, our results include 57 male, 38 female, 2 other genders, and 4 preferred to not specify. Respondents specified their age, averaging 30.3 years (min: 18; max: 75; sd: 11.10). Overall 91% of the respondents came from Germany, Egypt, and the USA.

4.3.5 Pre-processing

We measured response time to check for outliers completing the survey too quickly or slowly. We used the Tukey method of the 1.5 quartile distance for survey completion time. All respondents met the inclusion criteria based on completion time, we did not exclude any respondents. To create a uniform scale from positive to negative, we inverted the polarity of the negative Likert items (i.e., stronger agreement equals a positive attitude towards the scenario). Where multiple questions applied to a single construct, we grouped these responses as shown in Table 4.2.

4.3.6 Analysis

The survey data was analyzed using quantitative techniques for ordinal Likert data responses. We applied the Aligned Rank Transform (ART) procedure [427] to our data before performing repeated measures analyses of variance (ANOVA) for each of the questions with the within-subject factor scenario (8 levels) and the between-subject factor previous experience with EMS (*EMS Exp.* – 2 levels). For previous experience with EMS, we grouped respondents into two groups: respondents who did not use EMS before (58) and respondents who used EMS once or more often (43) based on their self-reported prior experience with EMS.

[14] https://www.limesurvey.org/

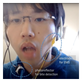
Type	Label		Name	Reference
	Action 1		Cruise Control for Pedestrians: Controlling Walking Direction using Electrical Muscle Stimulation	[319]
Action	Action 2		Preemptive Action: Accelerating Human Reaction using Electrical Muscle Stimulation Without Compromising Agency	[185]
	Action 3		Building a Feedback Loop Between Electrical Stimulation and Percussion Learning	[73]
	Perception 1		Study on Control Method of Virtual Food Texture by Electrical Muscle Stimulation	[293]
Perception	Perception 2		Muscle-Propelled Force Feedback: Bringing Force Feedback to Mobile Devices	[246]
	Perception 3		Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation	[248]

Table 4.1: HCI Scenarios used in the survey.

Construct	**Model**	**Question**
Social Value	UTAUT [412]	I will not use the EMS technology when I am home alone. I will not use the EMS technology when I am home with friends/family. I will not use the EMS technology when I am in a public place alone. I will not use the EMS technology when I am in a public place with friends/family.
Perceived Usefulness	TAM [59]	I think it is inconvenient/ not useful to have EMS on my body.
Perceived Enjoyment	UAWD [438]	I think this application would not be enjoyable to use.
Anxiety	Almere [150]	I am afraid to hurt myself while I am being actuated. I am afraid to hurt others while I am being actuated. I think this application would be comfortable to use.
Trust	Almere [150]	I trust being actuated by the EMS system.
Intention of Use	TAM [59]	I think I will use EMS in the near future.
Functionality	UAWD [438]	I think this application provides a realistic functionality.
Compatibility	UAWD [438]	I think this application is compatible with my existing activities.
Attitude	Almere [150]	I think I will use the EMS technology.

Table 4.2: Questions and related constructs asked in the questionnaire.

We explored significant effects for all comparisons in more detail using Holm-Bonferroni-corrected post-hoc pair-wise t-tests. We conducted the evaluation based on the individual scenarios as well as with categorization of action and perception (cf., Table 4.1).

We also did a control analysis in which we checked the control factors of tech-savviness (low vs. high – split in half based on median), gender, country (Western vs. the Middle East), and age. We found one statistical difference for the country. Respondents from Western countries ($Med = 4.33$, $Mad = 1.48$) are less anxious than respondents from middle eastern countries ($Med = 3.33$, $Mad = 1.48$), $F(1,97) = 14.082$, $p < .001$. We found no further statistically significant main and interaction effects.

4.3.7 Results

Figure 4.2 and Figure 4.3 give an overview of the nine survey constructs for each of the eight EMS scenarios. Table 4.3 gives an overview of statistical comparisons for each construct based on the scenario and previous experience with EMS as reported by respondents including the effect size of each factor. In the following, we provide an overview of the analysis of the survey results, where we highlight the main findings.

We looked into the influence of different scenarios and how they are perceived by the respondents. For each construct, we found statistically significant differences in the scenarios (cf., Table 4.3).

Overall Rating We averaged the responses over all constructs and found statistically significant differences for scenario and previous EMS experience (cf., Table 4.3 and Figure 4.4). We also found interaction effects between the scenario and previous EMS experience.

Averaged over all constructs, respondents rated the health ($M = 5.03$, $SD = 1.00$) scenario significantly better than all other scenarios (all $p < .05$). In contrast, they rated Perception 1 ($M = 2.91$, $SD = 1.42$) (all $p < .05$, except for Action 1: $p = .46$) and Action 1 ($M = 3.29$, $SD = 1.52$; all other $p < .05$ except for Perception 2: $p = .19$) worst. Action 3 ($M = 4.35$, $SD = 1.41$) was rated second highest (Perception 2: $p = .03$, all other $p > .05$) followed by Action 2 ($M = 4.24$, $SD = 1.46$), Perception 3 ($M = 4.17$, $SD = 1.47$), Sports ($M = 4.11$, $SD = 1.49$), and Perception 2 ($M = 3.75$, $SD = 1.41$) where we could not find any further statistically significant differences (all $p > .05$).

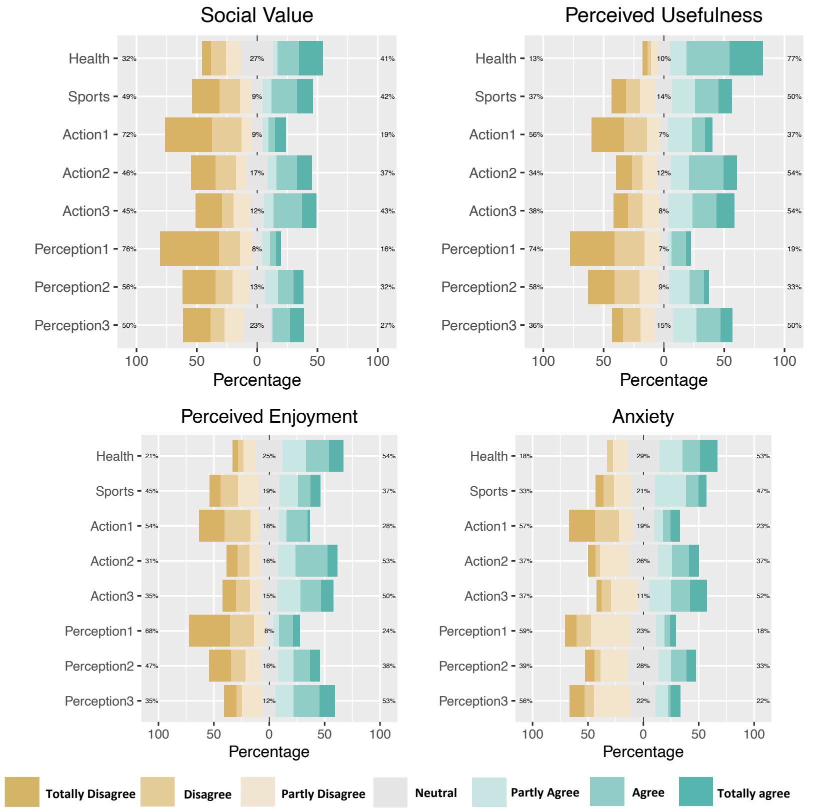


Figure 4.2: Stacked bar charts of the responses of the online survey ($N = 101$) for the *Social Value*, *Perceived Usefulness*, *Perceived Enjoyment* and *Anxiety* constructs listed in Table 4.2. Note that constructs with multiple questions are averaged per scenario.

Social Factors and Acceptability Figure 4.5 shows responses to questions about social factors. Overall, Health ($M = 4.33$, $SD = 1.79$) is rated highest followed by Action 3 ($M = 4.03$, $SD = 1.85$) and Action 2 ($M = 3.97$, $SD = 1.91$). Perception 1 ($M = 2.66$, $SD = 1.76$) is rated lower compared to all other scenarios ($p < .05$) except for Action 1 ($M = 3.07$, $SD = 1.79$; $p > .05$). Action 1 is additionally rated lower then Health ($M = 4.34$, $SD = 1.76$; $p < .001$), Action 2 ($p = .010$), and Action 3 ($p = .004$). Health is rated higher than Perception 2 ($M = 3.46$, $SD = 1.84$; $p = .012$). All other comparisons could not show statistically significant differences ($p > .05$).

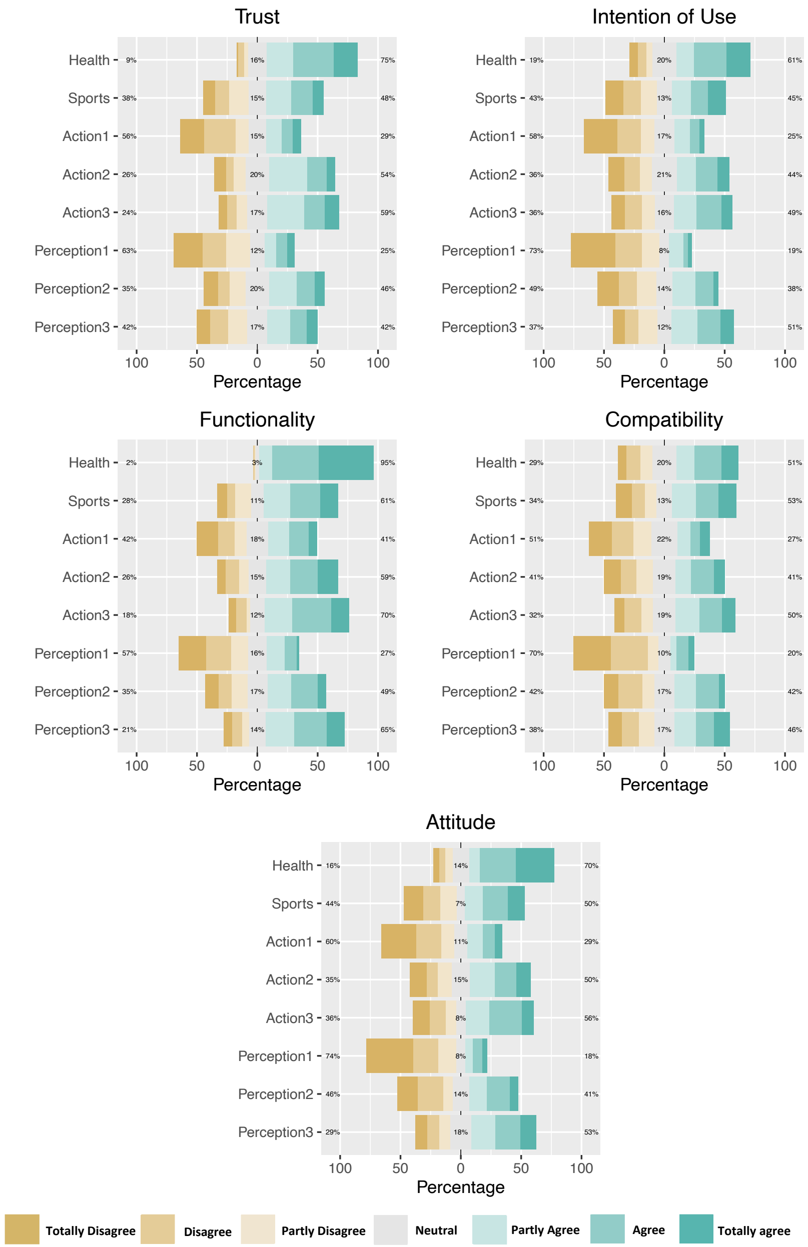


Figure 4.3: Stacked bar charts of the responses of the online survey ($N = 101$) for each of the *Trust*, *Intention of Use*, *Functionality*, *Compatibility* and *Attitude* constructs listed in Table 4.2. Note that constructs with multiple questions are averaged per scenario.

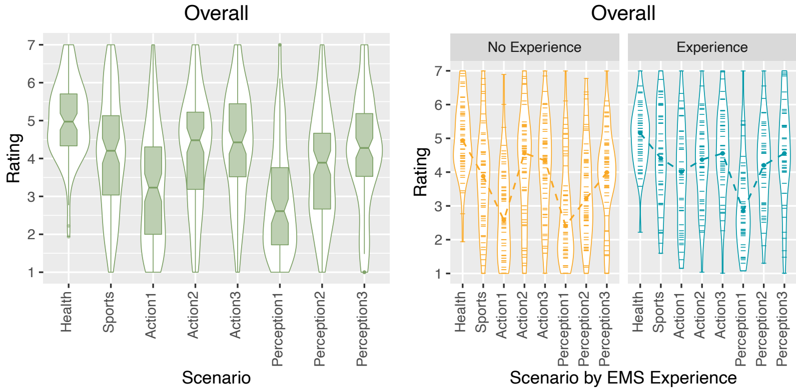


Figure 4.4: Boxplot and Violinplot of the responses averaged over all constructs per scenario (left) and split by experience (right).

The experienced respondents ($M = 3.99$, $SD = 1.88$) rated scenarios on average higher compared to non experienced ones ($M = 3.32$, $SD = 1.83$). Further, we observed an interaction effect of EMS experience on the scenario. Experienced respondents rated all scenarios except for Perception 1 similarly whereas non-experienced respondents rated Action 1, Sports, Perception 2, and Perception 3 lower (cf., Figure 4.5 – left).

Comparing the questions about EMS usage home alone (cf., Figure 4.5 – center) and EMS usage in public alone (cf., Figure 4.5 – right), we found that experienced respondents ($M = 4.31$, $SD = 2.14$) compared to non-experienced respondents ($M = 3.22$, $SD = 2.17$) tend to be more willing to use EMS home alone ($F(1,99) = 12.867$, $p < .001$, $\eta^2 = .063$). In contrast, we could not find a statistically significant effect for experienced ($M = 3.74$, $SD = 2.09$) compared to non-experienced ($M = 3.36$, $SD = 2.05$) respondents for the same question in public with friends (cf., Figure 4.5 – right; $F(1,99) = 1.554$, $p = .216$, $\eta^2 = .008$). The only exception in the rating of experienced respondents is Perception 1 which was rated low independent of the location and experience of the respondent.

Anxiety Figure 4.6 shows a summary of responses to questions about *Anxiety* towards using EMS applications grouped by previous experience with EMS. Experienced respondents have significantly less *Anxiety* towards EMS compared to non-experienced respondents.

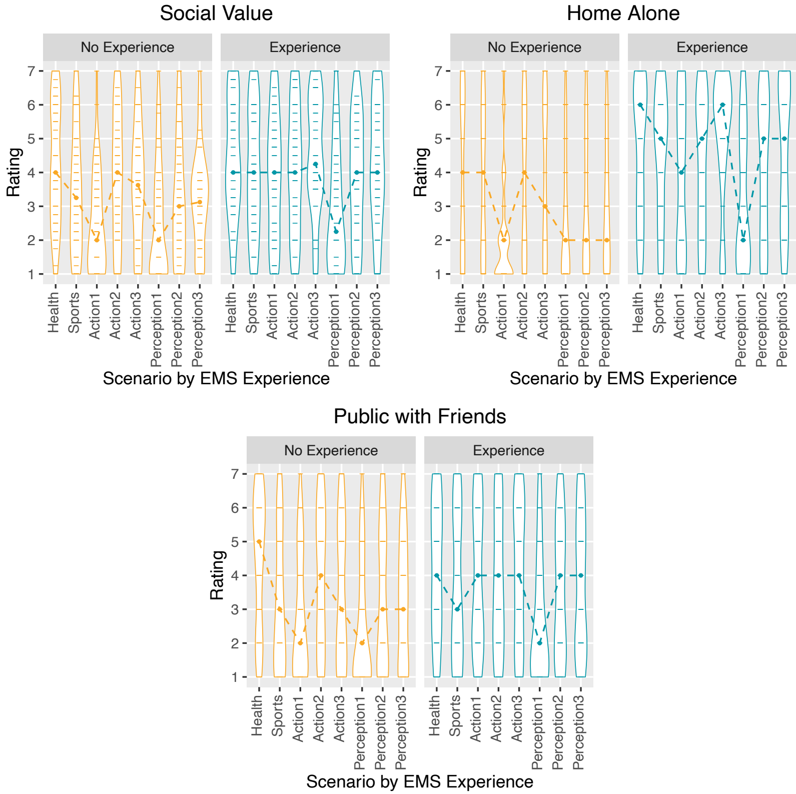


Figure 4.5: Respondent ratings for social factors related to EMS applications in sports, health, action, and perception. Respondents with previous experience with EMS responded significantly differently, with more positive attitudes than those without.

Looking into the specific scenarios, Health, Action 2 and Action 3 are rated significantly better compared to all perception scenarios ($p < .05$). In contrast, Action 1 was rated significantly worse compared to every other scenario ($p < .05$) except for Perception 1 ($p = .10$). Health is rated better than sports ($p = .01$). All other comparisons could not show statistically significant differences ($p > .05$). We also found that respondents in general are more anxious about hurting others ($M = 4.48$, $SD = 1,63$) than hurting themselves ($M = 3.71$, $SD = 1,94$) (cf., Figure 4.6 – center and right).

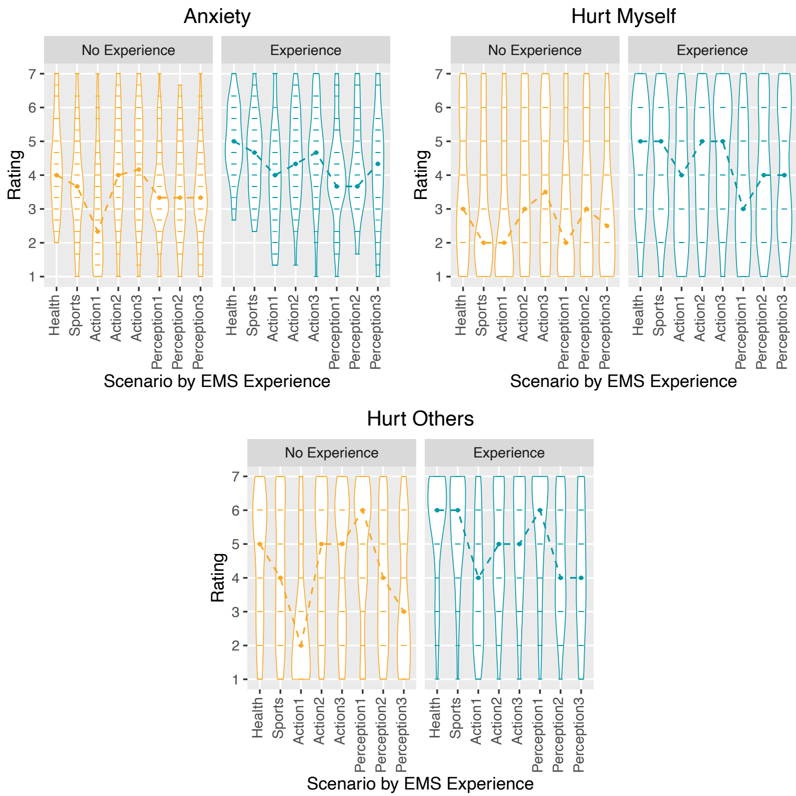


Figure 4.6: Respondent ratings for *Anxiety* related to EMS applications. Overall, respondents with previous experience with EMS respond significantly differently, with lower levels of *Anxiety*, than those without (left). Similarly, the ratings of the questions whether they would think they would hurt themselves (center) or others (right).

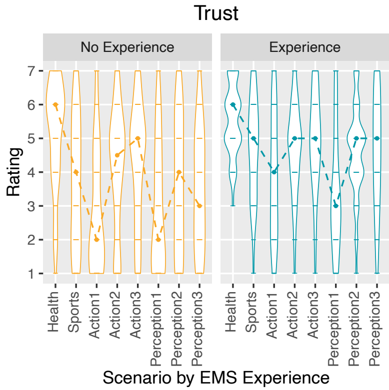


Figure 4.7: Respondent ratings for *Trust* related to the different scenarios. Respondents with previous experience with EMS respond significantly differently, with higher ratings for *Trust* than those without.

Trust Respondents rated the health scenario particularly high with regards to *Trust* independent of experience (cf., Figure 4.7). Likewise with *Trust*, those with previous experience have significantly more *Trust* in EMS than those without. Although, *Trust* in health-related applications is uniformly high across both groups. Particularly Action 1 and Perception 3 are rated higher by experienced respondents compared to non-experienced respondents.

Comparing the scenarios, we found that health ($M = 5.33$, $SD = 1.39$) was rated better than all other scenarios ($p < .05$). On the other hand, Perception 1 ($M = 3.15$, $SD = 1.85$) is rated lowest (all comparisons $p < .05$ except for Action 1: $p > .05$) followed by Action 1 ($M = 3.30$, $SD = 1.89$) that was rated second lowest (all other comparisons $p < .05$ except for Perception 3: $p = .09$). Furthermore, all other comparisons did not show statistically significant differences ($p > .05$).

Further Influence of Experience We also found that previous experience has a significant effect on *Perceived Usefulness* with experienced respondents ($M = 4.28$, $SD = 1.95$) rating higher compared to non-experienced respondents ($M = 3.75$, $SD = 2.07$). The *Attitude* towards the EMS scenarios also changed with the experience. Experienced respondents ($M = 4.25$, $SD = 1.99$) had a more positive *Attitude* compared to non-experienced ones ($M = 3.77$, $SD = 2.10$). The experience also influenced the rating for the different scenarios with respect to *Intention of Use*, *Compatibility*, and *Attitude*.

	Scenario	EMS Exp.	Interaction effect	η^2		
Construct	**F(7,693)**	**F(1,99)**	**F(7,693)**	**Scenario**	**EMS Exp.**	**Interaction effect**
Social Value	16.445 ***	6.928 **	2.238 *	.074	.034	.011
Perceived Usefulness	29.064 ***	5.386 *	1.706	.149	.021	.010
Perceived Enjoyment	16.125 ***	0.560	1.769	.084	.002	.010
Anxiety	18.334 ***	10.583 **	1.220	.079	.054	.006
Trust	28.316 ***	9.718 **	1.622	.121	.047	.008
Intention of Use	20.421 ***	3.615	2.388 *	.114	.013	.015
Functionality	40.070 ***	3.272	1.465	.210	.011	.009
Compatibility	12.992 ***	1.112	2.311 *	.071	.005	.014
Attitude	25.383 ***	4.966 *	2.220 *	.137	.018	.014
Overall	37.541 ***	6.803 *	2.880 **	.169	.031	.016

Table 4.3: Results of the ART ANOVA for the factors Scenario and EMS Experience as well as the interaction effect Scenario x EMS Experience. The tests are presented for each construct (mean overall questions if there is more than one question – cf., Table 4.2) and overall (mean of constructs). Statistically significant results are marked: '***': $p < .001$; '**': $p < .01$; '*': $p < .05$. Effect sizes (η^2) are calculated without the random effect of respondents.

4.4 Interviews

Following the results of the online survey, we conducted 10 semi-structured in-depth interviews to gain further insights into users' attitudes, motivations, and acceptance of EMS technologies.

Participants and Procedure

We started each interview by presenting the chosen scenarios again and highlighting that they represent different application domains, namely, health, sports, action, and perception. Next, we went through all the constructs and revisited each question to shed light on the reasons behind their answers.

Recruitment We recruited interview participants from the respondents of the online survey. Overall, 25 respondents from the survey volunteered, out of which we selected 10 interview participants (cf., Table 4.4). To further understand our survey findings on the impacts of previous experience with EMS and acceptance, we selected five participants with no experience and five participants with experience using EMS. Paritcipants' experience with EMS varied from using it for fitness training, overcoming health problems (e.g., physiotherapy) and researching EMS in HCI (cf., Table 4.4).

Procedure and Asked Questions We conducted the interviews partly via video conferencing software (i.e., Zoom) and in physical meetings (e.g., in our lab environment). Interviews lasted on average seventy-five minutes and were audio recorded. The interview protocol explored the nine constructs from the survey with a focus on eliciting the reasoning and motivation behind participants' answers. At the beginning of the interview, we reminded the participants of the eight presented scenarios. Then, we asked questions about each construct from the survey (cf., Appendix A). At the start, we mentioned the questions as presented in the survey, then we extended these questions to get more insights. For example, in the *Perceived Enjoyment* we repeated the question as in Table 4.2. We proceeded by asking them what would they expect as *Perceived Enjoyment* and what benefit would the users need so that they would enjoy using the system. We applied the same strategy with all the constructs with a varying number of questions for each construct and asked for more insights whenever possible.

Qualitative Analysis We analyzed the interview transcripts following thematic analysis [36], an approach that allows for both inductive and deductive theme generation. The flexibility of thematic analysis was important because we aimed to uncover the reasons and patterns behind the results of our earlier, larger-scale survey. A deductive orientation allowed our existing construct to act as a 'lens' to interpret the collected qualitative data in light of the earlier survey. Simultaneously, inductive theme generation allowed us to account for unanticipated patterns and more closely examine the factors that contextualize the participants' perception of EMS. After a phase of familiarization, the initial codes were extracted by the first author and then iteratively discussed and refined in collaboration with the team of authors. We started out with code clusters (candidate themes) that were then developed further, revisiting the original interview excerpts where necessary. In this process, a thematic map, including a mapping of patterns across the interview data, was created using a Miro board[15]. Along this process, code clusters were contextualized and contrasted with the constructs asked in the questionnaire (cf., Table 4.2) which lead to overarching themes, spanning multiple of the original constructs (e.g., Urge to Use, Causes of Anxiety), as well as more nuanced, refined notions covering two distinct aspects of one single construct (e.g., *Social Value* relating to External Image as well as Design Requirements). In total, we generated six themes that provide essential background information to our survey results and derive and motivate design recommendations for future EMS applications.

4.4.1 Results

Since we conducted semi-structured interviews to uncover the rationales behind the answers given in the survey, our questions were aimed at gaining further insights into the nine used constructs. However, for clarity, we named the themes in a way that is distinct from the constructs avoiding any overlaps in terminology. For readability consistency, we link each theme to the answers obtained from the interview (cf., interview questions – Appendix **??**).

Urge to Use It reflects the necessities and main intents behind using an EMS system and came in response to the questions related to *Perceived Usefulness*, *Perceived Enjoyment*, *Intention of Use*, *Functionality*, *Compatibility* and *Attitude*.

Participants often highlighted that their responses depended heavily on the use case and the *reasoning why it is useful* [P10]. P8 clarified that he would be using the system *"if a system, is clever and helps on achieving a specific goal"*. Analyzing the answers, it became clear that the Urge to Use would be highly individualized. For example, P2 said *"I would use it in doing faster*

[15] https://miro.com/

Participant ID	Age	Gender	Previous Experience	Technology Interest
P1	38	Male	No experience	high interest
P2	37	Female	No experience	medium interest
P3	31	Female	No experience	low interest
P4	35	Male	No experience	high interest
P5	37	Female	No experience	low interest
P6	30	Female	Sports training & HCI studies	high interest
P7	57	Female	Medical Treatment & HCI studies	medium interest
P8	39	Male	Sports apps developer	high interest
P9	29	Male	Medical Treatment & HCI apps developer	high interest
P10	29	Male	HCI apps developer	high interest

Table 4.4: Characteristics of the participants in our interview sample.

housework definitely" or for a different interest as *P4* mentioned *"I would use it to enhance my experience in gaming in a meaningful way."*

When asked to categorize the applications according to their potential use cases, participants indicated that the health-related applications are the most important, with a focus on medical applications as they have a strong motivation to use them. P2 reflected that by saying *"I would use it if I have a disability and I know that there is a system out there that could help."* P6 reflected on a critical situation, for example, *"if I am in a desperate need and normal measures don't work."* P5 who had low interest in using new technologies in general elaborated *"I am not a tech fan, I will not use it unless it is used for rehabilitation or physiotherapy."* As another practical use case, participants indicated that sports would be interesting as this was also related to health and could be used to *"motivate lazy people to do exercise"* [P9]. As P8 elaborated: *"It could support training for the muscle strength [...] improve performance aspects for an athlete for example."* That was further supported by P6 who had previous experience in training, stating that *"short fitness training sessions could help joints of overweight"* [P6]. Overall, the Urge to

Use is the participants' main motive and it differed from one participant to the other. However, all of them agreed on using it in health-related applications.

Participants also discussed their acceptance of the action and perception use cases, again highlighting the importance of individual scenarios. P10 commented *"it can generate some feedback that cannot be generated by the other systems or prevent me from danger"*. This participant's preference for the use case was dominant, with more focus on the outcome. P4 had an interest in gaming and discussed gaming-specific scenarios (i.e., entertainment), while P3 had less interest in technology and preferred applications for learning music (i.e., artificial trainer). Participants also related the *Intention of Use* to their feeling towards the use case as P1 expressed it *"I think it is an emotional point of view, but I would feel comfortable using it whenever I have an interest."* The Urge to Use could be summarized in the P6 quote *"if the desire is big enough to use new technology, you will find a way to work around"*.

Design Requirements It shows the design aspects that should be considered while implementing an EMS system, which is linked to the question of the *Social Value* constructs. The participants indicated both functional as well as hardware requirements. P10 highlighted that the system should be interactive as *"you can't get good control and natural movements of overlapping muscles without having a full image of the body state"*. This point was also confirmed by P6 who said that she would like to see an *"adaptive system"*. Others indicated that they would like to have an easily controlled system that they could *"fine tune"* [P1] to reach certain *"control levels"* [P3]. All of the participants wanted an easy system to use that would not be *"cumbersome" [P10]*.

Participants also reflected on the hardware requirements, with all of them highlighting the necessity of small size and familiar look as P5 described *"it would look weird to have electrodes and wires, it would make me feel nervous. If it is like a glove it would be better"*. While all the participants' comments related to the positioning of the electrodes and safety measures, P7 mentioned it from an out-looking perspective. She said *"I would think about the electrodes at the head from a beauty aspect. It is easier to have them on the body."* Two participants compared EMS to a smartwatch, a technology that one can wear and easily operate [P4, P10]. Other general design aspects were then presented like size, mobility, battery life, re-usability, and hygienic use.

External Image It indicates the community perceived image of EMS-based systems users, which are linked to the question of the *Social Value* constructs. All participants indicated that EMS should be integrated into other objects such as clothes or accessories as a way to avoid the impression of being controlled by a computer. As P1 explained *"appearance sells, the more it is not obvious the better in order not to feel different. Everyone wouldn't like to go around with wires"*. Whereas P10 noted: *"In public, I won't use it as long as it is visible to others unless it is integrated into clothes then it is ok."* He further explained: *"In the public transport some people might look at me and wonder. I would use it when I am alone in running or VR when no one is watching me. This would be my border in the public area, market, or cinema, it would look strange to others."* Further, participants were afraid of attracting attention by behaving non-human. P10, for example, mentioned that *"if my movements would be robotic-like, people would look at me, even when I have the option to override it, still I would look weird to others if I am suppressing the EMS signal."* While all participants expressed their concerns about using EMS in public, they discussed their acceptance when it comes to others using EMS. P6 explained *"Usually I don't pay attention except to odd stuff. If the kit is visible, yes I would look [...] again curiosity of the use case, but I wouldn't see it as inappropriate"*. In particular, *"if people with disabilities are using the system, it would look like a medical device and then it is a design question"* [P8]. In general, the participants feared being perceived as odd by the surrounding community either because of their appearance using EMS or the EMS influence on their movements.

Causes of Anxiety It maps the anxiety-related concerns that impede the users from adopting EMS systems, which are linked to the questions of both *Anxiety* and *Trust* constructs. When participants discussed the positioning of electrodes, they expressed their fear of approaching the head, neck, private, and vital parts of the body. P1 further elaborated *"we don't know everything about the body. I know people with nerves problems and don't know the impact on them"*. The fear of damaging nerves was also brought up by P6 as she said *"I would not use anything that directly targets the nerve ending, I don't want to have them electrocuted."* Other participants expressed their concern about long-term side effects. P4 mentioned the need for further *"debates regarding long-term effects and implications"*. P1 highlighted his fear of long-term effects as he wondered *"what would happen when the strength of the signal going to the muscle tricks the brain to send different actuation strength"*. With similar concerns, P7 expressed her fear of losing the ability to *"have the feel of grabbing an object in hand"*. Another group of concerns targeted the perceived safety level while being actuated. P4 started by giving an example based on the food texture. He said: *"Sometimes when I eat something old, I feel that because of its texture. If I used the chewing system I would not be able to do that."* P9 gave an example relating the cruise control scenario with a system failure, where a user might be erroneously guided to a dangerous area. P8 used the same scenario, to highlight that the system could make him stumble as a result of actuating his feet. However, he mentioned that the user has an active role as well, as he further elaborated *"this is something that you have to adapt to the system and change your behavior to be able to use it. Like modifying my gait while walking."* P6 mentioned: *"I would keep distance and I would warn those in a close range."* Confirming that, P4 explained further that he would not want to have his kid around him as he *"would be worried about the precautions to endanger my family"*. Both P3 and P8 mentioned that the lack of knowledge of how far the system can go would prevent them from using it. Even when we informed participants that muscle strength can overcome EMS actuation, participants still raised the concern that overcoming actuation might look *"weird"* [P10], *"be accompanied with pain"* [P6] and might not be at the *"right moment"* [P4]. All in all, the participants were most concerned about the consequences of a system failure and the side effects of using EMS on their body as well as perception.

The participants proposed solutions that could overcome the challenges of *Anxiety* and safety. Most of the proposed solutions could be grouped as characteristics of a smart system. All of the participants highlighted the importance of having an emergency safety switch that would instantly disengage the system. One of the participants further commented *"I would assume it is there by default"* [P5]. Out of our ten participants, eight indicated a higher sense of safety if the system was recommended by a person with experience or if they could use it in presence of an expert (e.g., medical doctor), but this raised the question *"who would you consider as an expert?"* [P8]. P6 further elaborated: *"I need to trust the algorithm to do what it should in different conditions and even when I mess stuff Need to understand the implications."* Another aspect is the adaptivity to the body state as described by P10: *"A smart system would detect the user parameters, for example, user's sweat level and heart rate and would stop in case of reaching certain measures."* This would also prevent the user from *"overexerting the muscles by knowing the maximum limit"*, P6 further explained. Another safety measure that affected the participants' acceptance was system transparency. P5 explained: *"I would need a manual with a clear description, relevant to my use case [...] with rules, regulations, and limitations."* P2 further clarified: *"If it is trusted, I would use it in any case whenever I need it but I always need the feedback of the system's intention."* Another direction of safety addressed the research field more generally. As P6 wanted to see *"clear measures and expectations"*. That was further clarified by P1 who said that *"the system should be widely tested, along a well-prepared* *introduction with numbers and safety aspects presented to the public"*. P9 additionally clarified: *"I would trust it if it comes from a bigger company than a small one as they have more resources so I would consider it ideal."*

Agency It reflects on the users' sense of control over their own actions, which is linked to the responses related to *Anxiety* and *Trust* constructs. Nine of the participants commented on Agency. One of the participants described having EMS as *"playing a game with your own body"*, which summarizes the concerns of many of the participants. All of the participants commented on the cruise control scenario. As P6 expressed her concern with this particular scenario, mentioning that *"I need to have enough autonomy on my body."* Others also expressed their non-acceptance of being controlled. P5 elaborated: *"I don't like the idea of being pushed to do something. I hate the idea of the system agency, it would make me nervous."* P10 expressed his worry about the system's decision in critical situations. For this, he used the preemptive action example (i.e., Action 2). He elaborated: *"The system has to know what to do, which is tricky. If the system would speed up my reaction time to catch a coffee cup instead of a pen, I wouldn't trust using it."*

Ethical Perspective It represents the participants' concerns that extended beyond just safety, for example, worry about legal issues and regulations. These comments were retrieved when the participants were talking about the *Anxiety* construct. P4 further expressed his worry, saying: *"Who is responsible for the errors, do we have risk management? I doubt we have a holistic view of the whole chaotic environment."* P9 and P10 expressed their worries using examples like regulations for autonomous vehicles. For example, P9 said: *"In the cruise control, it is like GPS or system failing to guide someone, like dangerous autonomous cars GPS failing experience"*. Four participants showed their concern that EMS could be used to control other people. P1 said: *"I don't judge but I won't accept it if it is a mother controlling her child [...] I will not perceive it negatively unless it is touching the negative ethical point"*. P7 explained further *"when the pulses are higher, the probability of hurting someone is higher."*

4.5 Discussion

Based on our results from the online survey and post-survey interviews, we reflect on the role of use-case, social factors, anxiety, safety, agency, trust, and previous experience with EMS on influencing the overall user expectations and hence acceptance of the EMS technology. We distill this discussion into design recommendations that support the developments of future EMS applications to achieve a higher level of user acceptance. These recommendations address the design of everyday applications without focusing on a special use case.

Recommendation 1: EMS constraints on muscle contact and power need to blend into the user's appearance.

For EMS social aspects play an important role in acceptance as indicated by our participants in the ratings of the *Social Value* construct (cf., Section 4.3.7) as well as their comments regarding their External Image in the interviews (cf., Section 4.4.1 – External Image). While the experience factor influenced the participants' willingness of using the technology alone at home, this influence was not observed in the public presence. Multiple participants mentioned that cables *"coming out of the body"* (i.e., from electrodes on the body) might not be appropriate in a public space. This is in line with Dunne et al.'s work on the social acceptability of wearables, in which they found that users are afraid that their wearables attract (negative) attention [72]. Throughout the interviews, we received multiple suggestions to integrate the electrodes into clothing and accessory. Here, our results support what has been hypothesized by Knibbe et al. [206] namely that future EMS devices should fulfill wearability criteria, including aesthetics and social acceptability. While the technology is not there yet, there are first approaches to include EMS in smart textiles [323]. However, not all parts of the body are always covered with clothing. Moreover, the position of the muscle is defined by human physiology, and the EMS electrode needs to be placed at the muscle that the system should actuate [323]. Thus, the design space with regard to electrode placement is limited, which requires more adjustable systems (e.g., [46]). This opens a challenge of the right approach to designing flexible, easily integrated systems.

Recommendation 2: The action elicited by EMS needs to be compatible with existing human dynamics.

Besides having a device that is designed to look natural, EMS also uses the human body as an output device. This induced movement should still look like existing human movements and dynamics. The different nature of EMS in terms of perceived feedback is not only confined to the design aspects but also extended to cover more factors, like the perceived social image of the user as elaborated by our participants in the interviews (cf., Section 4.4.1 – Design Requirements). While in other technologies like public displays, users showed similar feelings of perceived awkwardness [275], they are limited to the location of the device. Although EMS, as described before, would be integrated into some modest wearable gadgets, it does not mean that it leads to natural-looking movements that might not attract attention. This complies with the definition of social appearance anxiety, which could be defined as the *"fear of negative evaluation of one's appearance"* [236].

While EMS in general mimics the signal of the brain and therefore provides similar input to the muscle than the users themselves, the fine-grained control of muscles is still an open challenge. Particularly muscles that are covered by other muscles cannot always be actuated precisely (if at all) with electrodes placed on the skin. This challenge is not relevant for all the scenarios, but to achieve widely integrated and accepted applications (i.e., especially the daily life applications) this should be tackled. The actuation should be designed in such a way that the movements look as natural as possible. However, this should not be a limiting factor to exploring the different opportunities and potentials of the technology. The technology itself is, despite the many studies exploring it, still at an early stage. However, that does not mean that it reached a saturation stage. For example, the work by Takahashi et al., where they explored new EMS electrode placement for increasing dexterity [391].

Another perspective is the *Trust* shown to the user's actions and movements if they were to be perceived as robotic, sudden, or random. In some situations, where the application is stationary and the interface is clearly visible (e.g., in VR) the spectator's experience [347] will differ from scenarios where the user is using it in public in an unobtrusive way (e.g., cruise control [319] hidden by long pants). As a result, the spectator's *Trust* and caution towards the EMS user might also differ. For this reason, we recommend evaluating the perceived visual appearance of behavior elicited by actuation and perceived trustworthiness simultaneously.

Recommendation 3: EMS needs a safety net or emergency-off switch and a clearly communicated status.

Beyond visual appearance and perceived awkwardness, users are afraid of specific issues like control, pain, and agency. Previous work [205] has shown that participants have fear of losing control. This observation is further supported by our findings. Fearing that a system failure might hurt them directly or even hurt others, causes a high level of *Anxiety*. Throughout the interviews, participants mentioned their need for high safety standards. Participants were particularly afraid of failure in the safety measures and, thus, not being able to override the EMS signal and therefore lose their sense of Agency. This is particularly clear in our survey results for the non-experienced respondents. They were more anxious to hurt themselves compared to experienced respondents (cf., Section 4.3.7 – *Anxiety*). The respondents' comments comply with what was previously pointed out by Wiener and Curry [423] when they elaborated on the risky outcome of using unreliable systems, as it could be occasionally affecting human safety. Furthermore, it is in line with prior research exploring the users' desired sense of Agency when interacting with technology [240]. Thus, even if the safety of an EMS system can be ensured through technical security measures on the software and hardware side, the EMS system would still need to provide options for manual interrupt or override to support the user's sense of Agency and – in consequence – feeling of comfort. How to exactly design this kind of intervention is, however, an open research challenge, especially given the wearability aspect.

Moreover, these kinds of safety measures should be introduced first, before exploring the user experience. The potential users would refrain from using such a system just by thinking of drastic consequences that are based on speculation. Unlike other non-bodily interactions (e.g., clicking a wrong button), a system failure in the case of EMS is not only depending on the wrong action or results in consequence but would also result in a strange feeling that is difficult to communicate or display to users without previous experience. This is also linked to the interface guidelines of Shneiderman [376] that systems should provide an easy reversal of actions. While it is easily implemented in a conventional computing system, EMS actuates the human body in the real world and, thus, reversal of action is not always possible. Thus, an emergency switch or safety net seems to be necessary for systems using EMS.

> **Recommendation 4:** EMS applications should be targeting a specific use case that the users deem necessary.

The interviews demonstrated that Urge to Use, such as a necessary use case, is the main motivation to use EMS (Section 4.4.1 – Urge to Use). Novelty alone seems not to be enough to drive an Urge to Use. This observation is further supported by the survey results, where the scenario tends to influence the responses more than the previous experience with EMS. Additionally, we found that the *Perceived Usefulness* is also influenced by the users' prior experience with EMS. That is to say that the uniqueness of the feedback provided by the EMS (i.e., directly influencing the body) and the unfamiliarity with feedback of such a nature makes judging utility more complicated for novice users.

For all constructs, we found the scenario to significantly influence the ratings of the respondents (cf., Figure 4.4). That could be further observed in the *Functionality* construct, where the participants perceived the health-related scenarios to be providing realistic purposes. In the interviews, all participants mentioned that the value a scenario adds would be directly relevant to their personal benefit and is the most important factor to consider. For example, if they are planning to learn a new musical instrument and EMS might support them by guiding their finger movements, they would accept the technology. On the other hand, some of the scenarios we assessed did not provide enough value (e.g., changing the food texture [perception 1]) did not convince the participants about the added value).

The effect of the scenarios' differences appeared even more while comparing the action and the perception within the HCI applications. Participants justified that as they felt the perception scenarios as entertaining applications and, therefore, of less importance. On the other side, action scenarios were considered to be more practical. This is also applied in the more general comparison between HCI and sports, where the sport has direct influences on health compared to less necessary uses of the technology such as changing food texture or enhancing feedback in VR.

Users' limited knowledge of the EMS potentials is now an open challenge for the user acceptance of the EMS technology. This might change in the future, allowing users to gain what we can call "superhuman powers." For example, if EMS could improve human reaction times (e.g., preemptive action scenario), this raises new ethical challenges such as a group using EMS is favored. The consequences of using such technology should be further investigated. Furthermore, as the participants highlighted in the interview (i.e., Section 4.4.1 – Ethical Perspective) and what we consider as a similar aspect to autonomous vehicles [156], clear laws should be set to indicate the legal responsibilities of the users' action. For example, in the case of a system failure that resulted in hurting someone other than the user, who would be legally responsible for the resulting action? Although it was clear in our results that the use-case plays the most significant role in the technology acceptance, the ethical and legal aspects need to be further investigated to define clear boundaries and the role of the technology in each use-case.

Recommendation 5: Simple demo applications may help to overcome the high entry hurdle of EMS.

Throughout the survey data analysis, we found level of previous experience (based on self-report) influenced respondents overall ratings across all constructs as well as for *Social Value*, *Perceived Usefulness*, *Trust*, *Attitude*, and *Anxiety*. Respondents with previous experience in general provided higher ratings compared to respondents without previous experience. A core reason for this difference is users´ *Anxiety*. In the survey responses (cf., Table 4.3) and throughout the interviews (cf., Section 4.4.1 – Causes of Anxiety), particularly non-experienced participants emphasized that they were afraid of hurting themselves. This impression is also solidified by non-experienced participants mentioning that they would prefer the help of professionals while using EMS and, consequently, not feeling comfortable using it at home alone. In contrast, experienced participants prefer home usage due to social reasons.

The insecurity of the non-experienced participants was tied to having never perceived EMS. They were, for example, afraid that the EMS device could force them to move beyond their normal limits. While the latter might be addressed by providing explanations and reassurances, the lack of knowledge about how EMS actually feels, creates a significant entry hurdle. Experienced participants even mentioned that with a negative experience (e.g., tickling) in the beginning, they would still be willing to continue using EMS. Again this shows how EMS is different from other types of interfaces. Because the feedback sensation is in-body, it provides a sense of being controlled and not initiating the action. This goes in line with previous work that investigated how participants would describe EMS signals and cited it as personal experience [205], which cannot easily be generalized to the whole population. This is a challenge for future research and product development. For instance, this entry hurdle could cause self-selection bias [418] and in consequence skew research findings towards the opinion of extrovert, tech-savvy, and EMS-experienced participants. In the worst case, this would cause EMS to be employed as part of niche applications, and not for the most justified, acceptable, and promising use cases (e.g., assistive technologies).

Recommendation 6: EMS applications should provide suitable means to share control between the user and computer.

EMS has the ability to take control of the users' body if the users are willing to share it. Thus, users need to hand over some control over their own bodies to the computer. The challenge of sharing the control was a recurring theme in our results. Nine of the interview participants reflected on the fear of control loss and not having enough *autonomy* over their actions (cf., Section 4.4.1 – Agency). Expressing their worry regarding EMS systems, all the participants highlighted their fear of the consequences. One aspect that was mentioned is not knowing the extent to which the system would be actuating them. Particularly, non-experienced participants expressed concerns about how they would maintain their control and were unsure if they could easily overpower EMS actuation. Similar issues were discussed in the field of autonomous vehicles, for example handing over and regaining control from a driving system. The issue of sharing control and when would it be suitable for the human to take over the control from a vehicle has been extensively investigated [33, 79, 340]. While there is a list of differences between the two cases (e.g., nature of the interaction, system failure consequences .. etc), the control sharing or in other words the control overtaking from one of the two entities (i.e., the human and the computer) still needs to be researched for EMS systems. For the AVs, it is clear how the user is required to intervene with quite apparent implications (e.g., driving wheel).

In general, intervention interfaces [360] are designed in a way that they are only used to intervene when the user's intention differs from the intention of the system. In the case of EMS, the system action that should be overtaken is the human action itself. Therefore, the intention and the action of the users would be, to some extent, colliding. Our participants reflected on that by highlighting the importance of gaining control over their bodies whenever they want. While this applies to classical interface guidelines such as Shneidermans Golden Rules [376], which suggest that the user should maintain control of the system (i.e., be the initiator of action), it raises the challenge of how that should be done in cases where users want to hand over control.

4.6 Conclusion

In this chapter, we provide a set of design recommendations for EMS applications. We analyzed the replies of an online survey (N=101) and around twelve hours of in-depth interviews (N=10). On the one side, our results show differences between experienced and non-experienced users, indicating that the entry hurdle is one of the biggest challenges. On the other side, the scenario in which EMS is applied highly influences the acceptance. Overall, even for experienced participants, we conclude that different design aspects that affect the users' comfort, trust, and appearance, should be considered when designing EMS experiences.

Summary and Key Findings

In this part, we inspected the user's perspective when interacting via EMS. We started by exploring why is EMS different from other technologies, where we proposed a new relation to a classical human-computer interaction model. We proceeded by examining the different types of interactions and based on that proposed a taxonomy for EMS applications. We ended this part by exploring the user acceptance of EMS applications.

> **Key finding I:** EMS interaction differs according to the use case. It can target action or perception and can be used for augmentation or induction.

Our results in Chapter 3 not only show that the interaction cycle with EMS is different from other modalities, but it also differs for EMS applications in different scenarios. For conventional interaction modalities like auditory and visual feedback, the user reacts according to the presented feedback, wherein the EMS interaction technology could have control of the user's actions. Nonetheless, in some use cases where the user's action is not targeted, the EMS systems target then the human perception. We further found that the EMS applications could be used either to instantiate a new action or perception or to augment existing ones.

> **Key finding II:** User's acceptance of EMS is bounded by the absolute need for the technology.

In Chapter 4, our findings indicate that one main reason that would prevent users from adopting this new technology is unfamiliarity. Unfamiliarity was reflected in many aspects including the action appearance or personal outlook as well as the danger that could result from using EMS technology. While unfamiliarity is a huge challenge for technology acceptance, our participants showed a high level of agreement to use the technology in health-related applications in comparison to fun complementary scenarios.

III

Augmenting Human Action & Perception Using Electrical Muscle Stimulation

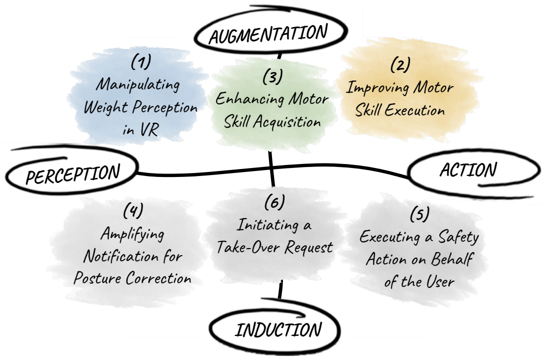


Figure 4.8: EMS Application scenarios presented in this part. The applications augment user action and perception.

Overview

In our previous chapters, we highlighted that the interaction with EMS applications is different than other conventional modalities. This comes as a result of having electrical signals communicated directly to the human body. Consequently, the influence on the human might not only be on the perception level but also on the action level. Therefore, we derived in Chapter 3 two main dimensions that define EMS application types. The first dimension is the *Action <> Perception*, which is based on our proposed theoretical relation describing the interaction via EMS. The second dimension is the *Augmentation <> Induction*, which describes the main purpose of an EMS application.

In this part, we focus on the applications that augment the user. To be exact, the applications presented here focus on enhancing the experience relevant to an anticipated influence of receiving the EMS feedback. If the user stopped voluntarily executing the action, the targeted influence of the EMS would change. We explore three different scenarios across the *Action <> Perception* dimension (cf., Figure 4.8). In the first scenario, we target mainly perception influence, where we manipulate the users' weight perception of a dumbbell curl in VR. In the second scenario, we target influencing users' actions by improving their putting performance in the golf sport. In some cases, as described in our model, the action and perception are clearly linked. Thus, any action carried out by the users would impact their perception as well. In the last scenario, we explore a use case where action and perception overlap.

Chapter 5

Manipulating Weight Perception in VR

This chapter is based on the following publication: Faltaous, S., Prochazka, M., Auda, J., Keppel, J., Wittig, N., Gruenefeld, U. & Schneegass, S. (2022, September). Give Weight to VR: Manipulating Users' Perception of Weight in Virtual Reality with Electric Muscle Stimulation. Mensch und Computer 2022 (MuC '22).

The first application is manipulating weight perception in Virtual Reality (VR). In our taxonomy, this application belongs to the *perception augmentation* category as the perception manipulation could only happen when the user is experiencing the weight lifting. Nowadays, VR environments provide a rich visual and auditory experience. Providing a rich haptic experience, however, is still challenging. This is amplified by the current trend towards direct interaction using hand tracking instead of the VR controller. Direct interaction has the advantage that it allows for more natural input such as grabbing or pushing of objects. However, currently, users receive no haptic feedback.

Researchers investigate new ways of providing haptic feedback for direct interaction. This can be either passive haptics [159, 19, 269] or active haptics (e.g., using robots [148] or drones [162, 18]). Each of these approaches has

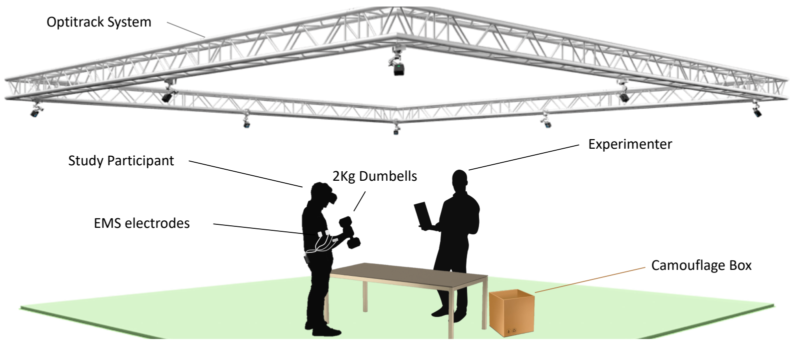


Figure 5.1: Study setup showing the tracking system (i.e., Optitrack) used to map the real to the virtual world. The participant with electrical muscle stimulation pads on the targeted muscles. The Camouflage box creates the illusion of having multiple weights. The experimenter logged in all the feedback mentioned by the participant.

its own advantages and disadvantages. While drones and robots are rather expensive, passive haptics is more limited in terms of their flexibility: a passive haptic object can be used to generate haptic feedback for its virtual counterpart. Researchers, however, start addressing this limitation. Haptic retargeting, for example, allows the users to reuse the same physical object for multiple virtual ones by providing visual illusions [19]. Other extensions explore how well the passive haptic approach works for different sizes [16]. Another approach that can be used to provide haptic feedback throughout a direct interaction is using EMS. EMS mimics the brain's signals to the muscles by inducing a current that results in a muscle contraction and subsequently a movement of a part of the body [364]. Research showed that this technology can be used to generate haptics out of the void in VR [254].

Contribution In this chapter, we focus on extending this approach to the objects' weight. We particularly look into how we can change the weight perception of users using EMS. In contrast to earlier work, we combine EMS with the passive haptics approach to change the weight perception of the user. Thus, we do not aim to generate a weight sensation but change the weight perception, that is, creating virtual objects that are perceived as lighter or heavier than their actual physical counterparts. We compared the effect of actuating four different muscles in a laboratory study ($N = 10$). We found that particularly the biceps brachii, as well as the triceps brachii, muscles allow increasing the perceived weight.

5.1 Background and Related Work

In this section, we explore previous work on how weight could be perceived and manipulated within a VR environment and how EMS can be used to manipulate a user's perception.

5.1.1 Haptics and Weight Perception in VR

Since it is not feasible to provide objects of a large range of weights within VR applications, researchers investigate methods to manipulate the weight perception of objects in VR [297, 349, 254]. Niiyama et al. created an object containing liquid metal that can be pumped in or out of it [297]. Therefore, the object is capable of representing different weights dynamically. Other systems provide kinesthetic perceptions, like Zenner and Krüger's weight-shifting VR controller [443]. This system uses a rod with weights inside that can shift positions from the grip to the end to change the center of mass and change the perception of weight. Further weight-shifting devices like a controller that can be reconfigured dynamically to create various distributions of mass are explored. The controller presented by Shigeyama et al. uses different configurations to imitate the feeling of holding objects in VR [374]. Additional approaches utilize haptic devices using integrated weights. When shaking the device implemented by Yamamoto et al., the user senses the inertial force as the weight of the device as the accelerated weight inside is moving [436]. Gravity provides a weight illusion using vibrotactile feedback, uni-directional brakes, and asymmetric skin stretch [51]. Archibet et al. create haptic feedback in VR using an elastic band. The band is attached to the shoulder of the user and provides feedback through resistance [4, 3]. Zenner and Krüger present a controller allowing to change of the air resistance to create the illusion of weight when dragging objects [444]. Aero-plane system renders weight changes on a plane (e.g., a baking pan) using jet propellers [178].

Besides the physical weight of an object, other aspects such as cutaneous and proprioception feedback also influence the perception of weight [120]. Another possibility is that instead of creating weight through real weights and forces visual and haptic stimuli can simulate weight in a virtual way that the user's brain interprets as the weight of an object as the overall perception is assembled from various senses [81]. Following this path, the idea arises that this effect could be even stronger in VR due to higher immersion and, therefore, more perceived spatial and sensory presence [30].

Rietzler et al. implemented a software-based approach to weight perception based on an offset. In their approach, they nudged the users to raise their arms in the real environment higher than in VR, which increased the perceived weight of the held objects [349]. In further work, visual cues are exploited to create an illusion of weight through a mismatch between the virtual hand of an avatar and the position of the user's real hand. When the user pushed a moveable object, the virtual hand stops while the user's hand was moving beyond the virtual object in the physical space, creating a perception of resistance [348]. Jauregui et al. manipulated the weight perception of a user by using a virtual avatar that is altered according to prerecorded animations using motion capture [177]. Amplifying the movement of an object's virtual representation on screen also creates a haptic illusion, in which the users perceive the weight of the moving object to be less [67]. Similarly, Pusch et al. simulated wind resistance in VR by hand displacement [337, 338].

Previous work mainly focused either on changing the physical weight of objects and applying forces or tried to manipulate the user's weight perception through other senses. While the former is bound to complex hardware devices, the latter creates illusions usually based on a displacement of the virtual representation. Our work uses EMS as a promising approach since it can be used to directly influence the user's proprioception.

5.1.2 Perception Manipulation in VR using EMS

The communication between the human brain and the muscles in the body is functioning via electrical signals. If a signal reaches the nerve endings inside a muscle, it actuates the corresponding muscle causing a contraction that induces movement. The intensity of the electrical signal determines the force the muscle contracts with while still being limited to the muscle's capabilities [57]. Luigi Galvani already observed in the 18th century that besides this natural way of actuation the stimulus' origin can be external [330]. By applying an electric current from the outside, the brain's electrical signals can be roughly mimicked. This can be achieved by electrodes that are attached to the skin since the muscle cannot distinguish between these signals and reacts to both currents with contraction and as a consequence with body movement. Using EMS, the body parts are moved by the user's muscles themselves instead of being externally moved. Since humans possess *"the sensation of the body position and movement"* [407], which is called proprioception, EMS even provides feedback beyond the apparent movement of the body parts.

While we reviewed numerous approaches to manipulate the weight perception in VR physically using hardware prototypes or virtually through the influence of other senses, EMS is less used to manipulate perception in VR so far. Auda et al. presented an approach to counteract the mismatch between physical and virtual space, creating infinite walking in VR using EMS [17]. Further, Khamis et al. created ElectroCutscenes which shows users video game cut scenes in VR, where the user embodies an avatar in the scene. Using EMS, the arms of the users are being manipulated to the positions corresponding to the avatar during the scene [197]. For the domain of weight perception manipulation in VR, Lopes et al. proposed an implementation using EMS. They explored how EMS and VR can be combined by presenting a widget set for games that provides haptics to virtual objects [254]. This also includes widgets that add weight to virtual objects when the user pushes, pulls, or lifts them.

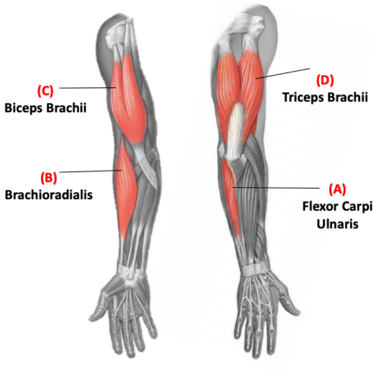
In contrast to previous work that generated a weight perception using EMS, we focus on how to change the weight of a physical item that already has a physical weight. Thus, we do not aim at creating a weight sensation out of the void but always use a physical item with its own weight.

5.2 Implementation

In this chapter, as previously mentioned, we aim to explore the use of EMS to manipulate weight perception. Therefore, as the first step in our approach, we highlight our choice of the tested scenario and our implementation.

5.2.1 Scenario and Muscle Selection

There are many types of manual lifting each of which engages certain muscles and body parts. For example, in powerlifting, the thighs, as well as the arm muscles, are involved. As a first step, to exploring the potential of using EMS to manipulate weight perception, we focus on a simple dumbbell biceps curl (DBC) as a scenario. We chose this scenario because dumbbells can be easily grabbed and the weight can also be changed. DBC are mainly performed to train the biceps brachii, brachialis and brachioradialis muscles [261] (cf., Figure 5.2 (left)). Since both the biceps brachii and brachialis are located in the upper arm, we picked the biceps brachii muscle from the upper arm and the brachioradialis muscle from the forearm. Also, depending on how the lifting action is done, the flexor carpi ulnaris muscle gets contracts in



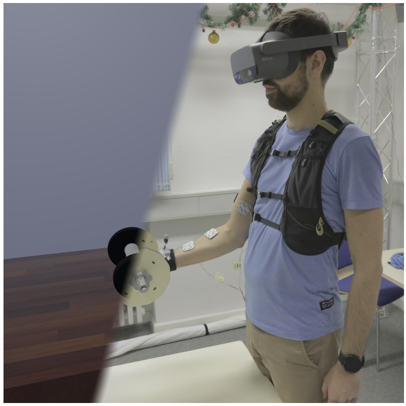


Figure 5.2: Left: the arm anatomy for the ventral and dorsal sides, showing the actuated muscles in our study; flexor carpi ulnaris (A) and brachioradialis (B) from the forearm and biceps brachii (C) and triceps brachii (D) from the upper arm. Image source: [262]. **Right:** side view of a participant carrying the dumbbell in the VR while having the electrodes mounted in reality. In our study, the VR is displayed using an Oculus Quest (scene posed for the picture, using a different VR headset).

case of a wrist movement (e.g., when the hand turns inwards) [222]. While executing a biceps curl, the biceps muscle experience eccentric and concentric contractions [305]. In the eccentric contraction the triceps muscle, being the biceps antagonist, contracts [402]. Taking into account these facts and to have preliminary insights into which muscle would best alter the weight perception, we targeted the flexor carpi ulnaris (A) and brachioradialis (B) from the forearm and biceps brachii (C) and triceps brachii (D) from the upper arm (cf., Figure 5.2 (left)).

5.2.2 Apparatus and Setup

We prepared a 4x4 meter tracking space (cf., Figure 8.1) with a table (50*100 cm) and a dumbbell (2 kg – as passive haptics) in the middle. In order to create the feeling that the dumbbells would be exchanged with different weights, we had a closed box placed next to the table where both the experimenter and the participant would be standing. This box is clearly visible to the participants when they first enter the room. We told the participants that the experimenter would be changing the dumbbell after each condition. The box contained other weights and objects but those were never used, the mere purpose of their presence was to create an illusion of manipulating the physical weight (cf., Figure 5.1).

Furthermore, we implemented a virtual environment that would be displayed using an Oculus Quest head-mounted display showing the same scene. Thus, the environment includes the same table (e.g., size, height) and the same dumbbell (e.g., width, handle thickness). We used an OptiTrack 13W optical tracking system to track the dumbbell, table, and the user´s hand using rigid bodies (cf., Figure 5.2 (right)) to link the passive haptics and virtual environment. We also show a virtual hand where the user´s hand is to ease picking up the dumbbell. As soon as the user approaches the dumbbell, we fade out the virtual hand and start a countdown. After three seconds, a virtual shadow (30% opacity) of the dumbbell starts slowly moving upwards to provide direction and velocity cues to the user.

Additionally, we implemented a control application that connects to the Let Your Body Move toolkit [318] that was placed with two EMS signal generators (Beurer Sanitas SEM 43 Digital EMS/TENS[16]) in a small backpack (see Figure 5.2 (right)). The control application sends EMS feedback via the let your body move toolkit. It controls the signal intensity and frequency that is sent to the targeted muscle. As soon as the user lifts the dumbbell from the table the EMS signal is applied to the user and stops when the user has returned the dumbbell on the table again after completing a DBC.

5.3 Evaluation

We conduct a user study to investigate how far EMS can enrich the haptic experience provided by passive haptics. In particular, we investigate the use of EMS to manipulate the perceived weight of passive haptics to adjust it to differently heavy objects. We strive to understand what muscles need to be actuated and what differences in weight can we achieve.

5.3.1 User Study Design

We conducted a within-subject study with the muscle (4 level: flexor carpi ulnaris (muscle *A*), brachioradialis (muscle *B*), biceps brachii (muscle *C*), and triceps brachii (muscle *D*)) as independent variable. As a dependent

[16] `https://sanitas-online.de/de/p/sem-43-digital-ems-tens/`

variable, we use self-reported feedback using 7-point Likert items regarding the perceived weight, the perceived intensity of the actuation, and the perceived comfort rating of the actuation.

5.3.2 Participants and Procedure

We invited 10 participants to our lab aged 20 to 59 years old ($Md = 29.5$ years, $SD = 12.5$ years). Three participants self-identified as female and seven as male. After the participants arrived in the lab, we explained the purpose of the study and asked for their written consent, following our institutional ethical procedure. We explained the basic functionality of EMS and checked that they met the prerequisites as stated in the manual of the EMS signal generator. Next, we asked the participants to fill in a brief demographics questionnaire stating their age, and gender. To remind the participants throughout the study of the positions of the electrodes, we marked a mannequin arm with the muscles labels: A, B, C, and D. We then calibrated all four muscles using the EMS system. We started at a low intensity of 3µA and increased with a step of 2µA until an actuation happened. As soon as the actuation is clear (i.e., through an observed movement), we stopped the calibration process and noted the specific value.

Next, we started the actual study in which we presented 2 dumbbells one after the other to the user. The user lifted each dumbbell once. While lifting, we actuated either one of the four muscles or none as a baseline. After a dumbbell was lifted, we removed it from the table and tracking space and put it back onto the table. Overall, they lifted two times ten dumbbells, thus, each muscle got actuated four times. The experimenter was noting down throughout the whole study the indications mentioned by the participant as well as any comments. In the end, the participants filled in a questionnaire that included questions regarding weight perception, actuation intensity, and comfort level using 7 points Likert item and a text field question. The questionnaire contained each question four times – one per muscle.

5.4 Results

Overall, we had two question categories; text fields and Likert items. For the Likert items, we substituted each item with a number to be able to quantify it.

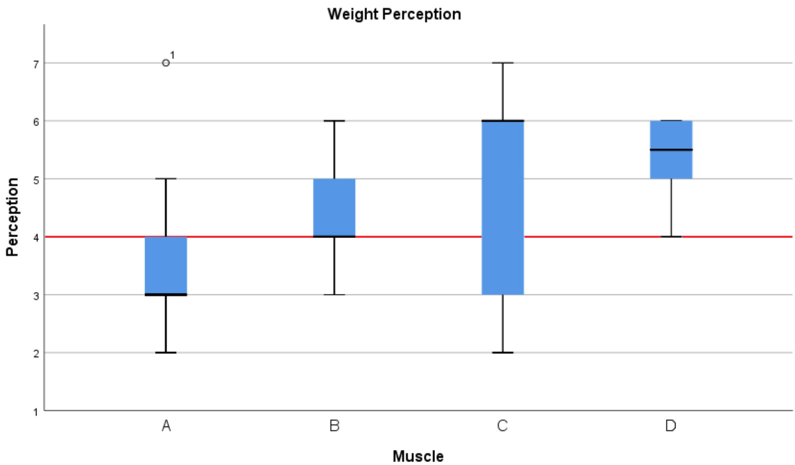


Figure 5.3: Weight perception ratings on 7-point Likert items (1:decreased weight; 4:no influence; 7:increased weight). The red line indicates no change in weight perception.

5.4.1 Weight Perception Ratings

Figure 6.5 provides an overview of the weight perception ratings on 7-point Likert items (1:decreased weight; 4:no influence on weight perception; 7:increased weight). The results show that actuating muscle A ($Md = 3$, $SD = 1.2$) reduces the perceived weight whereas muscle B ($Md = 4$, $SD = 1.0$), muscle C ($Md = 6$, $SD = 1.7$) and muscle D ($Md = 5.5$, $SD = 0.66$) increase the perceived weight. A Friedman test shows statistically significant differences in the ratings, $\chi^2(3) = 8.935$, $p = .030$. Bonferroni corrected pairwise comparisons using Wilcoxon Signed Rank tests show that participants rated the perceived weight statistically significant higher for muscle D ($Md = 5.5$, $SD = 0.66$) compared to muscle A ($Md = 3$, $SD = 1.2$), $Z = -2.642$, $p = .048$. All other comparisons could not reveal statistically significant differences ($p > .05$).

Concerning how often they train each of the four muscles (i.e., 1:Never, 2: rarely, 3:Monthly, 4:weekly, 5:Daily), the most trained muscle was B ($Md = 4.5$, $SD = 1.7$) followed by C ($Md = 4$, $SD = 1.4$) then D ($Md = 3.5$, $SD = 1.5$) and A as the least trained muscle ($Md = 2.5$, $SD = 1.5$). Except for two participants (i.e., P6 and P7) who often trained specific muscles, the participants were confused about what could be considered as training, indicating that some daily activities like shopping are the maximum training they do.

5.4.2 Intensity Rating

Asked about the intensity of the actuation, we found that participants rated muscle C ($Md = 6$, $SD = 1.0$) to have the most intense actuation, followed by muscle D ($Md = 4.5$, $SD = 1.5$) then muscle A ($Md = 4$, $SD = 1.7$) and muscle B ($Md = 3$, $SD = 1.1$). A Friedman test shows statistically significant differences in the ratings, $\chi^2(3) = 14.362$, $p = .002$. Bonferroni corrected pairwise comparisons using Wilcoxon Signed Rank tests show that participants rated the actuation intensity statistically significantly higher for muscle C compared to muscle B, $Z = -2,825$, $p = .048$. All other comparisons could not reveal statistically significant differences ($p > .05$). Next, we explored the influence of intensity on weight perception. We found a positive correlation between actuation intensity and weight perception, showing that a more intense actuation is related to a perception of a higher weight, $r(38) = .353$, $p = .026$.

5.4.3 Comfortable Rating

Asked about the level of comfort, participants rated an actuation of muscle B ($Md = 5$, $SD = 1.5$) most comfortable, followed by muscle D ($Md = 4$, $SD = 1.4$), muscle C ($Md = 4$, $SD = 1.9$), and muscle A ($Md = 3.5$, $SD = 1.6$). A Friedman test could not show statistically significant differences in the ratings, $\chi^2(3) = 4.330$, $p = .228$. Last we investigated if a more comfortable actuation influences weight perception. A Spearman correlation could not reveal a significant relationship, $r(38) = .141$, $p = .385$.

5.4.4 Qualitative Feedback

Following, we report on the qualitative feedback we gathered during the study. Concerning the best weight perception participants rated the muscles differently with some of them segmenting the movement into start, middle, and end. P1 described that muscle *A* is *"strong at the lift and then decrease"* while muscle *"D [is] not strong at the start but strong when the arm is at 90 degrees."* Similar observations were noted by P2, P3, P8, P9, and P10. As they all differentiated their experience from the *beginning* to the point where their perception state changed let it be in the *"motion"*[P9] or at the end of the movement.

When asked about which actuated muscle felt natural, there was no conclusive reply. Three of the participants (P2, P3, and P4) mentioned that the feeling was not always natural as it doesn't *resist*[P4] the movement or induce a *"tingling"* feeling[P4]. Two participants reflected in general by describing the experience as *"very real"*[P9] and *"contributed to the immersion"*[P1]. The rest linked their weight perception to specific resulted movements like *"muscle B ...maintaining the natural shape of the hand"*[P5] while carrying the dumbbell, their own expectation of the system of making the weight *"heavier"*[P6].

When asked about their experience during the actuation they described as it as *"tingling"*[P2,P4], *uncomfortable* [P2,P8] and *moving arms after sleeping*[P7]. On one side, with the bigger part of them (N=6) describing it with no effect on the immersion in the VR with one describing it as *"surprisingly convincing"*[P1], two of them described it as *distraction*[P10] and *scary*[P6] linking that to the novelty effect. P5 also described the novelty aspect throughout the experience as she said that *"at the beginning, you feel it but then you become part of it"*. On the other side, two participants (P2 and P7) linked their level of immersion to the more comfortable actuation as for example P2 describing that *"muscle A and B were okay because not so strong"* and P7 *"muscle C... was too much"*.

5.5 Discussion

Our results provide preliminary insights into weight manipulation using EMS. They show that using EMS is not only confined to changing actions [17] or communicating haptics feedback in VR [254] but also could be used to manipulate the perception of the weight of passive haptics.

Targeted Muscle Although the muscle mass is different from one person to the other, changing the users' perception of the weight was possible through the different muscle positions. In our work, the participants did not have to specify a certain weight but they only had to indicate with respect to the baseline, whether the weight was heavier or lighter. For that, the participants indicated the biceps brachii (muscle *C*) induced the heaviest weight. This is in line with the literature stating that the muscle strength that influences the movement in the joint most is generated through the biceps brachii (muscle *C*) [44]. This is also the case for the dumbbell biceps curl scenario we used in the study [261]. However, the biceps brachii also resulted in the highest variance in weight perception with three participants also indicating that they perceived the weight actually lighter compared to the baseline. This indicates that instead of providing the sensation of an additional force applied to the arm, the actuation rather supported the lifting and, thus, it felt lighter. In contrast, we were able to change the weight perception by actuating the triceps brachii (muscle *D*) more consistently. All participants argued that the weight felt heavier. Along the same line, the triceps is the biggest muscle in the arm (i.e., length-wise) and the biceps antagonist [180] that contracts when we extend the arm at the elbow, it induced the second heaviest weight perception. We, therefore, conclude that in order to induce the heaviest weight perception, the biggest muscle connected to the moving joint should be targeted.

Real-life Movement Dynamics Furthermore, as indicated by our participants, the actuation should not be focused the whole time on one muscle. However, it has to be adapted to the movement. Again reflecting on the explored movement (i.e., DBC), the most two actuated muscles were biceps brachii (muscle *C*) and triceps brachii (muscle *D*). However, they do not contract simultaneously but rather depend on the direction of the forearm, where the biceps brachii (muscle *C*) contracts in the upwards lifting movement and the triceps brachii (muscle *D*) contracts in the downwards movement. Therefore, we recommend segmenting the targeted movement and actuating the contracted muscle at each part of the movement.

Overall, we could not observe a pattern in the results linking the signal intensity perception to the comfort level, however, the participants indicated in their comments that the feeling of discomfort was linked to the feeling that the signal had its peaks of being *"too much"*[P7]. We, therefore, recommend using this approach for lightweight inducing.

Limitations We acknowledge the following limitations to our study. To start, we focused only on the weight perception of the participants, without reflecting on their performance under the different conditions (i.e., maximum joint angle). Therefore, we plan to explore the participants' performance under different conditions. Second, we only investigated a single scenario. While the scenario provides a clear foundation for investigating weight perception, other scenarios with different interactions need to be investigated. Furthermore, our approach only influenced the increase in weight.

5.6 Conclusion

In this chapter, we explore the use of electrical muscle stimulation to manipulate the weight perception of objects in virtual reality. We conducted a user study (N=10) in which participants perform dumbbell biceps curls while being actuated with EMS. We actuated four different muscles that based on the physiological background are linked to the arm movements. We found that actuating the biceps brachii and triceps brachii influences weight perception most. Both muscles are well suited to change the perception of weight. We conclude that EMS can be well used to change weight perception. While actuating a single muscle already yields good results, combining different muscles in different parts of the movement seems to be a promising direction for future research.

Chapter 6

Improving Motor Skill Execution

This chapter is based on the following publication:
Faltaous, S., Abdulmaksoud, A., Kempe, M., Alt, F., and Schneegass, S.. "GeniePutt: Augmenting human motor skills through electrical muscle stimulation" it - Information Technology, vol. 63, no. 3, 2021.

In this chapter, we proceed by exploring an action augmentation application, where we implemented a system that would improve the users' performance in executing a specific motor skill. Humans use motor skills for almost any task they perform in daily life. Walking and grasping objects are just two basic examples of motor skills that we master from early childhood [377]. Throughout life, we acquire different types of motor skills [286], for example, discrete motor skills, such as standing, aiming, and throwing a ball as well as serial motor skills, such as dancing, doing sports, or playing an instrument. Traditionally, we learn these skills by observing an instructor demonstrate them. We then try to mimic the exact behavior, thus adding a new skill to our repertoire [163]. Research showed that people improving a skill based on observing the outcome (external focus) can more quickly adjust their movement later on, compared to people who improved a skill by focusing on the movement itself (internal focus) [435].

Figure 6.1: A user testing GeniePutt in a mini-golf scenario. The EMS system supports the user by turning the wrist so that the club faces the target.

In this chapter, we explore how we can use wearable technology to augment human motor skills and, thus, improve motor control. In contrast to the common way of improving motor skills through training, we augment the learning process with computing technology. Computing technology has been used to provide feedback through projection to the user based on their performance [219]. While providing a feedback channel (i.e., auditory or visual) can help users reanalyze their motor skills and, thus, improve them, we provide an embodied way of supporting improvement. To achieve this, we use electrical muscle stimulation (EMS) [364]. EMS allows the movement of the user's limbs to be manipulated, which we exploit to let the user perform a specific movement. Thus, the user automatically performs the movement in a way defined by a computer. To test our approach, we use a mini-golf scenario in which the rotation of the club is controlled by a computer. We conducted a user study to analyze how our approach improves accuracy. To do so, we use a tracking system. We show that augmenting motor skills provides a benefit to users, particularly, if they did not master the skill before.

Contribution The contribution of this chapter is twofold. First, we present *GeniePutt*, a system that improves motor skill performance in mini-golf putting. Second, we report on a user study evaluating GeniePutt by comparing participants' performance while playing mini-golf on their own with being supported by GeniePutt (augmented) and with being fully controlled by GeniePutt.

6.1 Background and Related Work

One of the human brain's functions is to control various muscles across the human body to generate motion. Part of these movements is known as motor skills, which are movements elicited by the human as a result of perception-action coupling leading to a known action [430, 406]. There are different categories of motor skill learning [430]. Wolpert et al. [429] suggest that some are not unitary experiences (e.g., tennis games), but rather divided into four main sub-processes: (1) gathering sensory information (i.e., sensory input guided by previous experience), (2) learning key features of the task, (3) setting different classes of control and anticipating, and, (4) countering the opponent's strategy. Applying these sub-processes to a mini-golf game, only the first two points would be of relevance, as the last two are more concerned with games that need fast interceptive reactions (e.g., basketball). Our work aims at (2), improving the learning of the key features of a task.

6.1.1 Brain Muscle Interaction

Motor skills are controlled mainly by the motor neurons which are present in the neural cells [382]. They are initiated in the primary motor cortex M1 [404] and communicated to the body through electrical signals transmitted via the spinal cord to the muscles across our body [382]. Whenever these signals target certain muscles, they control the direction to which we perform a movement [404]. They can also manipulate the muscle stiffness by varying the signal intensities which in its turn regulate the muscle force [57]. In the 18th century, Luigi Galvani discovered that externally induced electrical signals would actuate the muscles, laying also the foundation of research in HCI [364]. Ever since Electrical Muscle Stimulation (EMS) has been heavily investigated in various fields. Hence, in this study as a bottom-up approach, we are investigating the effect of using EMS on learning and improving new motor skills.

6.1.2 Electrical Muscle Stimulation

One application of EMS is implicitly controlling the user while performing a specific task. Examples include the work of Lopes et al., who communicate the affordances of everyday objects to the user and let them perform certain movements to use such objects as intended (e.g., shaking a spray can) [250]. Similarly, Pfeiffer et al. use EMS to control the walking direction of users [319], as they rotate the leg to let the users either turn right or left. Other researchers examined the possibility of using EMS to either control the foot strike posture in running [144] or control the maximum contraction of upper limb muscles by actuating facial muscles [289].

Another research direction is more focused on improving the users' cognitive abilities. Kasahara shows how EMS can accelerate the users' reaction time [185]. Similarly, Lopes et al. used EMS to control users' hand movement to improve their technical drawing capabilities (e.g., wind tunnel results) through calculations performed by computers [253].

We build upon this work and explore how good the combination of user and actuation system is. Further, we investigate how externally controlling the human body would augment human performance.

6.2 GeniePutt Implementation

Motor skill improvement systems currently provide feedback on the performance to the user. In professional sports, players analyze their motor skills by watching a video recording and discussing their decisions and movements with coaches. They then need to correct their performed action to improve the execution of a certain motor skill.

Interactive computing technology is already capable of providing feedback in real time. For example, Kosmalla et al. grant real-time feedback on users' posture while slack lining [219]. They show an avatar of the user to help improve the posture. Similarly, climbers can correct their posture [218].

The main idea of our work is to automatically augment the users' motor skills rather than provide feedback on their performance. We rely on the effect of proprioception on motor learning, which was investigated initially by Adams et al. [5] and recently in more detail in several studies [137, 56, 431].

Early research showed that proprioception provides sensory input, affecting the perception of body position and movement [372]. We leverage this effect using EMS as the relation between proprioception and EMS was shown in previous work [249]. In particular, EMS triggers the motor movement of the user by mimicking the signals that are normally generated by the human brain based on users' cognition.

We envision two different forms of support through EMS. First, EMS takes over full control of the user's body and performs the movement completely. Throughout this chapter, we refer to this as *actuation*. Second, EMS works in combination with the user. According to Galati et al. [114], humans need multi-modal sensory inputs to execute fine movements. Therefore, users are actuated by EMS and are additionally capable of influencing motion based on their visual perception. In contrast to actuation, in this condition, they receive additional input from the visual sensory information. As subsequently motor skills as augmented, we refer to this mode as *augmentation*.

6.2.1 Mini-Golf Application Scenario

To explore the idea of improving motor skills, we first explored different scenarios. Given the current state of the art of EMS actuation, we chose a scenario that requires users to perform a motor skill with a small number of actuated muscles. For that, we decided on a mini-golf scenario, where we constructed a playing field in a closed room, in which the target, the golf club head, and the putt could be tracked.

The objective is to make the user adjust the clubface so that when the ball is hit, it moves in a straight line to the target. For this, we needed to actuate and adjust the angle of the user's hands prior to hitting the ball. We achieve this by actuating the pronator quadratus muscle of the user. This muscle is used to rotate the hand and, thus, the angle of the clubface. The targeted angle is computed so that it aligns with the center of the goal.

As a first step for gaining insights into the relation between an actuated performance and that of collaborative performance between the human and the computer. We focused on controlling the angle of the clubface at contact.

Research in the biomechanical field has been done to explore the effect of a golf swing and, hence, a golfer's skill on hitting a golf ball into a small hole with a minimal number of shots [170]. The golfers' performance can thus be measured either directly (i.e., ball movement and shot accuracy assessment) or indirectly (i.e., measuring club head velocity and clubface angle at contact) [196].

6.2.2 EMS Control Hardware

We therefore present GeniePutt, a system composed of a wearable EMS control hardware, a training loop, and a learning algorithm. We used the *Let Your Body Move* toolkit [318], consisting of an Arduino nano with control software and Bluetooth module. The toolkit has a wired connection to a signal generator

Figure 6.2: Anterior forearm showing the pronator quadratus, the actuated muscle that leads to the rotation of the hand (image: `https://www.kenhub.com/de/library/anatomie/musculus-pronator-quadratus`).

and self-adhesive electrodes that are attached to the user's muscle. An Android application communicate the system's output to the toolkit via Bluetooth.

6.2.3 Training and Learning Algorithm

We used an OptiTrack a system that sends its tracking data to a PC via UDP. An actual physical golf club and a golf ball were used. Three markers were mounted on the club to indicate the orientation of the head. The target was marked with a triangle-shaped marker. The target and the club markers were enough to indicate the angle to which the player should aim. We tracked the angle between the center of the club and the target center. This allowed the system to apply EMS feedback for correction.

We use a genetic algorithm to calibrate the EMS signal given the limited data points and variance of the data available, due to the user dependence of EMS. For implementing the algorithm, we used the Jenetics library [17]. First, we define a function that takes the current angle between club and goal as input and provides an EMS actuation as output. We then generate random sets of parameters that define a certain actuation. These sets of parameters are evaluated and the best ones are selected (i.e., the ones resulting in the best actuation). The selected parameters are now used to generate new parameters that slightly differ from the ones that performed best. This set is again evaluated

[17] `https://jenetics.io/`

and the parameters performing best are selected. This process is repeated until certain goodness is achieved. Thus, the values is optimized for each user

Population Generation The process starts by generating a random set of solutions to the targeted problem, each solution is called an individual. A group of individuals forms what is known as a population. An individual is defined through a set of variables so-called genes. Each gene is represented usually in a binary form (i.e., 0 or 1) Multiple genes are then attached together to form a string named chromosome, and several chromosomes are the representational form of an individual (i.e., solution).

In our work, each solution has 2 chromosomes: the intensity of the signal and the duration of the signal. Furthermore, each chromosome has constraints. In our case, the chromosome that represents the intensity is limited to a certain range of values that does not go below the value that starts actuating the hand of the participant and is lower than the pain threshold of the participant. After having both values of the participant from the calibration process (cf., Section 6.3.2), these values are used to set the minimum and maximum values of the chromosome representing the intensity of the signal. Also, the chromosome that represents the duration of the signal has constraints (i.e., by trial it is between 900 milliseconds and 1300 milliseconds).

Evaluation for Fitness To be able to decide which individual (i.e., solution) is the best one, a fitness function is used to set a fitness value for each individual. The fitness function is context-relevant, which compares the individual performance with that of the most optimal targeted value within a certain problem. The higher the fitness value resulting from a fitness function, the higher the probability that it would be used for reproduction.

The fitness value in our work is based on the best results obtained from the tracking system by measuring the angle between the golf club and the goal. That is the angle confined between the vector representing the club base and the vector joining the projection of the centroid of the club and the goal tip point (see Figure 6.4). We defined the optimal angle as 90°. Thus, angles in the range between 70°and 110°are considered acceptable. Angles that equal exactly 70°and 110°were given fitness values of 50. Angles greater than 70°to 90°were given fitness value proportional to how near they approach 90°(i.e., the optimal value). The values are calculated by the Equation 6.1 (e.g, angle = 80°was given fitness value $100-(90-80)\times 2.5 = 75$) and Equation 6.2 (e.g., angle 100°was given fitness value $(110-100)\times 2.5+50 = 75$). This process was done once for the dominant arm and once for the non-dominant arm.

$$Fitnessvalue = 100 - (90 - angle) \times 2.5, 70 < angle < 90 \tag{6.1}$$

$$Fitnessvalue = (110 - angle) \times 2.5 + 50, 90 < angle < 110 \tag{6.2}$$

Selection The idea behind the selection stage is to choose the best genes to be passed on to the next generation of the population. Therefore, the fitness value of all the individuals of a population is compared, the two individuals of the highest fitness values are then used for reproduction, and hence called parents. The Jenetics library has many types of selectors. For the survivor selector and the offspring selector, a Tournament Selector is used. The Tournament Selector, as the name implies, imitates tournaments so that the individual of the worst fitness value never survives, and the individual of the best fitness value always survives.

Recombination and Mutation In order for two parents to reproduce a new child (i.e., individual) a mating process known as variation is used. While there are two types of variations (i.e., recombination and mutation), one is used before the other. The first one is recombination, where a random crossover point is chosen in the binary form of the two parents. An offspring (i.e., child) is then generated by exchanging the two genes-sets separated by the crossover point. Afterward, a mutation process is applied, where according to a probability that we predefined, one or multiple bits (i.e., those in the genes) are flipped in the new offspring. The main aim of the mutation process is to expand the diversity of individuals for exploration. Each new child is then added as an individual to the population. Given a constant number of individuals in a population, the fitness values are re-evaluated and the ones with the least fitness values are eliminated.

Termination Each new set of individuals (i.e., children) is considered a new generation. The algorithm keeps producing new generations till the difference computed between the parents and the children is no more significant. Meaning, the fitness values of the children and the parents both reach a certain preset threshold. Applying this in our case means that the actuation signal parameters remain almost constant.

6.3 Evaluation

The goal of this lab study is to evaluate the idea of improving motor skills through EMS. We set up a mini-golf course within our lab that allows for

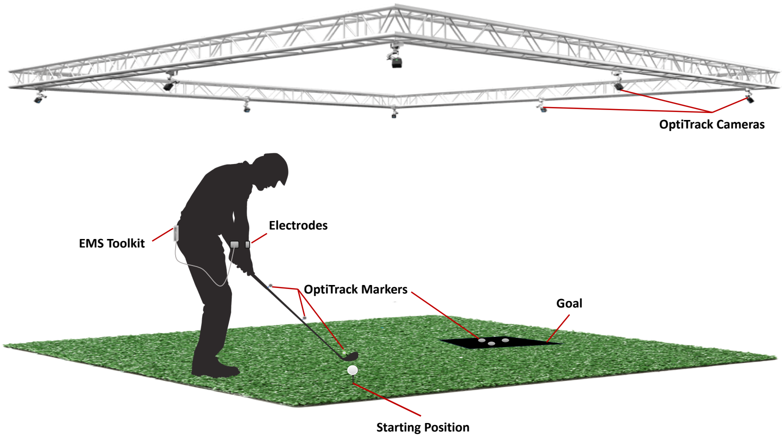


Figure 6.3: Setup of the user study. The participant is standing within the OptiTrack tracking space holding the club and EMS electrodes attached to the arm.

simple putting tasks. We deliberately started with a non-complex example to examine the overall feasibility of this approach.

6.3.1 User Study Design

We designed the study as a repeated-measures experiment. The independent variable is the actuation level that was either none (i.e., free condition), augmented, or (fully) actuated. For the actuation, we blindfolded participants so that they could not visually perceive the stimuli and, thus, fully relied on the actuation. For each condition, participants performed a putting action 10 times. As a dependent variable, we measured the deviation angle from the target.

6.3.2 Participants and Procedure

We invited 12 participants (11 males, 1 female) aged between 21 and 50 ($\mu = 26$, $\sigma = 7.97$) via University mailing lists and personal contacts. None played mini-golf or golf regularly. As participants arrived at the lab, we explained the overall purpose of the study and the EMS system. The study met the ethics regulations of our institution. We particularly explained the safety regulations of the EMS signal generator and made sure that participants understood them. After filling in a consent form, we first showed the basic functionality of the EMS system on the participant's wrist. Our study consisted of 3 main sessions, namely, the calibration, the training, and the testing sessions. The overall study duration was approximately two hours.

Calibration We started with the calibration session, in which, we depended mainly on visually observing the inward rotation of the hand as a result of inducing the electrical signal. We started with the dominant hand followed by the non-dominant hand. For each participant, we started the calibration phase with 5 µA and increase it with a step of 2 µA. The highest intensity value of each hand is then considered for the training part. We found a high variety in actuation possibilities so that for some participants, a two-handed rotation and for others a one-handed rotation performed well.

Training In the training session, we asked participants to hold the golf club with both hands. The evolutionary algorithm then controls the intensity and duration of the signal. Using the OptiTrack, the angle between the clubface vector joining the centroid of the club projection and the tipping point of the target is measured. Based on this angle, the fitness value of the individual for the evolutionary algorithm is determined. The learning algorithm is then executed twice. The first time, it runs on the dominant hand, using a starting position of the club baseline parallel to the line joining between the goal triangle base points. The values (i.e., intensity and duration of the signal) produced from the first run are used to set the initial rotation of the dominant hand to rotate the club in the second run.

The communication works as follows: the command is sent to the LYBM toolkit, waiting for the duration of the signal that is induced. The OptiTrack records frames for 1 second and angle calculations are performed. Then, participants move their hands back to the initial position. The second time it runs on the non-dominant hand, starting from the same starting position as in the first run. A signal is produced to rotate the dominant hand with the best values produced from the first run and then the evolutionary algorithm tries a value on the non-dominant hand.

Participants then performed ten shots in each condition, separated by 2 *mins* breaks. We randomized all presented conditions. In each condition, we video-recorded all shots from a top view, which we later used for the analysis.

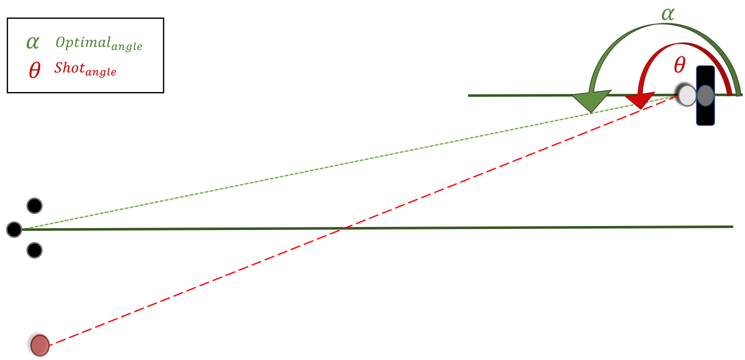


Figure 6.4: Graphical representation of the setup, where the α angle represents the optimum angle from the starting position till the goal. The θ represents an example of an actual shot deviating from the optimal angle.

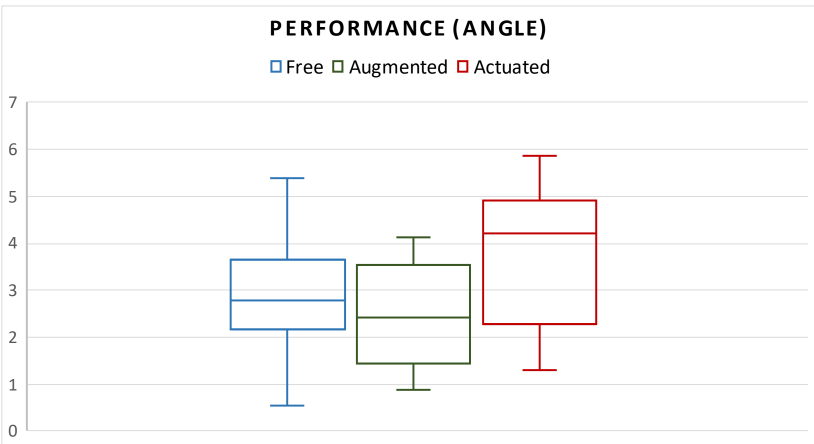


Figure 6.5: Boxplot of the performance of each condition reflected in the measured angle (degrees).

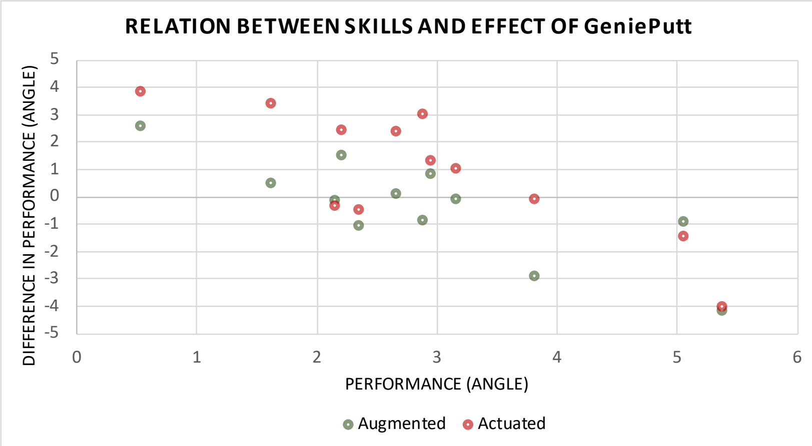


Figure 6.6: Scatterplot of change in performance based on the performance in the free condition. The worse the participants performed without EMS, the more actuation and augmentation improved their performance.

6.4 Results

To evaluate the performance of the participants across the three conditions (i.e., free, augmented, and actuated), we calculated the angle of deviation between the goal and the actual ball trajectory. Each participant performed 10 repetitions for each condition. We then computed the mean for each participant. To calculate the angle of deviation, we recorded top videos we analyzed post-hoc (i.e., using a protractor software, as shown in Figure 6.4). For calculations, we used either the one-handed or two-handed actuation based on better calibration results. Furthermore, we removed outliers (i.e., when the ball was not hit properly and was moving in an entirely wrong direction) using the Tukey method [182].

Comparing the deviation angle of the three conditions we found that *augmentation* performed best, followed by *free* and *actuation* (cf., Figure 6.5). A repeated measures analysis of variance could not show statistically significant differences, $F(2,22) = 2.998$, $p = .071$. We further used a Pearson correlation to analyze the relationship between the regular performance (i.e., free) and the change in performance through EMS. We found a strong negative correlation between the results of the *free* condition (i.e., user is not actuated at all) and the change through *augmentation*, $r = -.801$, $p = .001$, and *actuation* EMS_{only}, $r = -.805$, $p = .002$. A scatter-plot summarizes these results (cf., Figure 6.6).

6.5 Discussion

The results from our study provide primary insights into the potential use of EMS to improve the execution of specific motor skills (i.e, golf putting). Following, we highlight the main outcome of the obtained results.

Combining Human and Computer The results of our study indicate that combining external actuation (i.e., through EMS) and the user does provide the best results. This is in line with the findings of Vahdat et al. that suggest the process of executing new movements to be affected by both the sensory and motor changes, which eventually prompt a new behaviour [409]. Most human motion is a result of multiple simultaneous muscles' movements. In our case, the implemented actuation in this chapter allows us to stimulate individual muscles. When an individual muscle is actuated, the user, consequently, can assist this movement. The results of our study indicate that inhibiting the visual sensory input and only allowing the computer actuation led to the worst performance. This finding is in line with Galati et al. who showed that both sensory and motor contribute to the formation of spatial body-centered coordinates [114].

Following the classification of Wolpert et al. [429], the putting scenario consists of a set of control classes (e.g., swinging the arm, stiffening and twisting the wrist). While users still need to perform some of the control classes on their own (e.g., the swing of the club), the twist in the wrist is controlled by the GeniePutt system. This reduces the number of control classes users need to take care of.

Motor Skill Level of Users The strong negative correlation between the *free* and both the *actuated*, as well, as the *augmented* conditions shows that the level of motor skills of the participants influence the performance in the EMS conditions. The lower the performance is (i.e., the higher the angle), the more the intervention of the EMS improves the performances of the user. This observation also complies with the classification of Wolpert et al. [429] as they divided the experience of performing a certain movement into sub-processes, highlighting that one of the main sub-processes is learning the key feature of the task. In our case, that was reflected in the individual's ability in playing mini-golf apart from the actuation process. Furthermore, this suggests that a system such as *GeniePutt* mainly supports users with a lower skill level.

However, with further improvement in EMS actuation, this might in the future also work for users with better motor skills.

Challenges of EMS Motor skills are divided into fine and gross motions. Given current technology, actuating on a fine level is still challenging and, thus, most actuation is done on a gross level. Furthermore, EMS systems use surface electrodes to actuate muscles. Surface electrodes are limited in terms of the muscles they can be applied to. As soon as muscles are covered by other muscles or are simply too small, surface electrodes cannot actuate the muscles.

Agency Electrical muscle stimulation takes over the control of certain movements of the human body – in our scenario of the turning of the wrist. Users need to let the system actuate the muscle and should not work against the actuation. Prior work demonstrated that while EMS is able to suggest certain movements, users can at any time override this [250, 319]. For our work, this means users can at any time decide not to benefit from the advantages our system provides. Given that the GeniePutt system is used for a particular period (i.e., while playing golf), we expect users to not fear the loss of control.

Application Scenarios Augmenting certain motor skills has various potential applications. While we focus on a sports application, augmenting motor skills can also be useful in everyday life. One example would be preventing users from slipping by actuating their gait. Given that slipping is one of the main reasons for injuries, particularly for the elderly [353], posture control and regain of balance mechanisms have, therefore, been of particular interest for researchers [199].

Limitations We acknowledge the following limitation to our study. The duration of the user study might influence the results. The used evolutionary algorithm requires multiple rounds of actuation. When actuating the same muscle multiple times, fatigue effects might come into play. These effects might not always be well modeled by the evolutionary algorithm since they change over time. Also, while we investigate the effect of the system on improving human performance, we didn't explore the long-term learning effect.

6.6 Conclusion

In this chapter, we presented GeniePutt, a system that improves the performance of users in executing accurate motions through EMS. We conducted a user study with 12 participants comparing the actuation, augmentation, and raw performance of the participants. Our results indicate that the best performance achieved was in the case of augmentation, closely followed by no augmentation. Looking deeper into the data, we found that the approach works best for users that perform rather badly without actuation. This shows that the current technology might provide benefit in terms of improving motor skills but are still limited and cannot improve users that execute their motor skills on a specific level. Nevertheless, the results provide promising first insights into how the interplay of humans and computers can improve motor skills.

Chapter 7

Enhancing Motor Skill Acquisition

This chapter is based on the following publication:
Faltaous, S., Winkler, T., Schneegass, C., Gruenefeld, U., and Schneegass, S.. Understanding Challenges and Opportunities of Technology-Supported Sign Language Learning. In Augmented Humans 2022 (AHs 2022).

In this chapter, we explore another application that influences both human perception and action within the augmentation dimension. This application targets teaching sign language signs, where an anticipated movement is caused by the EMS actuation. The perceived influence of this actuation appears then in the learning effect.

With almost half a billion people living with hearing loss [306], sign languages have become a widely used alternative to verbal communication, empowering many people with hearing loss to better communicate [274]. Moreover, learning sign language can benefit everyone: it can be a solution for hearing people if verbal communication is not feasible (e.g., it offers an opportunity to communicate in noisy environments), and, more importantly, it makes communication between the hearing and deaf or hard-of-hearing (DHH) members

Figure 7.1: We investigated the learning effect of four different learning conditions to teach sign languages. In the example pairs of conditions and signs shown, the participant receives (top left) audio instruction for the sign *strong*, (top right) visual instruction for the sign *past*, (bottom left) electrical muscle stimulation for the sign *have*, and (bottom right) a combination of both visual and EMS for the sign *devour*.

of a community easier. Currently, sign language learning is often done either with the support of a teacher who provides in-person training or with subbed video tutorials [220]. However, autodidactic learning of sign language via video remains challenging because signs are complex. They consist of hand and arm movements, facial expressions, and body language [359], which are difficult to perform correctly using only videos. Hence, learning sign language without in-person training (e.g., over distance) remains challenging.

Previous research has demonstrated that technology has the potential to support the process of teaching sign language (e.g., through augmented reality [39] or with the help of robotics [442]). However, despite the promising results from studies demonstrating that electrical muscle stimulation (EMS) can support the execution of various muscle skills (e.g., [84, 319]), the feasibility of the technology to support sign language learning has not been investigated. Yet it remains interesting if the EMS technology can effectively support learning muscle skills that have the complexity of signs. Fundamentally, EMS works by inducing an external electrical signal, which is sent to the human muscle; the human muscle then contracts, leading to a movement that corresponds to the actuated muscle. In this chapter, we explore the potential of this technology to support sign language learning. To further investigate the suitability of the traditional language learning approaches, namely *audio* and *visual*, we conducted a comparative study in which *EMS* is compared to both *audio* and *visual* modalities. Additionally, we consider the combination of *EMS* and *visual* for our comparison as well. By comparing these technologies in terms of their effectiveness for learning sign language, the findings could contribute to making autodidactic learning more efficient.

Sign language, like any spoken language, is composed of many elements. Although many of them are common to spoken languages (e.g., grammar, vocabulary, structure, etc), other elements are more focused on sign execution (e.g., hand movement, fingerspelling, facial expressions). Our main goal is to explore the role that technology plays, through different modalities, in supporting sign language learning and execution. In this chapter, we focus on exploring signs that mainly rely on movement from the user's arms and hands, with fewer complex details added (e.g., facial expressions). This is defined as the first out of four strata in Sandler's categorization [359]. To be exact, we investigate the effect of using different interaction modalities for the autodidactic acquisition of sign language, namely *audio*, *visual*, *EMS*, and a *combined* condition consisting of both *visual* and *EMS*. As we do not only focus on deaf or hard of hearing (DHH) users but rather address users who are interested in learning sign languages (e.g., family and friends of DHH people), we included the *audio* modality in our studies. While the *audio* and *visual* modalities communicate instructions for performing a sign to the user, *EMS* allows direct actuation of the user. Thus, it involves performance based on direct feedback from a trainer (e.g., training device).

In a user study, we asked participants to perform four different signs instructed through the three modalities (*audio*, *visual*, *EMS*) as well as the combination of *visual* and *EMS*. After a two-week break, participants were asked to perform the signs again, this time without instructions. We were primarily interested in the correctness of sign execution, recall ability, and user experience for each modality type. During the evaluation process, we received support from ten ASL experts (with 22 years of experience on average) to judge the quality of the signs' execution. Our results show a significant difference between the *combined* and *audio* conditions, where the execution of the signs in the *combined* condition was better. In general, conditions involving *EMS* received better ratings in terms of user experience.

Contribution This chapter contributes thus to (1) a better understanding of the challenges and potential for technology-based sign language learning. Moreover, we (2) provide insights from a user study (N=17) in which we compare the learning effects of different instruction modalities on the example of American Sign Language including the rating from 10 ASL experts evaluating the performance of the participants.

7.1 Background and Related Work

Sign languages are a means of communication benefiting a large percentage of the world's population, including not only those living with hearing or speech impairments, but also many people in their communities, such as family members, friends, and teachers [50]. Sign languages are more than a system of communication for an existing language; they are "a true human language" ([424], p.7). However, there is no universal sign language, but rather a great variety of sign languages across the globe. As digitalization has progressed over the last 20 years, several technological approaches have been brought forward to support communication between the hearing and people with hearing or speech impairments.

7.1.1 Signs vs. Gestures

Until the end of the 19th century, the words *gesture and signs* were used interchangeably [193, 195]. In the 20th century, however, signs started to be considered linguistic [195, 204, 383, 388]. Previous research plotted the evolution from simple gestures to sign languages [194, 271], which was later also explained as transferring from no convention and speech (gestures) to convention and no speech (sign languages) [181, 224]. It further highlighted that people who are deaf or hard-of-hearing perceived gestures as a method of communication with hearing people who cannot sign [224]. Another perspective suggests that gestures could be seen as a natural feature that accompanies a language regardless of its modality (sign or speech) [128]. In this chapter, we will use the term sign instead of gesture to avoid confusion.

Sandler divided an existing sign language into four strata of increasing complexity in terms of gestures and grammar. The first stratum uses only a hand to communicate, while the fourth stratum uses the hands, head, face, and body [359]. In this chapter, we focus mainly on the first stratum and we use American Sign language (ASL). Thus, as a first step, we explore the role of different technologies in supporting the hands and arms in executing signs. While starting with rather simple signs is not recommended for machine-based sign language recognition, generation, or translation [35], they can provide a good initial set to investigate human-centered sign language learning as they reduce the number of influencing factors and make the results easier to interpret. Nevertheless, this choice certainly influences the generalizability of the results, and thus, future exploration of more complex signs is required.

7.1.2 Technological Support for Sign Languages

Technology can support communication between people with and without hearing and speech impairments in multiple ways. The main goal of previously-studied assistive technologies was to develop a medium for post-hoc or instant translation, usually from ASL to verbal or written English. The basis for the automated translation is the recognition of the signs. Examples of applying technology to sign recognition include using RGB [10] or depth cameras [225]. Further, sensing tools such as data gloves [102, 189] provide more detail about the signer's hand positions. To make the process of hand sign recognition less cumbersome, researchers applied sign recognition through Electromyography. For example, Abreu et al. [2] and Paudyal [312] used a consumer device for hand movement tracking called the Myo armband[18]. This armband uses Electromyography to sense the electrical activity in the muscles of the arm that is generated by hand and finger movement.

In their recent work, Gugenheimer et al. [135] evaluated existing assistive technology in this domain and requested a change in the design perspective. They highlighted the importance of supporting the learning of the subordinate rather than the dominant language in a society, identifying sign language as a subordinate language based on the number of signers compared to the speaking community. Hence, we take the stand that technological support should be designed to foster the learning of sign languages by people without hearing or speaking impairment. ASL is a complex language and is difficult to acquire without the help of a proficient teacher. However, technology can be used to enable autodidactic learning anytime and anywhere, appealing to a broader audience.

Teaching of Sign Languages Besides real-life courses teaching sign language, digital tutorials have become increasingly popular over recent decades. In these mostly video-based lessons, the learner watches a recording of a

[18] Myo armband. `https://support.bynorth.com/myo`, last retrieved March 30, 2023.

person or avatar executing a certain sign or sentence and is asked to repeat it. This form of digital video-based learning enables self-paced and remote learning without an actual human teacher. To assess the quality of the learner's sign execution and provide feedback, the system has to recognize the learner's movements.

There are several ASL learning applications available on the market (e.g., ASL Coach[19] or American Sign Language ASL[20]). These apps offer a variety of video tutorials but lack performance recognition; thus, they also lack feedback on the accuracy of a learner's sign execution. In recent studies, Paudyal et al. [313] highlighted the need for corrective feedback and investigated a combination of a camera-based sign recognition system with an intelligent tutoring system to teach ASL. By analyzing a learner's joint locations, hand and arm movements, and hand shape, the system compares the execution to an expandable database of target signs and provides feedback [313]. However, the effect of the feedback on the learning process has not yet been evaluated.

7.1.3 Research Gap

The most common technical approach to sign language teaching is video-based learning, ie. the learner is asked to repeat a sign performed by a human or avatar in a video. This approach is applied to mobile applications, online tutorials, and intelligent systems such as SCEPTRE [312] or Learn2Sign [313]. Yet, video-based learning has the drawback that it requires the learner to accurately mimic the signs performed by the teacher on their own and be aware of mistakes. Further, it remains unclear how well video-based learning actually performs in terms of recall compared to other modalities.

7.2 Teaching Modalities for Sign Language Learning

The Cognitive Load Theory describes the allocation of working memory resources in learning processes. It defines the terms *Intrinsic Load* (load

[19] ASL Coach. `https://play.google.com/store/apps/details?id=com.PLMUN.myASL`, last retrieved March 30, 2023.

[20] Sign Language ASL. `http://play.google.com/store/apps/details?id=tenmb.asl.americansignlanguagepro`, last retrieved March 30, 2023.

induced by the task itself), *Extraneous Load* (load induced by the instructional design), and *Germane Load* (resources needed for schema construction and memory integration, and thus, learning). Confusing instructions can use up cognitive resources that would otherwise be available, and can thus hinder learning [43]. Thus, one goal is to design the instruction in a way that does not induce more additional load than necessary.

In the following, we will outline different modalities for sign language learning instruction, which we will comparatively evaluate in a user study. Our teaching modalities include *audio* as we include people without hearing or speech impairment, representing relatives that use sign language as a means of communication with their deaf or hard-of-hearing friends and family members. We propose investigating the performance of the frequently-used (1) video-based instructions in comparison to three other instruction modalities: (2) audio instructions, (3) direct muscle actuation using EMS, and (4) a combination of visual and EMS. We decided to include *video* and *audio* as separate conditions to better understand their individual influence on the learning effectiveness. As previously mentioned in the related work, signs could be divided into four strata [359]. In our work, we focus mainly on signs using the hands (i.e. first stratum). We designed the instructions by observing professional online teaching videos (both front and side views) and cutting down each sign into a sequence of movements.

7.2.1 Audio

In our case, the audio modality includes a description of the movement. Describing a movement using words offers the chance to include specific details regarding its execution, which may not be obvious in a picture or video. Furthermore, the sign can consist of multiple smaller movements of different body parts (e.g., a hand posture combined with a head tilt or facial expression). In the audio format, the individual signs are outlined successively, while their order of execution is described verbally. As a result, the learner can focus on each individual movement required to execute a sign instead of perceiving all parts simultaneously, leading to a more profound way of processing.

7.2.2 Video

As described in Section 7.1, many sign language learning applications employ videos of either an avatar or a human demonstrating signs. This technique is founded on the assumption that observing a movement triggers similar processes in the human brain as does the actual movement execution [380]. Therefore, the combination of visual presentation and subsequent practice has the potential to create lasting motor memories.

7.2.3 EMS

Electrical Muscle Stimulation (EMS) is a method of externally stimulating the human body's muscles using small electrodes attached to the skin that send electrical impulses. Through EMS, a muscle can be actuated and, depending on the impulse's strength, can create a sense of force feedback or lead to movement execution [364]. In human-computer interaction, EMS has been investigated as a means to provide realistic force feedback in virtual reality, and also to train certain movements. For example, Hassan et al. [144] applied EMS as a teaching tool to help runners improve their fine-tuned movement execution while running. They were able to show that EMS outperformed slow-motion video-based feedback on their movements. Other researchers have focused more on hand movements, e.g., to improve typing skills [368], bowling skills [399], or the playing of musical instruments [167, 395]. For teaching sign language, we actuate the learners' muscles using EMS to provide them with the correct movement initially, reducing the need for corrective feedback.

7.3 Evaluation

This chapter focuses on teaching American Sign Language (ASL) signs, as it is one of the most widely used sign languages in the world. Although the actual number of ASL signers is hard to specify, the estimates range between 250-500,000 signers in the US alone [278]. Here, we focus on teaching signs that primarily rely on hand and arm movements.

Since our main goal is to compare learning of signs across the different conditions, we avoided any kind of linking between the word meanings and the sign itself (i.e., iconicity [400]). Consequently, we presented the executed signs by number for memorability (e.g., sign 1). There is a huge pool of signs performed using the hands in American Sign Language (ASL). Given the current limitations of EMS (e.g., a limited number of simultaneously actuated muscles or precision of actuation) and in favor of a simpler study design with fewer influencing factors, we chose signs that would ensure a fair comparison across all conditions. Thus, we chose four signs: two that require the movement of both arms and two that require only one arm to move. We communicated these signs in four instruction modalities. The first is *audio*, where the user hears a description of what is being communicated. The second modality is a *visual* representation that uses a video of an avatar performing the sign. The third modality is actuating the user via *EMS* to induce the performance of one of the signs. The fourth and last modality is a *combined* instruction, where the user can see the visual input and be simultaneously actuated via EMS. Any combination with audio instruction was excluded because the user has to hear the whole description, process it, and then execute it. This is unlike visual and EMS instructions, where the user starts to execute the sign the moment the instructions are communicated.

7.3.1 Initial Involvement of Signers

We asked a sign language student (20 years, female) and a teacher (60 years, male) for their opinion regarding the design of the different modalities and collected their feedback. For the *EMS* condition, particularly the student was positive by indicating that the *"exact movement could be controlled."* She expected the *audio* condition to be appropriate to communicate the correct arm movement. However, she was afraid that the audio could be easily misinterpreted. The teacher, on the other hand, expected that the *visual* condition would support the learning process best as he has been using it for his 25-year-long career. He was afraid that without visuals, learning will not be successful. Both agreed that the combination of visual and EMS can be beneficial.

7.3.2 User Study Design

To avoid participants seeing any meaning in the signs that would help to remember them, we assigned each sign a number (cf., Figure 7.2). In general, we had three modalities to communicate the teaching instructions: *audio*, *visual*, and *EMS*. In addition to these, we had a condition that we refer to as *combined*, which communicated the signs visually and with EMS simultaneously. Each sign was repeated 10 times in each condition. For both the *EMS* and *visual* conditions as well as the *combined* condition, the instructions were communicated for 3*sec*, with 3*sec* intervals between repetitions. However, for the *audio* condition, the communicated description lasted 6*sec* instead with a 3*sec* interval between repetitions. The audio instruction lasted longer to ensure that the participants had enough time to process the meaning and execute the movement in 3*sec*. This asynchronicity concerning the different times for

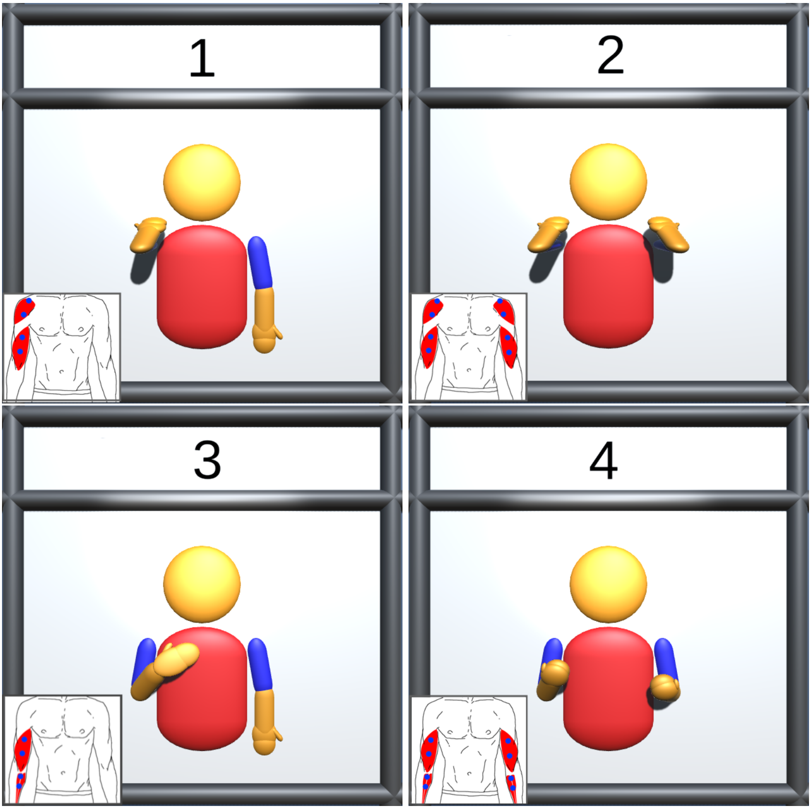


Figure 7.2: Visual representation and electrode placement for each sign. The audio descriptions for each are (a) *throw your right hand over your right shoulder*, (b) *throw both hands over your shoulders*, (c) *tap your chest with the fingers of your right hand*, and (d) *make a fist with your hands and bend both arms, bend the right arm more than the left one.*

visual and *audio* was one of the major reasons to not provide it as a combined condition but rather to rely on a combination of *visual* and *EMS*. To be able to record and later evaluate their performance in recalling as well as executing the signs, we recorded the movements via video documentation (mounted from the perspective of a communication partner) and an OptiTrack system[21] (to allow precise replay of the movements from different perspectives). Our approach would help us to identify the best memorized and correctly executed condition after the study.

7.3.3 Participants and Procedure

Overall, we had 17 participants (13 male, 4 female) with no prior knowledge of any sign language, aged between 22 and 32 years (mean=27.56, SD=2.98). The quantitative data of one participant was excluded as the actuation in the EMS condition yielded a different behavior after being actuated only once (i.e., the participant's forearms twitched toward the abdominal area instead of raising toward the shoulders). The study was conducted in two sessions, each lasting for about an hour, with a span of two weeks in between, as was done in previous work [134]. Each participant had to perform every sign in a counterbalanced order. Furthermore, the signs communicated in each modality were counterbalanced to eliminate any learning effect.

First Session At the beginning of the first session, we welcomed the participants and gave them the consent form, which included the safety regulations of the EMS as well as the study description. The study was conducted following the ethical guidelines of our institution. The first session consisted of two parts. The first part was the muscle calibration, in which we actuated the muscles of the participants and visually checked until the target motion was achieved similar to previous work [319, 95]. To be exact, we segmented each sign into a sequence of movements and after placing the electrodes we visually verified if all the segments were applied. In the second part of the first session, we asked the participants to wear OptiTrack markers in the form of armbands, a vest, and gloves (cf., Figure 7.4). We recorded images of the positioning of the armbands to ensure applying the same positioning in the second session. The participants stood in the lab facing a projection, through which we communicated the sign number (cf., Figure 7.3).

Then, we communicated the different instruction modalities and signs. The mix of the modalities and the signs followed a Latin-square design, where each

[21] OptiTrack. `https://optitrack.com`, last retrieved March 30, 2023.

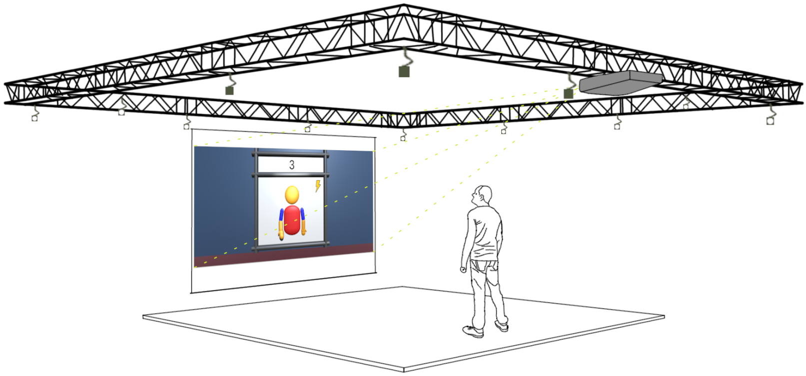


Figure 7.3: The general setup of our study, where the participant stands facing the projection showing the different instructions.

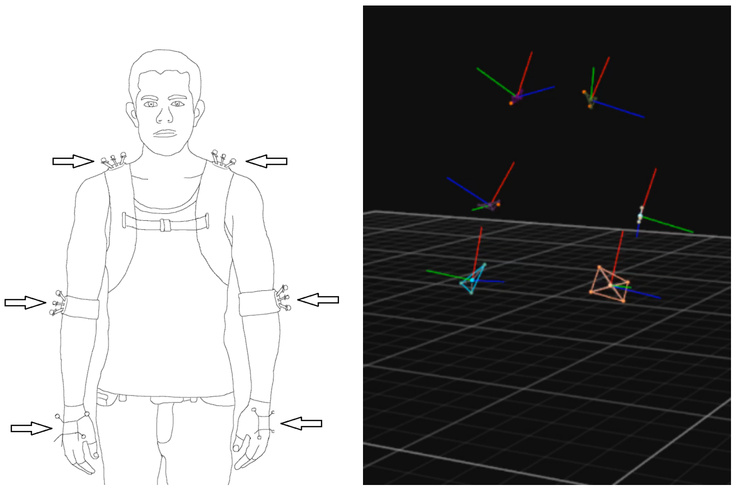


Figure 7.4: The participants' movements are recorded by a tracking system that tracks the participant's markers.

condition appeared four times in our overall data set. Between each condition, we asked the participant to fill in a user experience questionnaire [231]. At the end of the session, we asked the participant to rate each condition on a 7-point Likert item, indicating to what extent the sign was clearly communicated and to what extent they would remember it, as well as their learning abilities (e.g., ability to memorize and learn).

Second Session After two weeks, we asked the participants to come into our lab again for the second session. First, we asked them to indicate on a 7-point Likert item to what extent they remembered the signs they had learned in the first session. Then, we asked them to put on the OptiTrack markers and adjusted the markers' positions and orientations according to the images captured in the first session. We again presented the sign number known from the first session and requested them to execute each sign as soon as they saw the sign number. They were told that they should perform each sign as they remembered it from the first session. We then visually confirmed whether it was the correct sign. If the participant said that they had forgotten the sign or performed a wrong one, we provided a hint. We had a total of three hints that would be communicated in the same order for each condition and across all participants. Each hint would only be communicated if the previous one failed to remind the participant of the sign. In order, the three hints provided were: (1) the sign modality, (2) the number of arms used, and (3) the visual representation of the sign.

When the participant remembered the sign, they had to rate on a 7-point Likert-item to what extent they remembered the exact execution of the sign. They then had to repeat the sign 10 times, which was guided by signals (i.e., the sign number appearing on the screen). The signals appeared for $1.5sec$ and were separated by $3sec$ breaks. At the end of the session, we conducted an interview with the participant to gain more insight into how each modality affected their ability to remember the signs.

7.4 Results

Since the *EMS* actuation for one participant caused problems for the last trials of the second session, we excluded that participant for our performance measures but considered their feedback for the semi-structured interviews. Below, we report mean (M), median (Md), and interquartile range (IQR).

Overall, we had 17 participants, each of them learned four signs with one of four instruction modalities in the first session. Two weeks later, they were

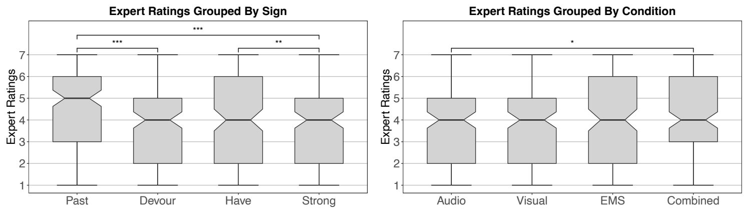


Figure 7.5: Ratings from the ASL experts on the signs performed by the participants at the second session of our user study. The significance levels are given by stars: *(<0.05), **(<0.01), and ***(<0.001).

invited to come and repeat all the signs again in a second session. For the quantitative part, we report only on 16 participants due to a technical reasons (cf, Participants, and Procedure 7.3.3). For the qualitative part, we report the comments of all 17, since all of them had the same experience across the 4 different conditions.

7.4.1 Ratings from ASL Experts

To understand how interpretable participants performed the learned signs during the second session of our study, we invited ten ASL experts (6 female, 3 male, 1 preferred not to say), aged between 28 and 54 (M=35.7, SD=8.2) with an average experience in ASL of 22.2 years (SD=14.6) to participate in an online questionnaire rating how well participants performed each sign. All Participants are residents of the USA. In particular, the questionnaire showed the video recordings of the performed signs (from the perspective of a conversation partner) and the intended sign. Then, we asked the experts to rate the statement "the participant correctly executed the arm and hand movements of the sign" (1=strongly disagree and 7=strongly agree). As we are inspecting the movements of only the arms, all the faces of the participants were blurred to eliminate any influence of facial expressions. Overall, each one of the ten ASL experts rated the signs of the 16 participants that performed all four signs each, resulting in 640 ratings (i.e., 10 experts * 16 participants * 4 signs).

For the signs, the mean (median, interquartile-range) ratings of participants' sign execution rated by the experts are: *past*=4.53 (Md=5, IQR=3), *have*=4.11 (Md=4, IQR=2), *devour*=3.68 (Md=4, IQR=3), and last *strong*=3.51 (Md=4, IQR=3) (cf., Figure Figure 7.5). Since we do not assume normality, we performed a Friedman test that showed a significant effect of the signs on the expert ratings ($\chi^2(3)$=25.61, $p<0.001$, N=10). A post-hoc test using Wilcoxon Signed-rank with Bonferroni correction revealed significant differences between the conditions. We found a significant difference between *past* and *devour* (W=15950, Z=4.394, p<0.001, r=0.25), *past* and *strong* (W=16675, Z=4.665, p<0.001, r=0.26), and *have* and *strong* (W=14938, Z=3.268, p=0.006, r=0.18). Here, we can conclude that *past* is rated significantly better than *devour* and *strong*, and *have* is rated better than *strong*.

For the different conditions, the mean (median, interquartile-range) ratings of participants' sign execution rated by the experts are (in descending order): *combined*=4.20 (Md=4, IQR=3), *EMS*=4.06 (Md=4, IQR=4), *visual*=3.87 (Md=4, IQR=3), and *audio*=3.7 (Md=4, IQR=3) (cf., Figure Figure 7.5). Since we do not assume normality, we performed a Friedman test that revealed a significant effect of the conditions on the expert ratings ($\chi^2(3)$=9.338, $p=0.025$, N=10). A post-hoc test using Wilcoxon Signed-rank with Bonferroni correction showed a significant difference between *audio* and *combined* (W=10992, Z=-2.794, p=0.030, r=0.16). We conclude that *combined* is rated significantly higher than *audio*.

Moreover, after rating the sign execution of our study participants, experts provided general comments about the rated performances. Experts noted that some signs came off as a bit aggressive. In particular, because the signs were executed too quickly. Here, the timing for some signs (*devour*, *strong*) is more important than for others (*past*, *have*). Furthermore, experts highlighted that facial expressions and the use of finger spells are important for the correct execution of signs.

7.4.2 Memorability

We report the number of hints needed as well as the correctness of the sign execution within and across sessions.

Number of Hints At the beginning of the second session, we asked the participant to start executing the sign as soon as we displayed the sign number. If participants had trouble remembering a sign, they could get up to three hints (one at a time). If they failed to remember the gesture we communicated one of three hints; the condition (i.e., hint number 1), the number of arms used (i.e., hint number 2), and the visual avatar (i.e., hint number 3). We checked visually the correctness of the gesture after each communicated hint. We communicate a hint only if the participants fail to execute the movement and indicate that they can't remember the gesture. For each participant, we logged the number of hints needed for each gesture (cf., Figure 7.6). In the following,

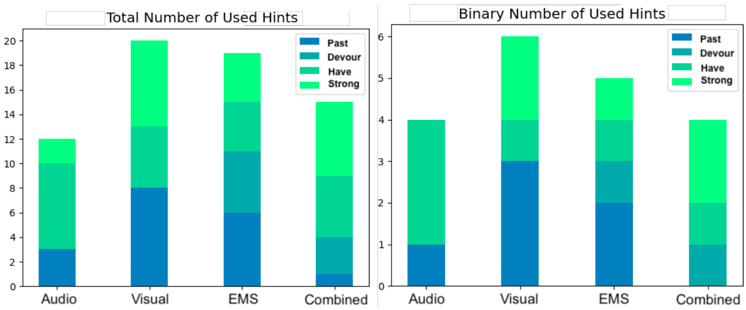


Figure 7.6: The number of hints communicated in each condition. In the left figure, we summed the number of hints presented. In the right figure, we counted the number of participants who needed hints more than the condition. The count depended on a binary decision, where any participant receiving 2 or more hints was counted as 1 entry. The P,D, H, & S stand for the signs of past, devour, have, and strong.

we report the number of hints needed per condition (in ascending order): *audio*=12 (Md=0, IQR=1.25), *combined*=15 (Md=1, IQR=1.25), *EMS*=19 (Md=1, IQR=2.25), and *visual*=20 (Md=1, IQR=3).

Since the total number of hints is strongly influenced by individual participants taking multiple hints for a particular condition, we looked at the binary decision if hints were provided or not (i.e., we used a binary code: 1, if we gave any hints, and 2, if no hints were given). The results indicate that equal numbers of participants needed hints for *audio* and *combined* ($N = 4$), followed by *EMS* ($N = 5$) and *visual* ($N = 6$). A Friedman test showed no statistical difference across the four different modalities (χ^2(3)=2.18, p=0.534, N=16).

Sign Correctness and Consistency We further explored how well the signs were executed within and across sessions. We based our evaluation on the video recordings of the two sessions. In our analysis of the video recordings, we judged the correctness of the sign execution in each of the two sessions. We did this by visually comparing the videos to the intended sign (cf., sign correctness in Figure 7.7). We focused on the used arm, the direction of the hand motion, and the final sign execution. Furthermore, we then carried out a third comparison to explore the learning effect (cf., sign consistency in Figure 7.7). In this, we compared the sign execution in the second session with that of the first one. Here, we ignore a wrong sign execution in the first session and simply assume participants practiced the correct sign to deduce to what extent they remembered the signs learned in the first session. To do so, we

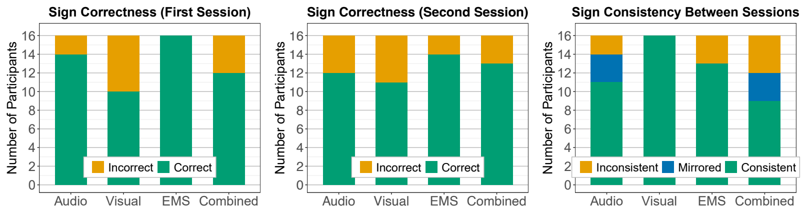


Figure 7.7: The correctness and consistency of the signs in each condition. In the first two subfigures, we compared the signs executed in each session to the intended ones (i.e., correctly executed). In the *sign correctness* figure, we explored the learning effect by comparing the signs executed in the first and second sessions. For consistency, we assume that signs were correctly executed in the first session.

categorized each compared pair into *consistent, inconsistent,* or *mirrored* based on whether the second session sign was the same, was completely different, or involved the wrong arm(s), respectively.

For the first session, *EMS* was the best in terms of correctness (N=16). *Audio* scored the second best, as 14 participants performed the intended motion correctly. This was followed by the *combined* condition (N=12) and finally the *visual* condition (N=10).

In our second comparison, which evaluated the correctness of the second session performance, *EMS* was again the best (N=14). This was followed by *combined* (N=13), *audio* (N=12), and then *visual* (N=11). There was no discernable pattern among the signs that were wrongly executed.

In the third comparison, sign consistency was measured by comparing each participant's performance in the second session to their performance in the first one. The sign consistency was best observed in the *visual* condition, in which all the participants, upon remembering the sign, executed it the same way as they did it in the first session (N=16). The second-best was *EMS* (N=13), followed by *audio* (N=11), and finally the *combined* condition (N=9). *Audio* and *combined* resulted in two and three participants performing the sign mirrored, respectively.

Measured Accuracy Each sign was repeated ten times in both the first and second sessions. We refer to each repetition as a trial. Since the execution speed and starting position differed between conditions and across all participants, we plotted all coordinates of each sign and manually defined the start and end positions of each trial for every sign. We also checked for a muscle fatigue effect in the *EMS* and *combined* conditions by plotting the maximum height of the hand position across the ten trials. No muscle fatigue was shown across trials, hence, we report on the median value of all trials of every participant. We based our measured accuracy on the angle between the upper arm and forearm as well as the distance difference between the shoulder markers and the hand (cf., Figure 7.8). The angle α then shows the degree of the bent elbow. The distance D reflects the maximum height of the hand in each trial. The difference between the two measures is that the distance incorporates the changes made by the hand (e.g., rotation), while the angle only reflects the extent to which the arm is bent.

Moreover, we only took the leading arm into consideration. For example, for the *have* sign, if a participant used their right arm in the first session but their left arm in the second session, the accuracy value then depended solely on the differences between the recorded distances and angles of the leading arm of each session.

Angle Accuracy By the angle accuracy, we refer to the consistency of executing each sign across the two sessions. For the single-arm signs, we took the median value of each of the 10 trials for every participant in all conditions. We computed the absolute value of the difference between the values measured in the second session from those in the first session. For the signs that required both arms (i.e., *strong* and *devour*), we applied the same strategy for each arm. We determined the mean of the resulting differences to be representative of the accuracy angles in these conditions, where:

$$\alpha_{accuracy} = \mid \alpha_{session2} - \alpha_{session1} \mid .$$

The condition in which the computed angle was most accurate was *visual* (M=6.25°, SD=5.3), followed by *audio* (M=8.6°, SD=6.5), then *combined* (M=9.7°, SD=6.7) and then *EMS* (M=10.14°, SD=7.8). Statistical analysis using the Friedman test showed no significant differences between the four conditions ($\chi^2(3)$=1.8, p=0.62, N=16).

Distance Accuracy To measure the distance accuracy, we applied the same approach as we had for the angle accuracy, but we computed the distance between the hand and the elbow (i.e., distance D in Figure 7.8) instead of the angle. Similarly, we took the median difference of the 10 trials for the single-arm signs. For the signs requiring both arms, we computed the mean of the difference between the first and the second session for each arm,

Our results indicate the same order as the angle accuracy: the most accurate sign execution was recorded in the *visual* condition (M=1.6*cm*, SD=1.4),

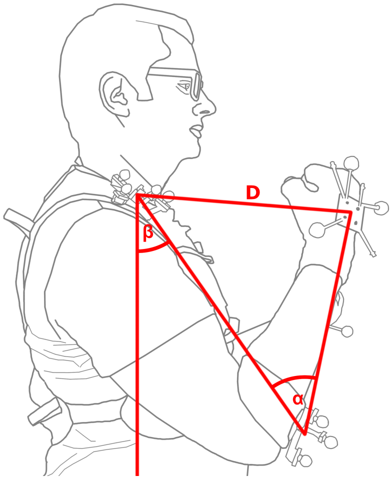


Figure 7.8: The angle and distance on which we based our measure of accuracy. The angle α shows to what extent the forearm was bent. The distance D then takes into consideration the different hand orientations (e.g., bent inwards).

followed by *audio* (M=2.0cm, SD=1.6), then *combined* (M=2.4cm, SD=2.2) and then *EMS* (M=3.0cm, SD=2.4). Statistical analysis using a Friedman test showed no significant differences between the four conditions (χ^2(3)=6.15, p=0.1, N=16).

7.4.3 User Experience Questionnaire

Based on the results of the User Experience Questionnaire (UEQ) [231], the overall user experience is equal for both *combined* (Md=1.5, IQR=1) and *EMS* (Md=1.5 , IQR=1.1), followed by *visual* (Md=0.3, IQR=1.06) and *audio* (Md=−0.31, IQR=1). Statistical analysis using a Friedman test revealed significant differences between the four conditions (χ^2(3)=36.38, p<0.0001, N=16). A Wilcoxon-Pratt Signed-rank test showed that there is a significant difference between *audio* and *EMS* (W=0, Z=−3.517, p<0.001, r=0.62), *visual* and *EMS* (W=0, Z=−2.600, p<0.01, r=0.46), *audio* and *combined* (W=3, Z=−3.518, p<0.001, r=0.62), and *visual* and *combined* (W=10, Z=−3.000, p<0.001, r=0.53). For the user experience, we can conclude that *EMS* and *combined* > *audio* and *visual*.

For the pragmatic quality *combined* was rated best ($Md = 1.7, IQR = 0.75$), followed by *visual* ($Md = 1.5, IQR = 0.6$), *EMS* ($Md = 1.25, IQR = 1.3$) and last but not least audio ($MD = 0.87, IQR = 1.5$). Statistical analysis using Friedman test, showed a significant difference between the four modalities (χ^2(3)=11.8, p<0.01, N=16). A Wilcoxon-Pratt Signed-rank test shows that there is a significant difference between audio and combined ($Z = -2.8, p < 0.01, V = 7.5$) as well as *EMS* and *visual* ($Z = -2.3, p < 0.05, V = 19$).

For the hedonic quality the same rating as the overall was observed where *combined* was the best rated ($Md = 2.5, IQR = 0.9$) followed by the *EMS* ($Md = 2, IQR = 1.25$) then *visual* ($Md = -0.75, IQR = 1.25$) and at last the *audio* ($Md = -1.25, IQR = 0.88$). Statistical analysis using the Friedman test showed significant differences between the four modalities (χ^2(3)=32.7, p<0.0001, N=16). A Wilcoxon-Pratt Signed-rank test shows that there is a significant difference between audio and combined ($Z = -3.4, p < 0.001$, $V = 0$), ems and visual ($Z = 3.4, p < 0.0001, V = 120$) as well as combined and visual ($Z = 3.3, p < 0.001$, $V = 132$).

7.4.4 Individual Likert-items

We asked the participants to rate several Likert items across the two sessions. The results are presented in the following section. In the first session, we asked them to indicate for each condition the likelihood that they would remember the sign in two weeks. The results show that all the conditions were rated the same (Md=4). A Friedman test showed no significant differences across the four conditions (χ^2(3)=1.06, p=0.7, N=16). We also asked them to rate the extent to which extend the sign was clearly communicated. The participants rated *visual* highest (Md=7, IQR=1), followed by *combined* (Md=6.5, IQR=1), then *EMS* (Md=5.5, IQR=1.25) and then *audio* (Md=5, IQR=4.25). A Friedman test again showed no significant differences across all four conditions (χ^2(3)=7.4, p=0.06, N=16). During the second session, we asked them to rate to which extent they remembered the sign in each condition. The participants rated *combined* as best (Md=6, IQR=2), followed by *EMS* (Md=5, IQR=4) and *audio* (Md=5, IQR=4) in the same rank. The least-ranked signs were those communicated via *visual* instructions (Md=4, IQR=5). A Friedman test showed no significant differences across all four conditions (χ^2(3)=3.88, p=0.2, N=16). In general, the self-rating of memory skills was higher in the first session (MD=5, IQR=3), than in the second session (Md=4, IQR=2.25).

7.4.5 Semi-structured Interviews

Finally, we report the general comments mentioned by the participants during the study along with the comments from the interviews. At the end of the second session, we asked our participants to provide further insights regarding their preferred modality and to share with us any general feedback.

Audio Instructions Out of the seventeen participants, eleven commented on the audio instructions. Nine of these expressed their confusion while receiving the instructions. They described it as *"the most confusing"* [P12] and the*"the most unclear"* [P8]. P9 further elaborated: *"I was confused about what the audio needed from me at the end. The thing is it might have meant that I raise my hand super high [...] audio was self-interpreted."* This was further supported by P7 and P13: *"[the] audio condition is not my favorite because of the uncertainty, it is intuitive [...] ground truth unclear, unclear which fingers and how the fingers need to be positioned on the chest and where to put the arm specifically"* and *"as usual you hear something you interpret according to your own understanding."* Two participants mentioned that it was the *"easiest"* to remember as *"the nature of the condition is different"* [P15] and *"it was not like the others [conditions]"* [P13]. P3 further elaborated that he *"had to think about the audio but none of the others."* This was further supported by P2, who commented on the sign clarity that *"I was not sure if I was doing the right thing, maybe that is why it stayed because it was special"*.

Visual Instructions Eight of our participants commented on the visual modality. All comments concerning the visual condition were positive. They described it as *"quite delivering"* [P8] and *"pretty clear"* [P9]. P12 added that *"visual has a better connection to the brain than audio."* P9 further elaborated that for *"everything without visual,"* he was unsure if he executed it correctly. P10 further confirmed that *"in the visual condition, I am pretty sure I did the same as the one displayed."* However, P13 disagreed with that, reporting *"I thought visual should be worst while learning, it just disappeared from my memory."*

EMS Condition Out of our 17 participants, 10 commented on the EMS, with 7 of these mentioning that they remembered it best. P6 said that his *"hands moved unintentionally."* P11 further elaborated that they *"remembered EMS the best; from the EMS one can just notice the feeling of being actuated and that was easier to notice."* This was further supported by P12, who mentioned that *"EMS is just the best because it was a stimulation that the one did not learn or know from daily life."* Six participants said that they might have changed the sign execution during the second session. P3 explained that he *"adjusted it because of cables in the first time that might have influenced the movement."* Others based their reasoning on the lack of noticeable details. P11 explained that *"especially in EMS, the height of arms was not obvious."* P9 further elaborated that *"EMS is an impulse that indicates the direction, but the specific movement (endpoint) is hard to learn."* Two participants preferred having a more *"natural"* feeling [P9, P10].

Combined Visual-EMS Instructions Of our participants, 7 commented on the combined instructions, with 6 of them rating it positively. They described it as a *"good way to learn"* [P10], *"better than the others"* [P5] and *"hard to forget"* [P8]. P15 further explained that *"it was clearly communicated."* P8 elaborated, saying *"combined was the best. However, EMS was dominant in combined, like it was opposing what I was trying to do."* P13 provided further explanation: *"seeing and being actuated leads to not forgetting the sign [...] EMS and visual worked best because of the actuation, as I knew the correct movement because ems helped me to move and then I could double-check with the visual"*.

7.5 Discussion

In this chapter, we explore the feasibility of various instruction modalities or a combination of them for sign language learning. For that purpose, we investigated the use of audio, visual, EMS, and a combination of EMS and visual instructions. Our findings highlight the challenges of each modality and the potential for future use.

Our findings are based on two main results: (1) the data that we collected from the participants, including the Likert-items, and semi-structured interviews, and (2) the results from the online questionnaire with ten ASL experts along with their additional feedback. The expert evaluation of the signs showed that signs executed by one hand (*past*, *have*) are better learnt than signs executed by two hands (*devour*, *strong*; see Figure 7.5). This may indicate that the more body parts a sign involves, the harder it is to perform it correctly. Thus, our findings can probably be seen as an upper limit for technology-based sign language learning as they focus on a selection of rather simple signs. Moreover, for both the *have* and *past* signs, the facial expression and the speed of execution would depend on the context, which is not necessarily linked to certain facial expressions. While the *strong* sign is completely dependent on the speed of execution as well as the facial expression. Also, the *devour* sign depends on the facial expression (e.g., open mouth) to complete the meaning.

Our findings indicate that these aspects (i.e., speed of execution and facial expression) should be included in any similar future research in order to add further dimensions, thereby, allowing one to obtain more generalizable results.

Audio Instructions One of our experts, who is not DHH, reported knowing two sign languages. One she learned for her family, the other for a friend. Throughout her long learning period (46 yrs), she never came into contact with auditory learning instructions. Nevertheless, since sign language is not only a language for the DHH, but also for whole communities (including friends, family, and people of interest), we believe that audio instructions can prove useful and should not be neglected right from the start.

In terms of the memorability assessment (i.e., number of hints required in the study), in the *audio* condition, participants needed the lowest number of hints. Furthermore, in the interviews, when the participants commented on the audio instructions, they often remembered specific parts of the sign description, such as *"fingers on chest"* [P13]. Participants mentioned that they *"had to think about the audio but none of the others"* [P3]. This indicates that their cognitive involvement was higher while learning the signs via *audio* instruction. This is also in line with the work of Chi and Wylie, who argued that more involvement with the learning material increases the learning performance [49].

However, participants also mentioned in the interviews that the *audio* instructions were the *"most unclear"* instructions [P8] and that they partly needed to *"self-interpret"*[P9] the meaning. These comments were further reflected in the user experience questionnaire rating and in the individual question of the first session (i.e., the clarity of the sign communication), where *audio* was perceived worse than the other conditions. Although we only used signs that did not require a lot of fine detail (i.e., no complex finger movement), the *audio* condition ended up inducing uncertainty and confusion about the exact execution of the sign in our participants. This is supported by the ASL experts evaluation in which *audio* received the lowest ratings and performed significantly worse compared to *combined*. Hence, we think that *audio* can be beneficial in combination with another modality but should not be used to learn sign language as an exclusive modality.

> **Implication 1:** While our findings indicate that audio instructions can prove useful, they should not be used as a standalone instruction modality for teaching signs.

Visual Instructions Our experts indicated that video instructions are one of the most common methods for teaching sign languages. In addition, previous work indicated that video-based learning can yield good recall effects [179]. However, our results indicate that it is the least memorable (i.e., the participants needed the maximum number of hints). One of the participants even stated that the *visual* instructions *"just disappeared from my memory"* [P13]. On the one hand, the participants had trouble remembering the shown signs. On the other hand, they executed them in a similar way as in the first session upon being presented with them (see section 7.4.2).

Nevertheless, the *visual* instructions were mostly perceived positively by our participants, who described them as *"delivering"* [P8] and *"clear"* [P9]. They reinforced this impression through their high confidence in executing the right sign. One of the participants expressed his confidence in his execution accuracy by describing his performance as the *"same as the one displayed"* [P10]. Similarly, when asked about the clarity of sign communication, participants rated the *visual* condition the highest. This observation is in line with previous work that showed that a video-aided approach to teaching a skill leads to a better performance than audio instruction alone [134].

Implication 2: Visual feedback introduces a certainty aspect for the sign execution, as it is unambiguous and easily perceived.

EMS Condition The feeling of experiencing *EMS* was described by the participants as *"different"* [P8], *"unconventional"* [P2], and nothing that one knows from *"daily life"* [P12]. In the user experience questionnaire, it was rated the second highest and was significantly better than *audio* and *visual*. On the contrary, our participants highlighted that they might have executed the signs differently in this condition. One participant said that through *EMS*, one does not receive enough feedback about the sign details. As one participant commented, the sign is *"not obvious"* [P11]. This could be based on the different nature of *EMS*, as it does not necessarily involve human perception [96]. In other words, the conditions containing *audio* and *video*, *EMS* does not require the participant to process the information and then act upon it. Instead, it directly actuates the human to produce the targeted movement. Although the *EMS* condition was least accurate, it achieved the highest correctness in both sessions (see Figure 7.4.2 and 7.4.2). That was further indicated by our expert evaluation and participants, as P9 explained that *"EMS is an impulse that indicates the direction"* and P11 stated that *"the feeling of being actuated is easier [...] noticed."* This is in line with previous research that showed the role of proprioception in improving motor skills [431] by storing, updating, and maintaining a *motor skill program* [152].

> **Implication 3:** EMS is suitable for guiding sign execution because it enhances the learning experience by directly actuating the limbs. However, without any additional feedback, the user might not be certain about the sign execution details.

Combined Visual-EMS Condition For the participants, the *combined* condition was the most positively perceived. They said it was a *"good way to learn"*[P10], *"better than the others"*[P5], and *"hard to forget"*[P8]. P13 further elaborated that *"seeing and being actuated leads to not forgetting [...] I knew the correct movement because EMS helped me to move and then I could double-check with the visual."* Furthermore, the signs learned using the *combined* condition were rated the best by our ASL experts and resulted in a better user experience than *audio* and *video*. Additionally, our results show that it was the second best after audio in terms of memorability, which was reflected by the number of hints needed.

Overall, this condition has the potential to combine the benefits of the *visual* and *EMS* conditions. Specifically, it provides feedback and clear instruction via the visual component and a feeling of guidance via the EMS component. On the one side, visual instructions add a high level of certainty as it provides visual cues for how to execute the overall sign. On the other side, the EMS feedback reinforces the visual cue by initiating and stepwise guiding the execution.

> **Implication 4:** Using EMS and visual instruction together provides a good user experience. Moreover, using EMS actuation along with visual instruction might help to prevent errors that can happen if only EMS is used

Limitations We acknowledge the following limitations in our work. Learning ASL requires one to learn hundreds of signs and to perform them in sequence, which takes a long time, and therefore, requires users to stay motivated. In our study, however, we focused on only four signs to be remembered for two weeks. Thus, the generalizability of our results towards sign languages, in general, remains uncertain. However, our findings can be understood as an upper-performance limit because with more signs and higher complexity better learning results are unlikely. Furthermore, we mainly use signs as a part of sign language learning. We do not explore further aspects of these languages, such as hand shapes and facial expressions, which take additional time to learn, and therefore, require users to maintain motivation.

In addition, our focus in this chapter is to investigate the role of technology in teaching sign languages. Therefore, we started from the beginning by exploring a small aspect before reflecting on the bigger picture. This small aspect is the arm and hand movements used in executing signs (the first stratum of four [359]). Based on the feedback received from our experts, if the technology were to be used in real life, the sign as a whole should be evaluated, not only part of it. However, given the complexity of covering the sign (e.g., knowing the meaning, using facial expressions), we started by exploring the primary potentials of each modality.

7.6 Conclusion

In this chapter, we explored the use of EMS in enhancing the learning experience of sign language. In a user study, we compared the learning effects of various modalities (ie. audio, visual, EMS, as well as a combination of visual and EMS). While deaf or hard-of-hearing people may not benefit from all the presented learning conditions, it was still interesting to carry out a primary investigation to highlight the challenges and potentials for each modality (including audio), especially considering family members and friends of DHH people. A two-week study with 17 participants showed that visual-based instruction is preferred for the most detailed communication and conditions including EMS provide the best overall experience. The evaluation by ten ASL experts indicates a significant difference between the overall performances of the signs learned via the combined condition and those learned via the audio condition, with the combined condition rated as best. We identified the strengths and weaknesses of each modality used, contributing to the understanding of how the choice of modality can impact the learning effects and experiences in technology-based learning. Thus, we believe our work help improve the technology-based autodidactic acquisition of sign languages.

Summary and Key Findings

In this part, we investigated the use of EMS technology to augment the human across several scenarios. We started by exploring a weight manipulation scenario in VR. We proceeded by exploring the potential of using EMS for improving golf putting angles. Ending with a scenario for teaching ASL. From these three studies, we conclude the following main points.

Key finding I: The key to a realistic perception manipulation via EMS is to actuate all the muscles involved as in real-life movement dynamic.

Our results in Chapter 5 showed that weight manipulation via EMS in VR is feasible. Furthermore, the results highlight the difference in weight perception across the different actuated muscles. One main outcome, however, that was retrieved from the participants' comments is that the different muscles should be actuated at different time points to imitate a real-life biceps curl.

Key finding II: The combination of EMS and human can outperform an actuation without human involvement.

In both Chapter 6 and Chapter 7, the results indicate that the participants were best in the conditions that involved visual input along with the EMS actuation. Although the source of the visual input came from two different entities (i.e., system feedback as in Chapter 7 & real world observation as in Chapter 6), having another sense involved is better for motor skill acquisition and execution.

Key finding III: EMS is well suited for motor skill correction for beginners.

In Chapter 6, we observed that the EMS system improved the performance for the participants who did not perform well in the base condition. Further, in Chapter 7, we noticed that participants were trying to perform the signs wrongly when we also provided visual feedback. However, as soon as they felt the actuation, they corrected their movements. Based on this, we conclude that EMS could be used to guide beginners to execute a certain motor skill.

IV

Inducing New Human Action & Perception Using Electrical Muscle Stimulation

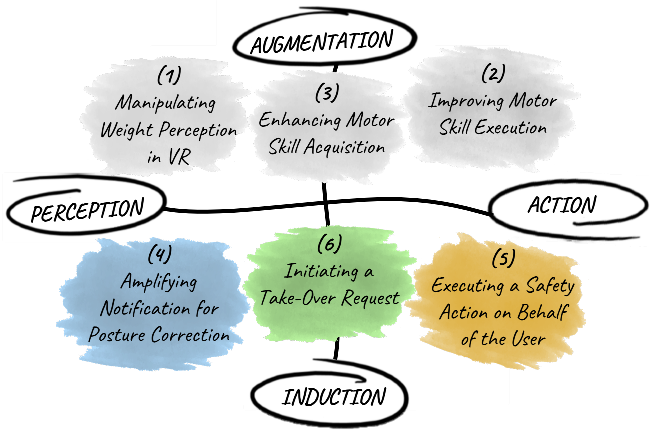


Figure 7.9: EMS Application scenarios presented in this part. The applications induce new actions or perceptions in the users.

Overview

In this part, we focus on the applications that introduce to the users a new action or perception. The applications focus on directing the users' attention to a certain request. The decision of executing the action differs then according to the use case. Throughout three different studies, we explore three different potential levels of EMS feedback to direct the user's attention to do an action, initiate an action execution, and execute an action on behalf of the user.

In the first scenario, we use EMS to communicate posture correction notifications in racket-based sports. The decision of executing the action (i.e., correcting the posture) is fully dependent on the users. In the second scenario, we execute a safety action on behalf of the user. Here, to avoid any potential collision with the real world, we pull the users' arms backward using EMS while being fully immersed in a VR game. In the last scenario, the action execution decision level is shared between the user and the system. In an autonomous vehicle scenario, we use EMS to communicate Take-Over Request (TOR) by raising the users' arms towards the driving wheel. The decision of how the take-over maneuver should be executed depends then on the user.

Chapter 8

Amplifying Notification for Posture Correction

This chapter is based on the following publication:

Faltaous, S., Hubert, A., Karolus, J., Villa, S., Kosch, T., & Wozniak, P. W. (2022, February). EMStriker: Potentials of Enhancing the Training Process of Racket-based Sports via Electrical Muscle Stimulation. In Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI22).

In this chapter, we investigate the first scenario of using EMS to communicate a posture correction notification. This matches the *Perception Induction* in our taxonomy. In this use case, the EMS actuation does not lead to a movement but communicates a notification that the user can react to upon receiving the actuation.

Research in wearable gadgets is increasing every day. For sports practitioners, new sensors made it possible to track and quantify their activity. One example that is extensively used in racket-based sports is Zepp Tennis 2[22]. The data collected is used to represent the vital performance attributes of the athletes

[22] www.zepplabs.com/en-us/tennis

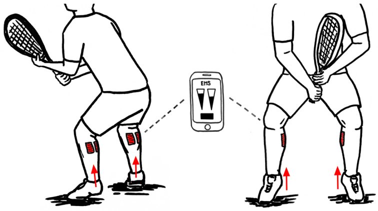


Figure 8.1: Adjusting the ready position of crossminton players by actuating the calf muscle to modify their feet posture using electrical muscle stimulation.

helping them to reflect on and develop their performance. In our work, we investigate alternative ideas to improve and augment the users' performance during sports training. To be exact, we explore the potential of using EMS in providing feedback in commonly practiced sports like crossminton [23] Our motivation is based on the complexity of learning racket-based sports as it depends on having a coach, continuously developing new techniques as well as the difficulty of obtaining exact measures [168] Sports training could be counted as a skilled motor performance that needs both cognitive and motor skills [9]. Acquiring such skills requires constant training, which is commonly verbally done through coaches' feedback [9].

Contribution This chapter investigates the user requirements and opportunities for augmented coaching using EMS in crossminton. To that end, we provide the concept for an EMS-based feedback system (cf., Figure 8.1) that supports players in maintaining the ready position while playing crossminton. We first contribute a (1) user study, where we compared the effectiveness of EMS feedback at varying intensities to vibrotactile feedback. We subsequently conducted (2) contextual interviews with crossminton players and coaches. Based on the gathered data, we present (3) insights on the integration of EMS into crossminton practices that help users to develop motor skills using EMS.

8.1 Background and Related Work

Given the complexity of executing such complex movements and performance, verbal feedback might not be sufficient. Previous work investigated the role of

[23] A racket sport that combines elements of tennis and badminton.

interactive technologies in supporting sports technique development. However, technology has been showing some potential in supporting the learning process of some sports through different modalities. Researchers have been exploring the effect of using visual feedback in VR to support tactical training in basket ball [166] or simulating outdoors rowing [111] or cycling environments [42, 276] as well as realistic archery scene [123]. Other research focuses on examining the role of auditory signals in the training of running athletes [80], providing feedback during gymnastics [25] or dance performance [371]. Other research has been investigating the impact of providing haptic feedback in virtual canoeing [398, 345], rowing [354] & golf area environments [109] or while running [410] or snowboarding [378]. Further work in deadlifts, GymSoles [78] showed that interactive feedback could guide the users in executing various complex techniques. Also, Subtletee [434] explored the role of augmenting the gold swing performance using interactive feedback. On one hand, the previous examples, while highlighting the potential of using technology in augmenting performance, their feedback doesn't depend on direct feedback. As they require the human to pay to attend and then act upon the received feedback. On the other hand, the EMS technology grants us the chance to provide direct intensified feedback that goes through the body and is not just externally communicated. Therefore, there is a need to investigate the role of such technologies in fostering the process of learning and developing new techniques.

Wolpert et al. [429] suggest that there are skills that are not unitary experience (e.g., tennis game), but rather divided into four main sub-processes: These sub-processes are (1) gathering sensory information (i.e., sensory input guided by previous experience), (2) learning key features of the task, (3) setting different classes of control, and, (4) anticipating and countering the opponent's strategy. In this chapter, we explore the role of EMS in teaching a key feature (i.e., ready position) in the Crossminton sport using EMS.

EMS offers potential in enhancing sports and training, where it has been used since the 1960s when the Russian Olympic team trained using EMS [416]. HCI researchers explored the use of EMS in adjusting the foot angle before landing while running [144] or correcting the putting technique in golf (cf., Chapter 6). While the previous work focused mainly on the potential of EMS technology, there was less focus on establishing the user requirements for EMS technology to be integrated into amateur sports, both for players as well as coaches. In this chapter, we investigate how players perceive EMS and if they would be willing to make it part of their sports practice. Moreover, past exploration of the use of EMS in sports HCI was primarily targeted at developing a corrective device. In contrast, this chapter explores the potential role of EMS in developing sports mastery and enhancing the existing coaching process.

8.2 Implementation

We consider using EMS-based feedback as an assisting modality while playing sports. We focus on crossminton because it is a sports discipline with a particular focus on training a correct ready position. This ability is key for quick preparation for the opponent's next actions. Informed by related work, we envision EMS as a training tool that subtly actuates the trainee to adjust their ready position, resulting in maintaining correct positions even when no EMS stimulation is present [186].

Vibrotactile feedback has been used in sports before since it is not high-priced and simple to use (e.g. [434]). In a scenario where vibrotactile feedback could be a viable design solution, we suggest an EMS-based system to assist racket sports practitioners. As a result, we compare vibrotactile feedback to EMS in our research. This allows us to (1) assess the feasibility of racket sports training using EMS-based systems and (2) compare the strategies and their benefits and drawbacks in a racket sports setting.

In our implementation, we used two systems one for the EMS feedback and the other one to provide the vibrotactile feedback. For the EMS, we used the *Let your body move* toolkit, presented by Pfeiffer et al. [318]. The basic frame of the prototype looks like a belt that has both the module and the battery attached to it. This ensures an easy connection of the electrode cables to the calf muscles. The module is then connected via blue tooth to a mobile application that the users could use to self-calibrate the intensity. To ensure high safety measures, the maximum signal strength set on the medical device couldn't be increased with the application (i.e., 50 micro ampere). Based on previous work, we set the stimulation frequency to 120Hz and the pulse width to 100 microseconds.

8.3 Newbie Players Study

In this section, we describe a user-centric evaluation of the feasibility of using wearable EMS-based feedback in crossminton sports.

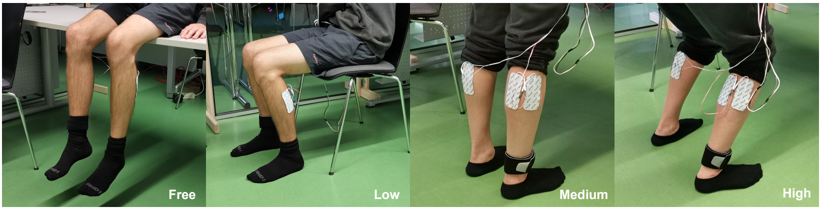


Figure 8.2: Tension

8.3.1 User Study Design

Electrical muscle stimulation generates external electric impulses that directly influence the muscles. As a result of externally inducing the current the muscles contract leading to a movement of the body component that is associated with that muscle (e.g., a calf muscle contraction affecting the foot movement). For professional players, muscles are continually adjusting the electric intensity (i.e., received from the brain) in order to move from one position to another, making this an important factor in our application. As a result, this variable is taken into account in our research. Using the previously mentioned system, we did a two-factor within-subjects study: (1) Feedback modality with two levels (EMS, vibrotactile) and (2) calf tension with four levels (EMS, vibrotactile) (Free, Low, Medium, High).

8.3.2 Participants and Procedure

We controlled the muscle tension level by varying the participants' positions. For the *Free* condition, we asked the participants to sit on a table, while leaving their feet hanging without touching the ground. For the *Low-level* condition, we asked the participants to sit on a chair, while having their feet on the ground. For the *Medium-level* condition, we asked the participants to stand up with a straight back. For the last condition with *High-level* condition, we asked the participants to apply for the ready position. We visually approved all the conditions. All the participants experienced all the conditions with various tension and feedback levels. The order of the displayed modalities and the different conditions within each modality were randomized to avoid any pattern effect.

Overall, we had 13 participants, of which 4 identified themselves as females and 9 as males. The age range varied between 19 to 61 years old (M=28, SD=10). Seven of them practice sports regularly (1 to 14 hours per week, M=6.43, SD=4.48). Six participants had no previous experience with EMS.

For the vibrotactile feedback, we used the so-called v-band actuators. They consisted of an elastic band to be mounted around the limbs, to target the same calf muscle as in the EMS condition. The actuators are connected to a microcontroller with four Linear Resonant Actuators (LRA) each, which is connected via WiFI to a mobile application. Again, the user could use the mobile application to adjust the frequency of the vibrotactile motor.

At the beginning of the study, after providing the study description and the consent form, we presented the participants with a manual explaining how they should wear the system and, mount the electrodes and the motors. Our study design met the ethics regulations of our institution. After experiencing each condition, each participant had to fill in a questionnaire, we customized four questions to reflect on the feedback quality provided by each condition (cf., Table 8.1). Furthermore, after each modality, we asked the participants to answer three questionnaires, namely; the intrinsic Motivation Inventory (IMI), the Sense of Agency Scale (SoAS) and the Perceived Creepiness of Technology Scale (PCTS). In the end, through a semi-structured interview, we asked the participants to provide more in-depth insights regarding feedback quality and reflecting on its use in the cross-minton. The study duration was around 65 mins.

8.3.3 Results

The placement time for the EMS setup ranged between four to seven minutes (M = 11.75, SD = 3.48) and between one to four minutes (M = 2.08, SD = 0.90) for the vibrotactile setup. A Wilcoxon signed-rank test on the feedback quality questionnaire yielded significant differences ($p < .05$) between EMS and vibrotactile modalities regarding items 1 and 3 (cf., Figure 8.3) For item 1,

Item	Question
1	The feedback nudged me in a specific direction.
2	The feedback made my body move on its own.
3	I was in control of my movements.
4	I could associate a movement with the feedback.

Table 8.1: Customized questions to assess the quality of the feedback.

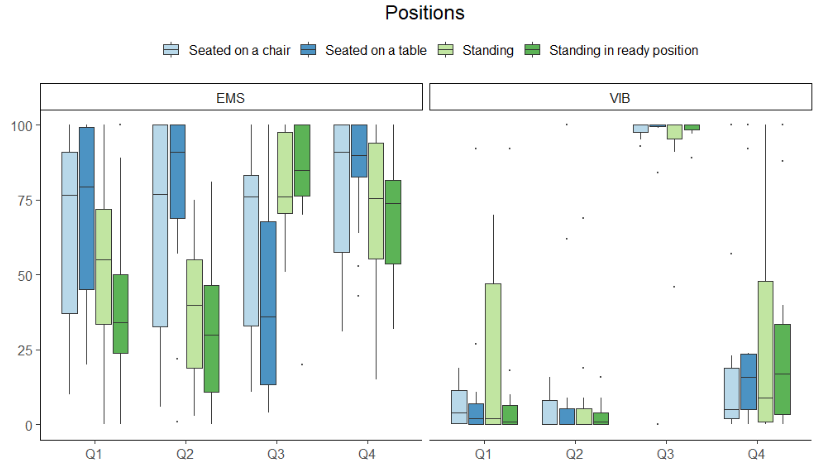


Figure 8.3: Customized questionnaire to reflect on the feedback quality provided by the different conditions and modalities. The ratings of feedback quality questionnaire in Table 8.1) from "Strongly disagree" (0) to "Strongly agree" (100) shows statistically significant differences for EMS and vibrotactile feedback, except for item 1 and 3 in the standing position.

participants perceived EMS moving them toward a specific direction. At the same time, vibrotactile feedback made them feel in control of their movements

A Wilcoxon signed-rank test showed significant differences ($p < .05$) in the IMI pressure subscale, which indicates less negative feelings towards vibrotactile modality (cf., Figure 8.4). The SoAS yielded significant differences ($p < .05$) in two of the subscales: Positive Agency (SoPA) and Negative Agency (SoNA). In both cases, participants experienced more agency while using vibrotactile feedback. Furthermore, the mean PCTS score for vibration is 43.5 (SD = 6.72), EMS scores very similar at 43.8 (SD = 8.54). An ANOVA confirmed that prior EMS experience had no significant effect on the perceived creepiness in participants ($F[1,10] = 1.23$, $p = 0.28$). within the study context, the EMS system induced a similar level of creepiness for the users as the vibration system despite the less experience and underlying knowledge of the technology.

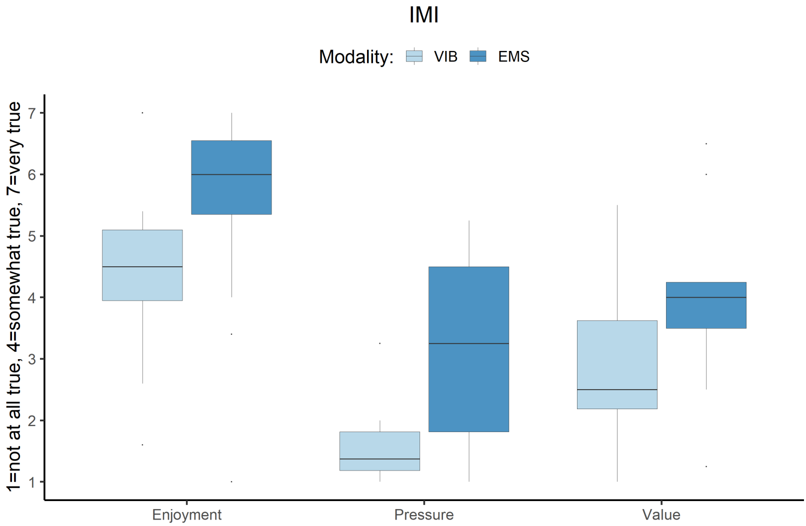


Figure 8.4: Participants' ratings of IMI Questionnaire. In contrast to enjoyment and value, a significant difference was shown between EMS and vibrotactile feedback for the pressure subscale.

8.3.4 Interviews

We used the pragmatic approach for the qualitative data analysis [31] ($1:58\,h$, transcribed verbatim). We identified three themes in the data: *Sense of Control*, *Feedback Clarity* and *Novelty Effect*.

Sense of Control Our participants indicated that in the case of EMS they could actively suppress the movement induced by the EMS as P3 mentioned *"I did not have to do anything that I did not want to actively do"*. P6 further elaborated that *"it's more like I was controlling my legs with my hand"*. This further reflected their sense of control over their own movements as P2 concluded *"I would not have the concern because I have the device in my hand"* and *"I was initiating or stopping what I was doing "* [P13]. Others linked the provided feedback as an external guide indicating what they should do as P6 explained *"it was like I was telling them to make movements."*. P13 further elaborated that he *"can have control over the test action...not in control of the test results."* In this use case, the participants still felt safe as P2 indicated that *in doubt I could pull the plug"*.

Feedback Clarity When comparing the vibrotactile feedback with the EMS, the participants stated they found the intent of the vibration feedback unclear, highlighting it as a *"passive information modality"* [P7]. The participants further elaborated, that in the case of EMS they felt like it was actually *"doing something to the body"*[P1] as it felt as if it was pushing them *"forward"* [P6]. The participants further highlighted that the EMS feedback was most noticed in the standings position as P2 described it *"I found that in standing you somehow got the impression that it pushed you forward a bit. While sitting, both on the table and on the chair, I hardly had that at all. I even think that normal standing is a little stronger."*

Novelty Effect The participants mentioned that they felt more comfortable using the vibrotactile feedback as it is more familiar. However, they mentioned that they would also use the EMS under clear predefined settings. On one side they described the feedback related to the vibrotactile as *nothing unfamiliar* [P12], *already known* [P4], and *vibrates like a phone in your pocket*[P6]. On the other side, they described EMS as *unknown feeling*[P9] that *one comes into a rare contact with EMS, if at all* [P2]. P11 reflected on the EMS self-adjusted intensity that he perceived as comfortable by mentioning that *as soon as you get used to it, you can go beyond it.*

8.4 Experts Interview

To further identify requirements and opportunities for EMS-based assistance systems, we conducted interviews with coaches, in particular addressing example use case scenarios and probing their expertise with regard to integrating such systems in existing training schemes.

8.4.1 Training schemes

The first use case that we asked the trainers about is agility training. This represents the first training part, which includes dry exercises to practice moving quickly on the court without real rallies (cf., Figure 8.6). We envision the EMS to be used to correct the ready position required by the players at each corner of the front line.

For a second example, we used Practicing rallies as the second use case we asked the coaches about, where the players practice different rallies such as fast rallies, front line, and backhand rallies. The main aim of the scenario is to internalize the correct movement on the court and to practice target shorts.

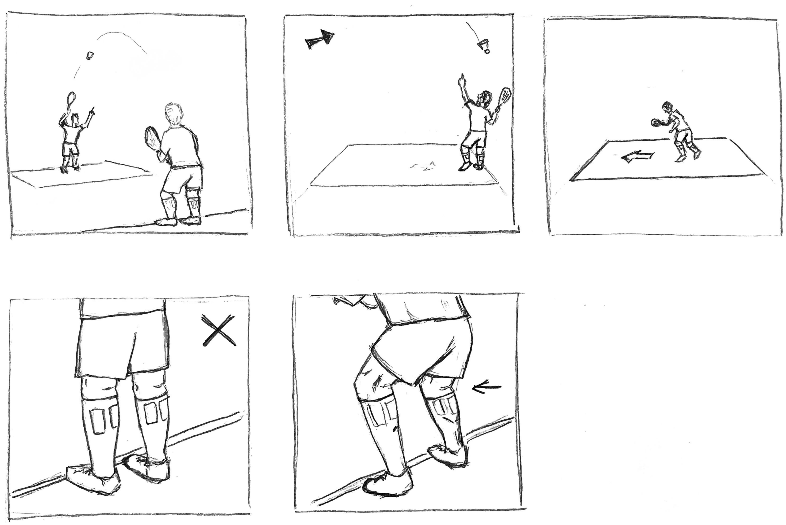


Figure 8.5: Practicing rallies in crossminton, where the players practice correcting their position in a real rally.

Again, similar to agility training, after each hit the participant needs to go back to the front line and take the ready position (cf., Figure 8.5). In the last presented scenario, we presented a training match, where the EMS could correct the players' position while waiting for the opponent to their serve. In the last presented scenario, we presented a training match, where the EMS could correct the players' position while waiting for the opponent to their serve.

8.4.2 Participants and procedure

We recruited a total of six coaches (5 males, 1 female), all teaching crossminton for multiple years ($M = 13.7y$, $SD = 14.0y$). All interviews were guided by three examples of training scenarios illustrated by storyboards. Two interviews were conducted face-to-face with experts (E2, E4) testing the EMS system personally, while the rest were conducted via an online video call presenting an introduction to the system.

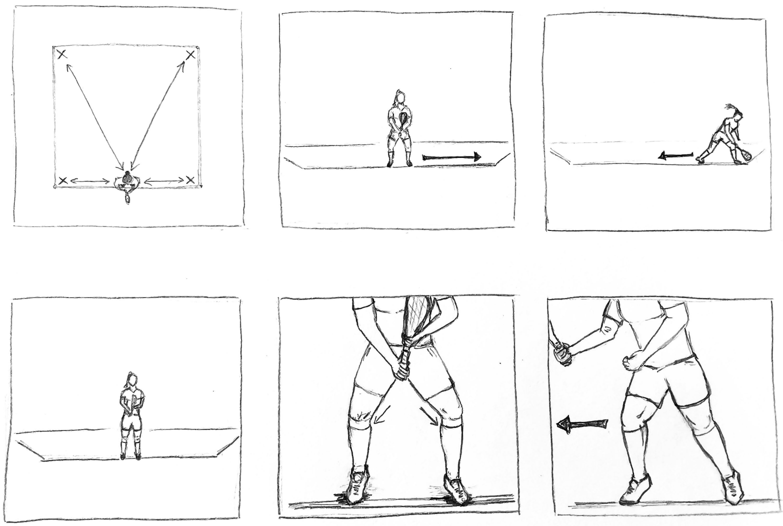


Figure 8.6: Agility training in crossminton, where the players train to adjust their position without being in a rally .

8.4.3 Results

We applied the same thematic analysis procedure as in the first study interviews (2 : 28 *h*, transcribed verbatim). Our analysis produced three themes, which address integrating EMS-based feedback in racket sports: *System Efficacy*, *Practice Integration*, *Learning Effect*. We shortly highlight each theme and its importance for EMS-based feedback systems below.

System Efficacy The experts identified the potential of EMS-based feedback based on its being punctual, precise, and clear. The most commonly used vocal instructions[24] are prone to misinterpretation by students. Here, the experts emphasized that EMS can directly trigger relevant muscle groups (push-to-action), which is especially beneficial in complex scenarios and deep concentration phases.

> "(...) it means that the focus is much higher on the relevant part and thus the implementation [of feedback] is easier because it

[24] A coach shouting from the sideline.

> does not pull you out of 20 factors, but you can really concentrate on one factor." [E4]

Further value was placed on the unobtrusiveness of such a system. No other players are disturbed and social stigma can be prevented.

Practice Integration Our experts confirmed that the three presented example scenarios were highly relevant in everyday crossminton exercises and commented that the unambiguous definition of this position is advantageous as it leads to clear design requirements on how and when to actuate EMS. Particularly in highly-focused scenarios like a match, where *"(...) you're thinking about something else and you're focused on every point but you're not focused on this [ready] position"* [E5]. E4 further added *" The problem is, we don't have a real coach and I think it's ideal as a complement and support for the coach, but maybe it can also be a boost when you say, "Well, we don't have a real coach, but we have systems so that a trainer only has to add a little to make a complete training out of it"."*

Overall, the experts identified basic movement training as a suitable use case for EMS-based feedback, making it a suitable addition to any practice routine as E2 elaborated *"Of course, I would not use it at the very beginning because people don't yet know what to do and there is still far too much complexity to think of everything. You might not focus on that first"*

Learning Effect Coaches commented that such feedback can effectively notify the players about posture mistakes, allowing players to reflect on the feedback and learn when to take up the ready position. Compared to other feedback modalities, coaches especially highlighted the ability of EMS to guide players into the correct position as E3 said *"(...) you will notice, "Aha, that's how I feel then, okay." I think that could only be positive."*

In the eyes of the coaches, the reminder effect and the immediate reflection on mistakes is a key elements to stimulate proper learning:

> "The idea is that [the student], who actually knows [the ready position], should be reminded "now I haven't done it". They do not even notice [the mistake] and are notified at the moment when the mistake happens. And I think that's where the learning effect actually comes into play." [E2]

8.5 Discussion

Following we discuss the results obtained from our studies. We, therefore, integrate the input from our participants and the experts.

Communicated Information Clarity Both the trainees and the coaches highlighted the advantage of using EMS over vibrotactile. Here, participants remarked that feedback via EMS is more explicit as the direction of movement is communicated as well. On contrary, vibrotactile communicated feedback was perceived as more alarm-like rather than guiding towards the correct action as was the case with EMS. The coaches further elaborated on the benefit of this point, as they implied that using the EMS to directly actuate the players would prevent inducing more cognitive workload. Vibrotactile feedback is an option when the user's priority is a simple notification to bring themselves into specific positions. Our results show that EMS communicates clear information that guides the players to correct their ready-posture in racket-based sports.

Experience and Agency Our results indicate that the participants favored the vibrotactile over EMS, due to two main aspects. The first one is familiarity with the feedback type, which they consider a motivating aspect to them. As one of the concerns they had is not having enough experience with the EMS. The second aspect is the sense of agency [308]. While the participants understood clearly the communicated feedback via EMS, they perceived it as a controlling system rather than a guiding one. Previous work has suggested manipulating the EMS signal attributes to overcome this challenge [265, 205]. In our work, the participants had the control to adjust attributes (e.g., signal intensity) of the induced EMS signal and the intensity of the vibrotactile feedback. The participants' rating of their sense of agency was better in the case of vibrotactile feedback. Furthermore, the control would be handed to the coaches in future real-life training scenarios, where the initial triggering of the signal would be done by the coaches. The need for negotiating agency remains an open question in HCI for sports. Our work shows that more comparisons between prescriptive (e.g., EMS-based) and reflective (i.e. feedback-based) systems are needed to better understand how we can effectively guide users to better sports techniques without building a dependency on technology. We conclude that negotiating agency is an open challenge with EMS, which is not limited to previous experience or self-calibration.

Practical Integration The coaches indicated that the system is practical for guiding the players to adjust their *ready* posture in racket-based sports. However, they highlighted that the system is not a standalone technology that could replace the coach's instructions, but rather an active reminder of what the correct actions should be. These findings echo past work in HCI for sports where users preferred devices integrated into existing equipment over adding new devices [201]. Therefore, EMS showed a potential for supporting posture correction during the training process, however, it should not be accounted for as training replacement.

Limitations We acknowledge the following limitations to our work. Participants experienced the EMS in a lab setting and not while actually playing, which would need to be further explored in real-life settings. Moreover, two out of six coaches that we interviewed have experience with EMS.

8.6 Conclusion

In this chapter, we present an EMS-based system that guides the ready position execution in crossminton. We evaluated the system through two user studies. In the first study, we explored the differences between EMS and vibrotactile feedback as experienced by trainees. In the second study, we interviewed professional trainers, who provided more insights into EMS feedback communication. From the two studies, we found that EMS has a higher potential of communicating the correct action to be executed in comparison to vibrotactile feedback. However, the communicated feedback is subject to design constraints, as detailed in our findings.

Chapter 9

Executing a Safety Action on behalf of the User

This chapter is based on the following publication:

Faltaous, S., Neuwirth, J., Gruenefeld, U., & Schneegass, S. (2020, November). SaVR: Increasing Safety in Virtual Reality Environments via Electrical Muscle Stimulation. In 19th International Conference on Mobile and Ubiquitous Multimedia (MUM20).

In this chapter, we shift to another category in our taxonomy that is *Action-Induction*. Here, we actively pull the users' arms backward as a safety measure to not collide with real-life objects while being immersed in Virtual Reality (VR). In the last decade, VR has moved from niche to mainstream. Recent technological advancements in VR headsets offer users an immersive open experience, even in narrow places (e.g., in living rooms). This sense of immersion is created mainly by addressing the users' vision, shifting their focus only to the virtual environment, and obstructing their perception of the surrounding real-world environment [428].

While the range of motion and immersion in the virtual scene continuously increases, perception of the real world further diminishes. However, loss of this perception can result in serious danger and injuries for users since they

Figure 9.1: SaVR uses Electrical Muscle Stimulation (EMS) to prevent users from hitting physical obstacles while experiencing Virtual Reality (VR) applications. EMS actuates muscles resulting in an automated movement that pulls the arms away from a physical obstacle and thus increases the safety of the user.

lose spatial knowledge and are thus unaware of obstacles such as furniture and walls. To our knowledge, little research has been conducted to investigate means for preventing these incidents and ameliorating safety in interactive VR environments. While systems that communicate boundaries to users exist (e.g., Oculus guardian system[25] and HTC Vive Chaperone[26]), the immersive experience can result in users not taking notice of systems' feedback.

To tackle this problem, we present SaVR, a wearable Electrical Muscle Stimulation (EMS) system, for increasing users' safety in VR. In contrast to visual and vibro-tactile feedback, EMS actively prevents the movement that would result in a collision with a real-world object by actuating the antagonist muscle to the user's movement. Thus, our primary goal is to actively prevent the user from hitting any object in the real world rather than communicate its existence to the user. For example, when the user wants to reach forward to catch items in VR, SaVR actuates the biceps so that the arm moves immediately backward and does not hit the cupboard in front (cf., Figure 9.1).

Contribution The contribution of this chapter is two-fold. First, we present SaVR, an EMS feedback system that protects the user in VR environments by controlling the arm movement. Second, we report on a user study with twelve participants, comparing SaVR to the commonly used feedback modalities (i.e., vibro-tactile, audio, and visual). Our results show that EMS was the best in

[25] https://nyko.com/collections/products/products/vr-guardian

[26] https://www.vrheads.com/how-customize-htc-vives-chaperone-steamvr

allowing the least overshooting out of the safe area. Additionally, it was the first-rated condition concerning the users' experience.

9.1 Background and Related Work

VR applications aim to provide an immersive virtual environment to the user. One approach to achieve a high immersion is to increase the haptic experience of users in the virtual world through, for example, a new controller [419], dynamic passive haptics [443] or flying feedback devices [208]. Others opted to improve the most common feedback modalities, namely, vibro-tactile, visual, and audio [259]. For instance, Rietzler et al. combined tactile haptics and visual manipulations to enhance kinesthetics in VR environments [348]. Furthermore, VR decreases the users' awareness of the real environment (i.e., bystanders or obstacles). Therefore, another research direction focuses on communicating information on the real environment either by providing notifications to the user [433, 303] or by integrating existing real environment objects in the VR [226]. These methods, however, reduce the immersion of the VR scene.

Recent studies have been exploring the application of EMS in VR. Auda et al. used EMS to control the direction of the user's movement similar to the work of Pfeiffer et al. [319]. They created the illusion of moving in a straight line while the user moves in a circular path avoiding bumping into walls of the real environment [17]. EMS was further used, along with vibro-tactile, to communicate haptic feedback for different virtual objects [326]. Within the same scope, it was extended to induce haptic feedback in VR. Lopes et al. proposed a way to enhance immersion in VR scenes by creating a sense of repulsion and counter-force whenever the user tries to hold an object or hit a wall [255]. Further studies additionally explored the application for providing realistic impacts [248] or applying such a system in mixed reality [256]. In contrast to this, this chapter's goal is not to increase immersion by communicating haptics of virtual objects but to protect users of virtual reality systems from hitting obstacles in the real world.

9.2 The SaVR Approach

We propose using Electrical Muscle Stimulation (EMS) as a new modality for increasing safety in Virtual Reality (VR) environments. Our approach has two main benefits. The first benefit is that it has a direct intervention on the body movement, ensuring the users' safety even in cases of high immersion and late reactions to warnings. The second benefit is that it does not interfere with the users' cognitive load, as it does not require any attention shift to the presented cues. That allows more attention to be on the actual task [7].

The concept of EMS is to directly influence the body motion using electrical impulses to elicit muscle contractions. These contractions lead to different motions, depending on the actuated muscle [266]. An external signal generator is used to generate the impulses, which passes the electrical signal to an electrode placed directly on the targeted muscle. EMS imitates humans' physiology, as in real life, the brain actuates our muscles by sending action potentials (i.e., electrical signals) generated from our nervous systems, causing different muscles to contract, and resulting in the corresponding body-part motion [266]. Previous research used EMS to control different movements of the body. Researchers actuated the arms empowering users to perform sign languages [146], or the hands allowing users to play an instrument [395]. Further, EMS has been used to actuate the legs to induce navigational commands [319] or correct gait [58, 422].

In this approach, we strive to protect the user from injury. One of the most common movements that might result in injury is when the user reaches out to an object in the virtual world. To prevent that movement, we actuate the antagonist muscle (i.e., the biceps).

9.3 Implementation

The suitability of the used feedback stimuli depends on the use-case [37]. Given that VR devices are nowadays mainly used for games, we implemented a game in Unity3D, where the participant's task was to catch falling balls. We placed a hidden hypothetical barrier 1500*mm* in front of the participants' starting position. This barrier mimics the real use case of having a physical obstacle (e.g., a wall) that hinders users from moving freely. Thus, the participant could freely move within this 1500*mm* barrier but would receive feedback as soon as the barrier was crossed. We designed the participants' task so that 20 balls fall at a random position in front of the barrier, and 10 balls fall behind it. Consequently, participants would be forced to move around and stretch their arms, trying to catch the falling balls, and for some crossing the safety barrier.

We used an Oculus Rift to display the VR application. We tracked the users' hands using a Leap motion mounted directly on the Oculus Rift and visualized it to increase the sense of immersion [379]. We conducted the study in a 4m by 4m tracking space. Our main measure is the movement of the participants' hands outside of the safe zone (i.e., beyond 1500*mm* from the participants' starting point). For that, we needed to track their hand position with respect to the real world when they were reaching for the balls. As soon as a participant's hand reached the barrier, we communicated the feedback to them. To compare our approach to the state of the art, we developed three other types of feedback (i.e., vibrotactile, visual, and auditory).

Vibro-tactile stimuli For the vibrotactile stimuli, we developed two wristbands using a battery-powered NodeMCU microcontroller and a disk vibration motor for each. We placed the vibration motor on top of the wrist of the participant as is done with the Nyko VR Guardian system. Once the activation trigger is received, the wristbands keep vibrating until the trigger is deactivated (i.e., the user moves his arms back to the safe area).

Visual stimuli For visual feedback, we implemented a translucent blue wall at the location of the barrier. We designed the barrier similar to that of the guardian system of the Oculus Rift. This feedback appeared as soon as the participant reached the barrier.

Auditory stimuli The auditory feedback stimuli were in the form of a beep similar to those of parking assistants in cars. As soon as the participant moved a hand through the virtual barrier, a beep sound was played.

9.4 Evaluation

We conducted a study in a controlled lab environment to evaluate the SaVR approach, which is based on communicating feedback via EMS. We compared our approach to three other feedback stimuli: visual, auditory, and vibro-tactile feedback. We investigated the objective measurements of the logged data (i.e., tracked position of the participants' arm) and the participants' experience measured through the user experience questionnaire (UEQ) [161] and the presence questionnaire [426].

9.4.1 User Study Design

In this study, we used a within-subject design. The overall goal is to compare the different feedback modalities (i.e., *EMS*, *Visual*, *Audio*, *Vibro-tactile*) with one another. Thus, the feedback modality is the independent variable. As dependent variables, we assessed the performance of the participants (i.e., reaction time, over-crossed distance), as well as their user experience and presence.

9.4.2 Participants and Procedure

We invited 12 participants (3 female, 9 male) aged between 19 and 33 years ($M = 25.75$, $SD = 4.59$) to our lab. The study took place in a quiet room without any other sources of noise. First, the participants filled out consent forms and read the study description. In addition, we verbally explained the study to ensure that the participants were aware of the different stimuli used. In particular, we made them aware of the safety restrictions of the off-the-shelf EMS we used. Then, we equipped the user with the EMS device and the vibrotactile wristbands. We attached two self-adhesive electrodes on each bicep muscle of each arm (cf., Figure 9.1). The contraction of these muscles would result in the arm's pull-back motion. Next, we calibrated the EMS device using the *let-your-body-move* toolkit [318]. At the beginning of the EMS trial of each participant, using signal generator, we adjusted the generated intensity to actuate the targeted muscle (i.e., biceps). As the actuating signal intensity differed from one person to the next as well as from one arm to the other, we started with a base signal of 5 micro Ampere and used a step-increase with the same value. We stopped when the actuation resulted in pulling the arm upwards.

We also indicated the sequence of the displayed modalities. Then, without using any feedback modalities, we provided a $1min$ trial, just to familiarize the users with the task. After the introduction, we presented each of the four conditions to the user in a counterbalanced order using a Latin square design. Every participant played the game with each of the four stimuli for around $2\ minutes$ each. The game was divided into two parts. In the first part the players had to catch 30 falling balls spread randomly across the play field (i.e., 10 after the barrier and 20 before the barrier). In the second part, without any falling balls, the participants had to guess the permitted playing area (i.e., area before the barrier). Afterward, after catching all the falling, we asked the participants to guess how big the permitted playing area was, namely, that before the barrier. For this, we asked participants to walk slowly around the playing area as close as possible to the border. We did not present any feedback during this measurement. For that, the participants verbally gave us a start signal for recording the tracked position.

Throughout the user study, one researcher made sure that participants did not bump into a wall. After every stimulus, the participant filled in the UEQ and the presence questionnaire to assess user experience and presence.

9.5 Results

For the evaluation of our system, we first measured the device-related delay for each of the modalities. Based on the observed delay, we analyzed our recorded data. We then examined users' experience and presence with the user experience and presence questionnaires, respectively.

In our study, we compared four modalities, relying on different devices to communicate the feedback to the participant. Since we measured reaction time and had two modalities using a wired connection (*Audio*, *Visual*), and two modalities using a wireless connection (*vibro-tactile*, *EMS*), it was necessary to take the delay induced by each device into consideration. To measure the delay, we implemented a simple UI in Unity3D (our main application), consisting of one button for each condition. Then, we used a camera to record the button press in the UI, and the response from the feedback-inducing device. For *Vibro-tactile* and *EMS*, we had to additionally use an oscilloscope to visualize the electrical activity and capture it with the camera. For example, for *EMS*, we connected two oscilloscope probes, one to each end of the *EMS* pads. In total, we took nine measures for each modality (one per minute). In line with previous work [133], we found the mean delay to be *85 ms* for *visual*, while we did not find a delay for *Audio* (likely because no rendering factor caused any delay). For *Vibro-tactile*, we measured a mean delay of *200ms*, and for *EMS*, we measured a mean delay of *390ms*. For *EMS*, we assume that the larger delay results from the used modulation device (to generate the EMS signal, cf., [318]), which adds further delay to the wireless connection [260].

9.5.1 Delay measurement

In our scenario, we used four modalities, in which we deployed different devices to communicate the feedback. Since our main focus is the reaction time, it was important to take into consideration the delay values induced by each device. For the visual modality, as we used Oculus Rift, we considered the delay value to be *85 ms* based on Gruen et al. [133]. For the Electrical Muscle Stimulation (EMS), we used the [318], which depends on 2 wireless connections. The first connection is a WiFi connection from the

PC to the android device. The second connection is through Bluetooth from the Android device to the EMS module that communicates the signal to the user. Previous literature has suggested that there would be observed latency in both connections [283, 260]. To measure the latency, we connected two oscilloscope probes to the two ends of EMS pads. Then, we implemented a UI button in Unity that would send a signal to the EMS when pressed. We video-recorded the electrical activity detected by the Oscilloscope throughout 9 trials. The mean value of the recorded delay was measured to be *390ms*. For the vibrotactile feedback, we used bracelets with vibrotactile motors. We communicated the signal also through WiFi. We computed the delay in a similar procedure as in the EMS delay (i.e., video recording). Our results showed that the mean delay based on the WiFi communication is *200ms*. No delay was computed for the Audio signal since it was communicated through a wired connection and no rendering factor caused any delay.

9.5.2 Reaction Time

We also investigated the reaction time in each of the modalities. That is the mean time taken by the participants from the moment they receive the feedback to the first moment in which they start to withdraw their arm.

The results show that the participants were fastest in the *Vibro-tactile* condition ($M = 1085ms$), followed by *EMS* ($M = 1307ms$), then *Visual* ($M = 1336ms$), and finally *Audio* ($M = 1840ms$). A Shapiro-Wilk-Test showed that our data is not normally distributed ($p < 0.001$), and thereafter we ran a Friedman test that showed no significant effect across the four modalities ($\chi^2(3) = 4.5, p = 0.212, N = 12$).

9.5.3 Over-crossed Distance

Next, we inspected the maximum over-crossed distance across the four conditions. That is the distance crossed from the time the participants received the feedback until the first moment when they pulled their arms backward.

The results show that the best-recorded performance was in *EMS* ($M \approx 200mm$), followed by *Vibro-tactile* ($M \approx 238mm$) then *Audio* ($M \approx 325mm$), keeping the *Visual* feedback ($M \approx 338mm$) with the highest over-crossed distance (cf., Figure 9.2). A Shapiro-Wilk-Test showed that our data is not normally distributed ($p = 0.036$), and thereafter we ran a Friedman test that revealed a significant effect across the four modalities ($\chi^2(3) = 11.9, p =$

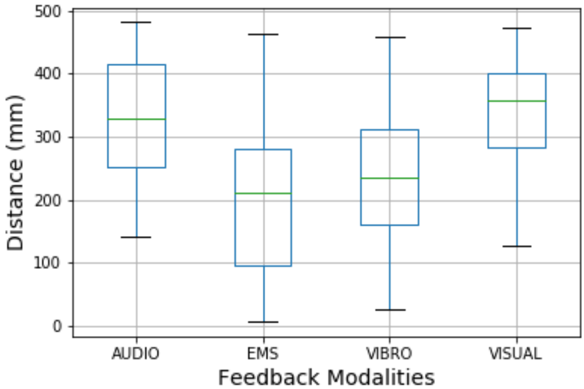


Figure 9.2: The maximum distance over-crossing the hypothetical barrier across the four feedback modalities

$0.008, N = 12$). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between the *Audio* and *EMS* conditions ($V = 4.0$, $p = 0.03$, $r = 0.77$), as well as the *EMS* and *Visual* conditions ($V = 2.0$, $p = 0.02$, $r = 0.19$).

9.5.4 User Experience Questionnaire

Looking at the results of the User Experience Questionnaire [230], the overall user experience is highest for the *EMS* condition ($MD = 1.68$, $IQR = 0.62$) followed by *Audio* ($MD = 1.12$, $IQR = 1.09$) and *Vibro-tactile* ($MD = 0.87$, $IQR = 0.56$). The *Visual* condition received the overall lowest ratings ($MD = 0.81$, $IQR = 1.46$) (cf., Figure 9.3). We ran a Friedman test that revealed a significant effect across the four modalities ($\chi^2(3) = 9.18, p = 0.0269, N = 12$).

Further analysis into the pragmatic qualities show that *EMS* ($MD = 2$, $IQR = 0.5$) and *Audio* ($MD = 1.62$, $IQR = 0.8$) have the best scores followed by *Visual* ($MD = 1.5$, $IQR = 0.5$). *Vibro-tactile* had the worst score among the four conditions ($MD = 1$, $IQR = 0.43$). A Friedman test showed a statistically significant difference in the scored pragmatic qualities across the four conditions ($\chi^2(3) = 11.97, p = 0.007, N = 12$). However, no statistically significant difference was observed from post-hoc tests.

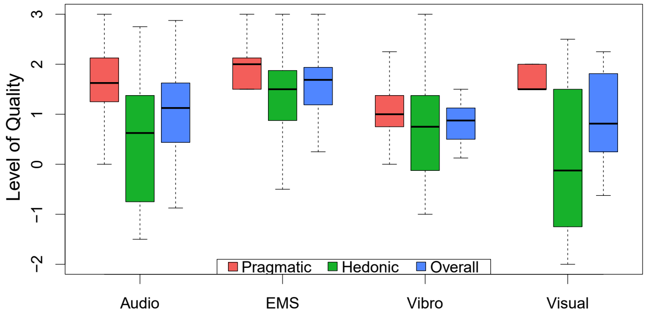


Figure 9.3: User experience questionnaire results. This shows the comparison between the four tested conditions overall and across both the hedonic and pragmatic evaluation.

In addition, the hedonic qualities show that *EMS* ($MD = 1.5$, $IQR = 0.75$) has the best score followed by *Audio* ($MD = 0.62$, $IQR = 1.93$) and then *Vibrotactile* ($MD = 0.5$, $IQR = 1.18$). The *visual* condition in this case had the worst score among the four conditions ($MD = -0.12$, $IQR = 2.62$). A Friedman test showed a statistically significant difference in the scored pragmatic qualities across the four conditions ($\chi^2(3) = 8.77, p = 0.032, N = 12$). However, no statistically significant difference was observed from post-hoc tests.

9.5.5 Presence Questionnaire

The results of the presence questionnaire show similar results for each condition except for the quality of interface sub-scale (cf., Figure 9.4). Here, visual feedback was rated as worse than the other conditions. However, Friedman tests could not show any statistically significant differences, each ($\chi^2(3) = 4.56, p = 0.2, N = 12$).

9.6 Discussion

Modality Previous literature shows that tactile feedback has the shortest reaction time when compared to visual and audio feedback [287]. That was also confirmed in our study, where the participants reacted fastest to the *Vibrotactile* stimuli followed by *EMS*. Further, it supports our approach of taking into consideration the delay in the analysis process. However, in the future, we

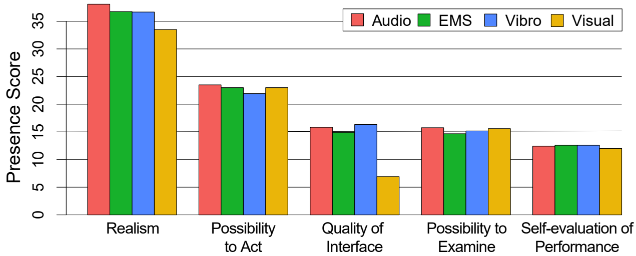


Figure 9.4: Presence questionnaire results. They show the comparison between the four tested conditions in each of the dimensions of the questionnaire.

recommend avoiding wireless connections. In a VR game, both the auditory and visual channels might already be overloaded [361]. Given this, it is better to use a different channel to prevent the user from missing the feedback, as our results indicate may happen. As previously examined [339], the latency for both the wired audio and visual feedback was negligible (i.e., 4ms) since they were communicated through the VR-headset, compared to the vibrotactile (i.e., 200ms for WiFi) and EMS (i.e., 200ms for WiFi and 190ms for Bluetooth), which had wireless connections. Thus, we reanalyzed the data accordingly removing the delay. This could be achieved by connecting the vibrotactile or EMS feedback directly to the head-mounted display. The results then show that in the case of vibrotactile and EMS feedback users reacted fastest and avoided the restricted area blocked by the barrier.

User Experience and Immersion In general, the gathered data generated promising results. The results of the user experience questionnaire show that users have a high acceptance level of *EMS*, as they rated the hedonic quality of *EMS* the highest. That was also reflected by the pragmatic quality, since *EMS* has the second highest rating, after the *Visual* condition. However, the *Visual* condition has the drawback that it reduces the immersion considerably by altering the visuals. Also, we highlight the fact that *EMS* has a different nature than the other stimuli. *Visual*, *Audio*, and *Vibro-tactile* require a different amount of attention and induce various cognitive loads which might further negatively impact the user experience.

Application Scenarios In this chapter, we explored a simple grasping scenario. Besides grasping several other movements might result in injury. We used *EMS* to actuate the biceps to prevent the user from grasping further.

Related work shows that other muscles could also be actuated to either prevent the user from walking into obstacles [17] or kicking them [248].

Limitation We acknowledge the following limitation of our study. We designed an interactive virtual reality scene to provoke the user to actively move and, consequently, have a high sense of immersion without paying attention to the real physical world. The falling balls were good for that purpose, yet, the balls fell in one direction (i.e., in front of the user). Therefore, the user did not experience moving in a different direction (i.e., rotating). This affected the kinesthetic motion learning curve. Furthermore, the scene provided only visual stimuli. This is slightly different from current VR games which typically provide auditory feedback as well.

9.7 Conclusion

In this chapter, we presented SaVR, an Electrical Muscle Stimulation (EMS) system that increases user safety in Virtual Reality (VR) environments in which the users' spatial knowledge is limited only to information provided by the VR environment. The concept of EMS is to induce an electrical signal on a targeted muscle to actively pull it away from hitting any obstacle in the real world. While there are several stimuli to communicate warnings to users in VR (e.g., visual, auditory, and vibro-tactile), none of them influence the user's actions without requiring additional attentional shift and increasing cognitive load. We implemented our system and evaluated its performance with 12 participants by comparing the results with the most known feedback stimuli (i.e., *Audio*, *Visual*, and *Vibro-tactile*). We demonstrated that SaVR provides the best secure performance and results in the best user experience.

Chapter 10

Initiating a Take-Over Request

This chapter is based on the following publication: Faltaous, S., Schönherr, C., Detjen, H., & Schneegass, S. (2019, November). Exploring proprioceptive take-over requests for highly automated vehicles. In Proceedings of the 18th international conference on mobile and ubiquitous multimedia (MUM19).

This chapter is the last scenario we explore in the induction dimension. The scenario presented here represents an overlap between action and perception. The user is actuated as part of a take-over request (TOR) while autonomous vehicle. The decision of completing the TOR is then up to the user.

The near future-offered autonomous vehicles would mostly belong to level 3 automation, which allows the driver to have "eyes-off" driving granting the chance to be engaged in a non-driving task (e.g., reading a book or watching a movie [329]). This level, nonetheless, still requires the driver to intervene whenever the system fails to operate under specific conditions. In other words, if the system accuracy is below a certain threshold the driver would be notified to take over. The research explored various aspects of such (TORs). Particularly the modality used to communicate the TOR has been explored

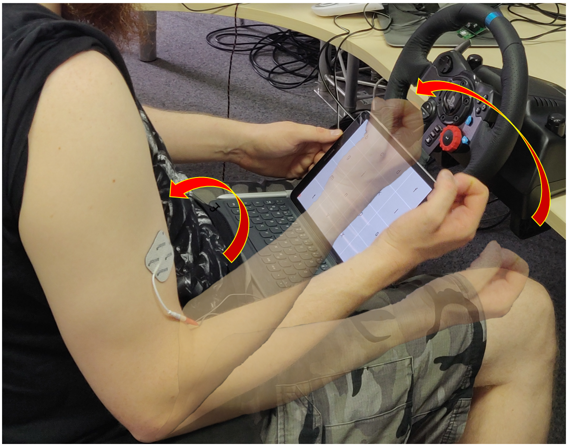


Figure 10.1: Arm motion actuated by the EMS to be pulled upwards reaching the height of the driving wheel the drivers could afterward grab and steer the wheel into the opposite direction easily.

in detail. Currently, research focuses on classical modalities (e.g., visual, auditory [413, 316, 33]) that are also engaged by the secondary task that can be done while the car drives autonomously. Thus, the driver might not immediately react to the TOR since that the used communication channel might be overloaded.

In this study, we explore actuating the human body as a novel way of communicating take-over requests in autonomous vehicles. For this purpose, we use electrical muscle stimulation (EMS) to actuate the drivers' arms to be directed to the driving wheel. This is communicated through proprioception to the user. We conduct a user study comparing the proprioceptive approach to currently used modalities. We found that the proprioceptive approach results in the second fastest reaction time and the best performance in the non-driving task.

Contribution The contribution of this study is two-fold: (1) We present the concept of proprioception as a novel modality to communicate take-over requests in highly automated vehicles. (2) We report on the results obtained in a user study, comparing proprioception to conventional modalities (i.e., Audio, Visual, and Vibro-tactile).

10.1 Background and Related Work

With the rise of Level 3 of automation, the role of human intervention in case of automation failures became crucial. Hence, researchers have been focusing on designing new techniques to communicate take-over requests (TOR). The main challenge facing the implementation of such techniques is how to get a disengaged driver back into the *"the driving-loop"*. They, therefore, have been trying to improve the quality of TORs either by implementing new techniques or improving the existing ones. One major quantifiable attribute that determines the quality of the TOR has been identified as a time to react (TTR). Note that this is also known as time buffer [118] or time budget [127]. To be able to measure it several aspects are being investigated, namely driving scenario, non-driving task impact, TOR issuing time, and modality. Not only that they are correlated but also each of them has a direct impact on the TTR.

10.1.1 Non-Driving Task Impact

In one study by Gold et al. [125] they showed that drivers are likely to intervene faster in urgent situations when they have their focus completely shifted to the road and don't have the automated feature on. This arose the issue of workload induced by non-driving tasks, as in another study [124] they inspected the drivers' performance under four different tasks (i.e., visual-motoric SURT task and cognitive 2-Back task, cognitive-motoric task, and a laptop-based fill-in the blank text) compared to a baseline condition with no automation. Results showed that the different tasks had a small role to play with respect to the TTR and the conclusion was similar to the previously mentioned study. However, they highlighted the importance of the situation complexity.

10.1.2 Driving Scenario

Situation complexity, or in other words the driving scenario, was further examined in several studies under similar conditions. For example, Radlmayr et al. [340] investigated the drivers' performance in a critical takeover scenario (i.e., high-density traffic). They deployed a cognitive 2 back task and visual SURT task, reaching the same conclusion as Gold et al. [124], furthermore they indicated the impact of the driving situation on the overall performance. Later, Gold el al. [127] confirmed similar findings using a different secondary task (i.e., verbal 20-Questions Task) and under various traffic densities. In a recent study from Brojeni et al. [355], using a motion simulator, they showed that TOR in curves affects the take-over quality more than that of straight roads. This goes in accordance with what was previously reported by the participants in Walch et al. [413] examining similar situations. Borjeni et al. [355] further recommended that the TOR should be adapted to the road and the driver's responses. That would mean that both the right timing and a suitable modality should be conveyed.

10.1.3 Take-Over Request Modality and Timing

To inspect the issuing time, Gold et al. [126] compared the drivers' performance given two different TTRs (i.e., 5s and 7s). Their results showed that the shorter the TTR, the worse the driver is likely to perform (i.e., swerve). While the timing would remain always relevant to the driving situation and system's limitation, the communicated modality would totally depend on the drivers' state. In a survey by Bazilinskyy et al. [26] with 3000 replies across 102 countries, participants were presented with 5 different driving situations and were asked to indicate their preferred modality to receive a TOR. Their preferences indicated mostly multi-modal systems, combining either two of these: visual, audio or vibro. These qualitative preferences have been further confirmed in recent studies. As auditory-Vibro multi-modal yielded better performance and ratings compared to either [316] .

10.2 Proprioceptive Take-Over Requests

To date most of the research done in the field of TOR design deploys either uni-modal or multi-modal cues to notify the driver. Targeting one or multiple human senses (i.e., hearing, sight, and touch), they focus mainly on using audio, visual, or vibro-tactile feedback signals.

Given the potential workload generated in future highly automated cars (e.g., through reading or texting and hearing music [329]), the driver's visual and auditory channels might already be occupied [420]. Similarly, the vibration in a driving vehicle might already put a load on the tactile perception. Thus, we propose targeting human proprioception as a new way of communicating TOR. According to research work in neuroscience [121], proprioception *consists of the sense of position (limb position sense) and movement of the limbs (kinaesthesia) in the absence of vision*. This means that humans are capable of perceiving the position and movement of their limbs without visually focusing on them.

In this study, we propose using electrical muscle stimulation (EMS) [363] to actuate the drivers arm. Researchers use EMS in multiple different scenarios from communicating navigation cues to the leg [319], drawing computer calculated graphs [253], or communicating affordance of physical objects [250]. In this TOR scenario, we strive to pull the arm of the drivers upwards to the height of the driving wheel so that they can easily grab the driving wheel and steer it in the communicated direction. This is achieved by actuating the biceps muscle (see Figure 10.1). The direction is communicated by the actuated arm. We actuate the left arm to communicate a movement to the left and the right arm to communicate a movement to the right.

10.3 Implementation

To evaluate the idea of proprioceptive TORs, we first developed a driving simulation environment. This simulation environment consists of a hardware setup and a driving scenario. Second, we designed four different ways to communicate a TOR using visual, auditory, vibrotactile, and proprioceptive cues respectively.

10.3.1 Hardware Setup

We present the simulation environment on three displays mimicking the view to the front (24 inches) and sides (22 inches) as depicted in Figure 10.2. We used a Logitech G29 steering wheel fixed at the table in front of the driver.

10.3.2 Driving Scene

Driving scenario We chose a collision avoidance scenario as a driving scenario that is commonly used to evaluate take-over requests [127, 94]. We designed a 3-lane highway road, where we placed the autonomous vehicle in the middle one (cf., Figure 10.3). The vehicle drives on the middle lane and accelerates up to a velocity of 100 km/h. Every 1.2-2.4 kilometers (i.e., every 50-100 seconds), an obstacle appears, either in the left and the middle, right and the middle, or middle lane only. These obstacles are accidents that block certain lanes. Once the obstacle appears a TOR is communicated to the drivers using a single modality (i.e., audio, video, vibrotactile, or proprioception). This gives the drivers five seconds to react, which according to a previous study [126] is enough time to react and take-over the vehicle. Besides reacting in time, they also need to identify the appropriate lane that is safe to use

Figure 10.2: The final setup of the simulation used in the study. We presented the view on three displays (i.e., one for the front and two for the side), along with a Logitech G29 driving wheel. The non-driving task is displayed in a tablet placed on the driver's lap.

(e.g., if the right and middle lanes are blocked, the driver should take the left lane). The drivers react by starting to steer in a certain direction they want to steer to by turning the steering wheel. The simulation interprets this interaction with the steering wheel in a binary way similar to the work of Borojeni et al. [33]. Thus, when the participant starts turning left or right, the car is automatically switching one lane to the left or right. If they react within the allowed reaction time (i.e., 5s), but wrongly choose the direction for the execution of the vehicle's cross-over maneuver (i.e., the obstacle appears on the right lane and the driver tries to turn to the right as well.), a warning message would appear giving them the chance to reconsider the executed reaction. If the drivers fail to react, an emergency stop occurs and they have to then press the *"x"* button on the driving wheel to continue the simulation. The car would then go backwards, shift to a free lane and then speed up in the driving direction to reach again the 100 km/h.

Figure 10.3: The autonomous vehicle driving on a 3-lane highway road, when it encounters an accident blocking the right and the middle lanes. A visual TOR is issued, indicating the free open lane for crossing.

Take-Over Request Design For the TOR design we used four different modalities. The goal of the TORs is to communicate the potential upcoming obstacle and the potential direction that can be used to avoid the obstacle. If the obstacle is in the left and middle lanes, the drivers receive a TOR that directs their attention to the right lane, which is a free way to continue driving in. The warning signal would not disappear unless either the drivers react or the cars do an emergency break to avoid a collision.

We integrated the visual and the audio feedback in the driving simulator using Unity. In the visual TOR we show either an arrow pointing to the left, the right, or both sides. As for the auditory, a beep sound would be played, through external speakers, either from the left, right, or both speakers.

The vibrotactile feedback alarms the user via vibro-motors mounted on a bracelet that touches directly the drivers' wrists. The simulation controls the vibro-motors via a NodeMCU microcontroller connected through WiFi.

For the proprioceptive feedback, we used the Let Your Body Move (LYBM) toolkit [318]. LYBM is composed of an Arduino, an Android application, and an off-the-shelf EMS signal generator. Again, the simulation controls the LYBM toolkit through commands send via Bluetooth to the Android application. Whenever the TOR to be communicated is issued either the For communicating left, the left, and for communicating right, the right, and, for both, both arms are pulled upwards.

10.4 Evaluation

We conducted a user study to compare the proprioceptive approach to regularly used modalities to communicate take over requests. For this we used visual, auditory, and vibro-tactile notifications as this are modalities commonly used to communicate take-over requests [413, 316, 33].

10.4.1 Secondary Task

To create a realistic scenario and to ensure that the drivers' eyes are off the road, we chose a span task implemented by BrainTurk [27], displayed on a an android tablet. The task addresses the working memory, where the application displays a task separated by a span option. Overall, the application used 2 tasks along with 2 different kinds of spans. In these tasks, the drivers had to verify the correctness of words (i.e., appears for 5 seconds) or the symmetry of shapes which don't have an appearance limit. The words or shapes were then separated by letters or a grid with highlighted square that pop up in between for 1 sec. After random number of levels (i.e., words or shapes) sepearted by a constant of 3 spans, the drivers are required to renter the spans in the correct sequence as they appeared. We, however, told the participant that in case of an automation failure, they should take over of the car to avoid any accidents.

10.4.2 Participants and Procedure

We invited 12 participants (4 females and 8 males) age range from 21-70 years ($\mu(=33)$, $\sigma(=15)$). After welcoming the participants, we explained the purpose of the study and the participants provided written informed consent. In a first step, participants familiarized themselves with the driving simulator and the non-driving task. The study consisted of four conditions displayed in four different blocks, separated by at least 5 minutes breaks, and lasted about one hour. In each block, we used one modality. To avoid any pattern, we ordered the modalities using Latin square. Before the beginning of each block, the modalities were prepared and again briefly explained to the participants. In the vibrotactile condition, the vibrating wristbands were connected and attached to the wrist. In the EMS condition, the experimenter calibrates the EMS-electrodes by continuously increasing the intensity of the signal until the participant performed the desired movement. With the consent of participants, we video-recorded the whole study for post-hoc analyses.

At the beginning of each condition, a welcome screen would appear, where the experimenter sets the participant ID and chooses the presented modality (i.e., visual, audio, vibrotactile, or EMS). The experimenter then placed the

[27] https://www.brainturk.com/games

tablet with the secondary task on the participant's lap (cf., Figure 10.2).The participant presses first the start button of the simulation and then starts with the non-driving task. We measured the reaction time from presenting the feedback until the participant started steering, as well as the steering direction.

10.5 Results

Next, we report the results of the user study. Prior to the presented analysis, we corrected the recorded data to the delay of the wireless communication. For this, we measured the delay induced and subtract it from the measured time. Specifically, we subtract 200ms from both the proprioceptive cues (WiFi to the mobile phone and Bluetooth between the mobile phone and LYBM-toolkit) and the vibrotactile cues (WiFi to the NodeMCU). We had to exclude two TORs from 2 participants (i.e., P11 and P12) in which the proprioceptive cue was not delivered due to technical issues. When the participants did not perceive the feedback, we removed these measurements as well from the calculation of the time to take-over.

10.5.1 Time to Take-Over

The results show that the participants needed least time in the vibro-tactile condition ($\mu(= 1.76)$, $\sigma(= 0.36)$), followed by proprioception ($\mu(= 1.86)$, $\sigma(= 0.28)$), audio ($\mu(= 1.93)$, $\sigma(= 0.28)$), and visual ($\mu(= 2.62)$, $\sigma(= 0.76)$). A repeated measures analysis of variance shows statistically significant differences between the four conditions, $F((3,33)) = 11.89$, $p < .001$. Follow-up Holm-Bonferroni-corrected t tests show that the differences between audio – visual, $t((11)) = -3.446$, $p = .022$, and EMS – visual, $t((11)) = -3.579$, $p = .022$ and vibro–visual, $t((11)) = -3.691$, $p = .021$ are statistically significant (cf., Figure 10.4).

10.5.2 Error Rate and Directional Guidance

Overall, the participants reacted to all TORs except in the visual condition in which a total of 16 TORs were not perceived by the user. The direction, however, was always chosen as communicated through each cue. We further inspected the bi-directional trials ($N = 36$) in which we placed the obstacle only in the middle leaving the participant to either steer to the left or to the right. The video analysis showed that the drivers used both hands equally in all the trials under EMS condition ($N_{EMS_L} = N_{EMS_R} = 18$), unlike the other

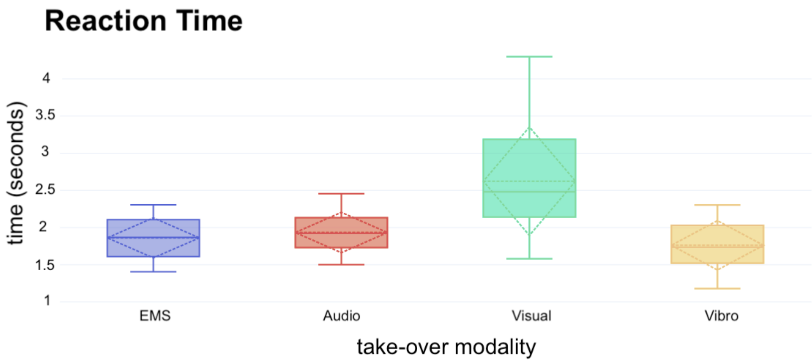


Figure 10.4: The reaction time in seconds. The drivers were given 5s to react to a 3-lane highway road accident.

conditions where the right hand was the dominant ($N_{Vibro_R} = 20$, $N_{Audio_R} = 21$, $N_{Visual_R} = 26$) (cf., Figure 10.5).

10.5.3 Non-Driving Task

Looking at the results of the non-driving task (i.e., score of span task), we found that auditory cues resulted in the highest score in the non-driving task ($\mu(= 12748)$, $\sigma(= 2792)$), followed by proprioception ($\mu(= 12515)$, $\sigma(= 2723)$), vibro-tactile ($\mu(= 12041)$, $\sigma(= 2121)$), and visual ($\mu(= 11999)$, $\sigma(= 2216)$) (cf., Figure 10.6). A repeated measures analysis of variance could not show statistically significant differences between the four conditions.

10.6 Discussion

In this section, we discuss our obtained results and position them among previous work.

Take-over Times The results show that both haptic TORs (i.e., vibrotactile and proprioception) perform best. This is in line with previous work which indicated similar results for the vibrotactile feedback [26]. These results also comply with previous studies, where participants reacted faster than visual feedback [287] or both visual and audio feedback [366]. In a recent neurophysiological and human imaging study, Luo et al. showed that both the auditory and visual cortices sense the inputs from the channels of one

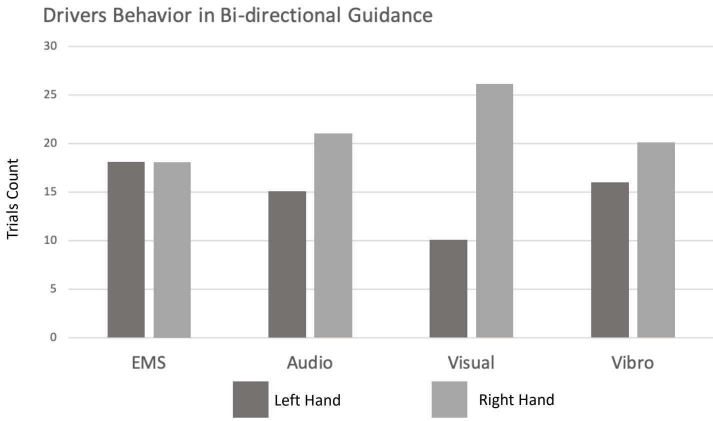


Figure 10.5: The drivers' behavior in the bi-directional trials, where they received the TOR from both directions and had the freedom to choose which direction to steer to.

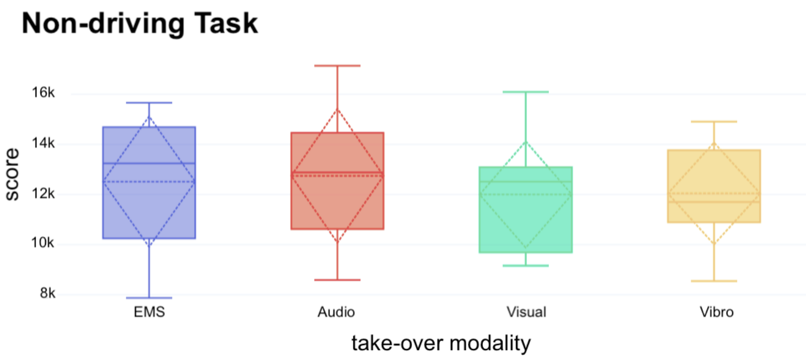


Figure 10.6: The score of the non-driving complex working memory span task.

another [258]. Having the drivers solve complex working memory tasks leads to having an overwhelming visual input, which explains why both the visual and auditory scored the slowest RTs.

The obtained score from the non-driving task reveals a trade-off between the reaction time and performance. A previous study by Zhou et al. [446] showed that vibrotactile feedback opposes the cognitive load. However, that wasn't the case with the proprioception condition. As mentioned by Schmidt and Young [361], the challenge sometime lies in *how to do* an action more that *what to do* for an action. Hence, by deploying the EMS actuation, the amount of cognitive load induced is less than that of the other conditions.

User Study and Task Comparing the lab-based setup we used in the user study with a real car, it becomes apparent that the background noise of the car as well as the vibration from driving is not simulated. Given that these would mainly, negatively, influence the audio and vibrotactile condition, we assume that the proprioceptive approach would perform better in a realistic environment. Similarly, the result is influenced by the non-driving related task. We used a span task that is commonly used for such studies [124, 86] and reflects potential future activities [329]. Using a task that focuses more on the haptics and less on the visuals would perhaps result in different results. Thus, the type of feedback might in the future be chosen based on the drivers' current activity.

Proprioceptive Cues In the user study we calibrated the proprioceptive cues and made sure that, in a relaxed condition, the drivers' forearms move upwards to reach the driving wheel. However, observing the participants' reactions in the recorded videos did not always show the same movement. As also indicated by multiple participants that while doing the study they didn't always feel the same actuation as in the calibration phase. Since the proprioception, as previously mentioned, is related to the sense of position as well as the awareness of the motion [121], having the drivers solve the non-driving task during the study, resulted in 2 different types of motions. The first one is the one directed by their brain to touch the correct answers buttons and move their hands. The other one is the artificial one that we suddenly induce. That might have resulted in a conflict leading to a delay in the reaction, yet not the signal perception.

Limitation We acknowledge the following limitation to our study. We used the EMS to actuate the drivers' both arms, which might have had an impact on the reaction time. As the drivers might have countered the incoming signals with their own.

10.7 Conclusion

In this chapter, we investigated the TOR performance in an L2/L3 autonomous vehicle. We deployed a collision avoidance system and tested a new TOR modality that addresses human proprioception via EMS. The concept of EMS is to induce an electrical signal on a targeted muscle to actively pull it to reach the same height as the driving wheel. While there are several modalities to communicate TORs to drivers (e.g., visual, auditory, and vibrotactile), none of them influence their actions without requiring additional attentional shift and, thus, inducing additional cognitive load. We found that the vibrotactile resulted in the fastest RT, followed by the proprioception condition, audio, and at last visual. The participants, however, performed the best in the non-driving task in the audio condition, then proprioception, vibrotactile, and visual conditions. We reflected on the obtained results and demonstrated the advantages of addressing human proprioception.

Summary and Key Findings

In this part, we explored the use of EMS technology to induce a new perception or an action across a span of three chapters with different use cases. In the first use case, we used the unique nature of EMS to communicate a posture correction in crossminton. In the second use case, we used the EMS actuation to pull the users' arms backward to avoid hitting real-life objects. In the last use case, we used it to initiate the take-over in an autonomous vehicle driving scenario. Following are the two main findings deduced from our studies.

> **Key finding I:** EMS is well suited to notify users' with high physical or mental demand.

In both Chapter 8 and Chapter 10, we showed the feasibility of communicating notifications through EMS. While the action required from the user in each use case as well as the mental or physical demand were different, EMS showed promising results in each use case. Even in the use case where EMS did not cause a movement (cf., Chapter 8), the link between the sensation at the muscle and the typical movement communicated what should be done in a subtle way.

> **Key finding II:** Notifications using EMS are communicating high urgency.

Across the three chapters in this part, EMS notified the users in three different levels. While other modalities like audio for example could also communicate different levels of urgency through different signal amplitudes, it still depends on the users' reaction. However, for the EMS, the reaction could be, depending on the use case, initiated and further executed by the technology. This in its turn adds a new dimension to notifications design.

V

Syntheses & Conclusion

Chapter 11

Syntheses

In this part, we present our observations that were obtained from the research presented in this dissertation. These observations highlight the potential for future research. We start by reflecting on the proposed-taxonomy categories highlighting the main aspects that are most crucial to each of them. We further proceed by formulating these observations as general research implications for interactive systems using EMS.

11.1 Taxonomy-based research implications

Throughout our research, we came across several factors that we deem necessary for the design of EMS applications. However, the weight that reflects the importance of each factor differs from one application scenario to another. The following points are linked to specific parts of the taxonomy as depicted in Figure 11.1.

11.1.1 Feedback Quantification

The first factor is feedback quantification, which reflects on measuring, depending on the scenario, the influence of the communicated feedback. A general challenge that faces the perception-targeted EMS applications is the

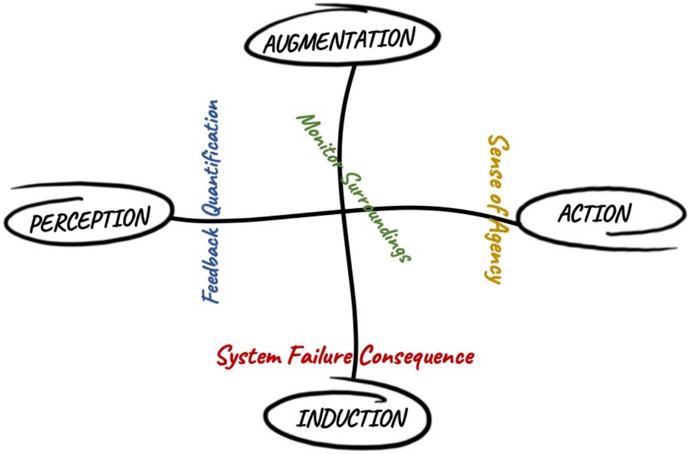


Figure 11.1: The most influencing factors in each category according to our proposed EMS applications taxonomy.

quantification of the communicated feedback. Across the three chapters where we targeted human perception, the measured impact was always subjective (i.e, relative to the user) and there was no way to unify it across all the users. Unlike action-targeting applications (i.e., applications in which a movement occurs) where the action itself could be detected and measured (e.g., hand rotation angle in the golf putting scenario in Chapter 6). This implication is also supported by previous research, which we inspected in the literature survey (cf., Chapter 3). Researchers have mentioned several aspects (e.g., intensity, voltage, and frequency) that could influence the actuation [364]. Additionally, the resulting actuation is highly dependent on the users' body and their current state [364]. In the surveyed application scenarios, there was no unified way of measuring the goodness of a calibration. While the calibration for action-targeting application scenarios might be visible by observing the movement (e.g.,[392, 84, 131]), this poses a huge challenge for the application scenarios that target the human perception. With the absence of clear measures to objectively quantify the influence of the communicated feedback (i.e., perception of the user), the interpretation of the evaluation result remains vague. It remains unclear how much change in perception is actually generated and how it is perceived by each participant in an evaluation (e.g., is the weight perception change perceived by the same overall participants [200]). This also makes the results hard to reproduce. Therefore, we encourage research to explore in-depth an objective measure to examine the influence of EMS on the user across different scenarios.

11.1.2 Sense of Agency

The second is the sense of agency, which reflects, as defined in previous work [136], *"controlling one's own actions and, through them, events in the external world"*. While our only measure of sense of agency was in a perception-targeting application, we find the action-targeting applications to be more challenging. We back up our argument from our literature survey. One of the main findings is the participants' expressions not being the masters of their own actions (e.g., also mentioned in prior research [395, 311, 250, 319, 98]). This is also one of the major concerns of our participants when we asked them about the technology acceptance (cf., Chapter 4. Previous work further highlighted the challenge of providing a sufficient sense of agency (SoA) while experiencing EMS [311]. Particularly for application scenarios in the *action induction* category, research has shown an influence of the unanticipated EMS actuation on the SoA. We argue that this is a major challenge facing such scenarios, especially since so far the work that focused on exploring the sense of agency targeted only the movement of fingers [390, 186, 185]. In these cases, both the executed action and action consequence are minimal. Therefore, we recommend investigating the SoA compromise level in all the action-targeted applications.

11.1.3 Monitor Surroundings

The third factor reflects the importance of monitoring the surrounding environment for any potential change that should be integrated into the system's action planning. This factor is linked directly to the purpose of a system and to the real-time actuation. Monitoring the surroundings could be crucial for all the categories except the perception induction. The reason is that the applications in the perception induction depend on the after-effect of the technology usage, the influence is not time urgent. Whilst, for example, scenarios that have the time factor crucial to them needs to have this taken into consideration. To be exact, the time instance of the actuation is the focus here. In all categories except in the perception induction, the EMS actuation is triggered to communicate a feedback that is crucial to be perceived or acted upon at this very moment. No delay (even if reaction time) could be tolerated.

Applying this to our scenarios, in the manipulating weight perception scenario in Chapter 5, if hypothetically speaking the participants are to rest their arms somewhere (e.g., on a table) instead of having them freely hanging while performing the bicep curl, the influence of the actuation would be bigger (e.g., might induce wrong weight perception). Same in the action-targeting scenario described in Chapter 9 (i.e., executing safety action), the user's arm action would, for example, hit a bystander which couldn't be observed by the player, the system should observe it. Applying this to previous work, in the cruise control scenario [319] for example. If the system is not aware of the traffic status, it might provide a wrong sense of safety. In general, monitoring the surrounding is important in all categories, but it is of the highest priority for *Perception Augmentation*, *Action Augmentation*, and *Action Induction* applications.

11.1.4 System Failure Consequence

The fourth factor reflects the resulting damage when the system fails to fulfill its purpose. This factor reflects then on the safety aspect linked to the system usage. Again, while we consider this factor to be relevant to all the proposed categories, we view this factor as of most relevance to the induction applications whether targeting perception or action. On one side, in augmentation applications, the system's activation is always linked to the user action. Thus, the user has the upper hand in controlling the received feedback. While in the On the other side, in induction applications, feedback control is not directly linked to the participants' actions but is rather granted to the system. We would apply this as an example to increasing safety in VR scenario (cf., Chapter 9), where the action induction is targeted. The system failure by constantly actuating the users' arms would result in an unpleasant experience and could result in harming the users themselves. If the system would not actuate the users' at the right time points, it might also harm the users or further cause damage to the users' surroundings and induce a false sense of safety. We could also observe a similar effect in communicating intensive notifications as in Chapter 8. As this might result in the users harming themselves. While the latter scenario is less grievous than the first, the harm can not be stopped or controlled by the user.

11.2 General Research Implications

Following we discuss general research implications that influence interactive systems using EMS, from our perspective, equally and thus are not linked to a specific category.

Research implication 1: EMS requires interdisciplinary expertise.

Throughout the studies, we referred back to experts from different fields either for the design or the evaluation of the systems. In Chapter 6, we always had contact with medical doctors since the rotation angles were for some participants challenging to achieve. The detailed medical knowledge of the body anatomy was then helpful in guiding us to the right calibration and alternative electrode positioning. We expect that consulting the medical experts would be beneficial for discussing ideas' feasibility. Conducting workshops with both technical as well as medical experts could highlight more potential for EMS technology. Furthermore, we often received a question from the participants regarding the long-term side effects of using EMS. While this is a mere medical aspect, it is of most relevance to EMS applications in any field.

Moreover, in the evaluation of the concepts of very specific use cases like in Chapter 7 and Chapter 8, we interviewed experts to gain further insights into the opportunities and challenges of the presented systems. The interviews always were of great benefit in highlighting aspects that we, given our limited knowledge of those fields, couldn't have reached without this high level of expertise. Therefore we recommend integrating the knowledge of those experts not only in the evaluation but also in the designing process of the systems.

Research implication 2: Proprioception is not the only influenced sense by EMS. Consider the impact of the EMS on the other senses and vice versa.

proprioception as defined in previous work [249] is *"the users' sense of the relative position of neighboring limbs of the body."* While exploring EMS's previous work mentioned in the literature survey (cf., Chapter 3), we came across many research works that linked EMS to senses other than proprioception like vestibular sense, visual (p.148 in [41]), pain [205] and even thermoception [108].

In Chapter 8 (i.e, notifications for posture correction), we investigated the potential of actuation to nudge the user to correct the ready posture in crossminton sport. While our focus was mainly to investigate the feedback communication on the calf muscle, the system was not tested in a real-life setup. The same is applied to the sign language teaching scenario (cf., Chapter 7), where we actuated the shoulder muscle. In both cases, given the position of the electrodes, the vestibular sense (i.e., the sense of balance) could be influenced depending on the intensity of the actuation and consequently the resulting impact. These are mere expectations based on theory, nevertheless, further studies are needed to verify and quantify this effect.

Another observation is the influence of the visual input not as a result of feedback like in sign language teaching scenario (cf., Chapter 7), but more like the effect of the visual input like in the golf putting scenario (cf., Chapter 6). In the latter, we observed that the participants performed best when they were actuated by the EMS while having visual input (i.e., not blindfolded). While in this case, it was one of our main targets to explore the influence of visual input, we didn't investigate that in all the explored use cases. Therefore, we encourage future research to explore the influence of being actuated via EMS, while being blindfolded and not blindfolded across the possible scenarios.

Further aspect that we consider crucial and we aimed to cover, is the user experience. For that, we normally used the user experience questionnaire [230]. However, what we didn't consider and is a limitation from our side, is the level of unpleasant feeling that the users might have experienced. We always considered asking them if the actuation is unpleasant to be sufficient to conduct the study. However, given the unique nature of EMS, and that it is something that most of our participants never experienced before, quantifying the level of unpleasant feeling might have provided further insights into what could be improved in terms of actuation or even study design.

Research implication 3: User acceptance is a first step that should be followed by social acceptance, and cultural acceptance.

In Chapter 4, we aimed to investigate user acceptance by presenting different user cases and exploring different aspects. While we consider this as a first step towards investigating technology acceptance, we also noticed that equally important aspects should be investigated, namely; social acceptance and cultural acceptance. Within the same Chapter, we received replies from Europe (i.e., mainly Germany), Asia (i.e., mainly Japan), and Africa (i.e., mainly Egypt), representing three completely different cultures. While no comparisons were conducted to compare the three groups since the participants' numbers were different, there was a tendency of differences in the replies, especially between Africa and both Asia, and Europe. Therefore, we expect that social acceptance would be greatly influenced by the targeted culture as previously indicted by other research [82]. Another aspect is the acquaintance and availability of new technologies. We expect that in developing countries, technology access is hard to reach, and the acceptance of such systems would be more difficult in comparison to developed countries, where trying new technologies is considered to be more of an enjoyable experience.

The last aspect is the influence of cultural rules. Throughout our literature search in Chapter 3.6, we came across a wide pool of scenarios. We expect that not all the scenarios would be accepted by all the cultures or even be deemed useful at all. We, therefore, encourage future research to investigate the boundaries of the technology from a cultural perspective if a technology is to be recommended for use.

> **Research implication 4:** To move from personal to public use, communities should discuss legislation and fairness.

Assuming that EMS systems overcame the many open challenges, was integrated into many fields, and made it to the market for public use, there would still be one major challenge to face. This challenge is the legal aspect with both its' legalization and legislation sides. To bridge the understanding to a similar problem that is more known, we take the example of self-driving vehicles. Accidents resulting from self-driving cars could vary between harming the in-vehicle passengers as well as other road users. Similar to self-driving cars, the EMS systems could direct actions that not only endanger the user's lives but also the bystanders' safety. In this case, who would be held responsible for the action, is it the user or is it the system provider? In a similar scenario, although more of a hypothetical one, in a war scenario where a soldier's fingers could be triggered by a smart sleeve connected directly to the commanding chief. In the case of firing, who would hold the responsibility and the consequences of the firing action? Till this point, the existing EMS action-inducing systems target sharing the control with the user. This means that the user can always overcome the actuation at the cost of a certain unpleasant feeling, but the question is should such systems be allowed to operate with our bodies in such (pain-full) conditions? If not, what should be the required modifications to accept the use of such systems from a governmental perspective?

Furthermore, given that while interacting with EMS systems, the human is either the subject and object or only the object, the impact of failure or the standards for use could differ from one country to the other. While we might seem miles apart from these points when the time comes and it's time to tackle these aspects not only the use case would be at focus but a whole detailed list of the technology capabilities and impact should be thoroughly investigated before it is out for public use. Another legal aspect is fairness, in 1960 EMS has been used to trainand improve the performance of the athletes for the olympic games [416]. Now with exploring more use cases for EMS, it could be used to augment human performance in some tasks (e.g., learning – Chapter 7). The question would be then if someone would refrain from using the system would their performance be then judged according to their situation or in comparison to those using the system ? These open questions while not directly relevant to the technology or the system itself, it is directly linked to the use of the system.

Research implication 5: Integrate EMS to existing systems for better acceptance.

We propose integrating familiar technologies and interaction modalities to overcome the fear of using EMS. Given that EMS is a novel technology that no longer require the users to act upon a provided feedback but uses the body directly as previously described in Chapter 3, we propose using a more familiar modality along the actuation. This modality could be used to communicate or assist in understanding the system status. In a study, Arts and Veuglers inspected 26 years of USA patent recordings in biotechnology for technology brokering [11]. Technology brokering is a term introduced in the late 20th century by Hargadon and Sutton [142], describing the reuse of old existing technologies to form new ideas and approaches. Art and Veuglers found that using more familiar technologies fosters the success of new innovations, however, they also highlighted that within a new invention the familiar component is to be used least. Although the entry hurdle of EMS is challenging (cf., Chapter 4) and would need intensive investigations to bridge the gap between the research probes and practice, we highly recommend this approach. We hypothesize that studies comparing the user acceptance of a proposed technology with a familiar interface would be more accepted than proposing systems that only depend EMS.

Chapter 12

Conclusion

This dissertation contributes to understanding the influence of electrical muscle stimulation on the human within human-computer interaction. The goal is to support researchers in adding value to their EMS-developed applications by overcoming challenges of the technology. In the following, we summarize the contributions of this dissertation and point toward future directions of research for non-medical EMS applications. We conclude with a final statement about the general use of EMS applications for everyday life.

12.1 Summary of Research Contributions

EMS is a relatively new technology to the HCI field. While researchers have explored the use of this technology in various scenarios, understanding not only the potential but also the influence of this technology remains scarcely explored. Thus, we provide an in-depth understanding of the technology and highlight the opportunities and challenges of EMS-based systems. In the following, we outline the three significant contributions of this dissertation and provide answers to the initially defined research questions in Table 1.1.

No.	Research Question
	I. EMS Application Fundamentals
RQ1	**How can one model human-computer interaction through EMS?** The nature of EMS is different from other conventional technologies. In Chapter 3, we present a new relation to Schomaker's interaction model. In this new relation, we explain that the EMS actuation doesn't only influence our perception, but also directly influences our actions. We proceeded by conducting a literature survey on which we based our proposal of a two-dimension taxonomy for EMS applications. The first dimension is action-perception and the second dimension is induction-augmentation. With these contributions, we formed a basic understanding of the interactive nature of EMS and its potential.
RQ2	**What are the users' requirements for using EMS?** Based on the previous literature review, we chose the six most-cited scenarios representing action-targeting and perception-targeting EMS applications. Along with medical and sport-related scenarios, we compared user acceptance through an online survey (cf., Chapter 4). We extended that by conducting interviews with ten participants to gain further insights into the obtained ratings. The results reflected several elements that the users deem necessary for using the technology, such as the necessity of blending into their appearance and dynamics. They further highlighted that unfamiliarity is one of the biggest hurdles for acceptance of EMS technology.
	II. Human Augmentation Applications
RQ3	**How can one augment user perception?** We conducted two user studies in which human perception was targeted. In the first, we aimed to manipulate weight perception in a VR environment by actuating different muscles (cf., Chapter 5). Our results showed that the concept works best by actuating the biceps and triceps muscles. We proceeded by exploring the influence of using EMS in supporting teaching American Sign Language (cf., Chapter 7). In one condition, we actuated the participants while having visual feedback of the sign, which added certainty to the motion execution. Our results showed that EMS is practical for correcting the coarse of movement.
RQ4	**How can one augment users' motor skills?** In Chapter 7, we also actuated the participants to execute a sign without providing any visual feedback. This condition best communicated the motion of the action itself. In a further study, we explored the use of EMS to control the rotation of the users' hands to improve gulf putting. We succeeded in improving the users' performances in the condition in which the participants were not blindfolded and had no experience. Overall, our results in both studies suggest that the most optimal approach would involve the visual input of the users along with the system actuation; thus, they would work together, rather than EMS taking complete control.
	III. Human Induction Applications
RQ5	**To what extent can we nudge the user?** EMS could be used to initiate actions, as we previously explored. Furthermore, the nature of the feedback itself differs from other modalities, given that it flows inside the human body. In a user study (cf., Chapter 8), we showed the feasibility of using EMS as a posture correction notification of ready-position in racket-based sports. In another study (cf., Chapter 10), we communicated take-over requests using EMS by moving the users' arms towards the steering wheel. We found that it provides the best trade-off of yielding a fast reaction time while still granting the drivers the chance to do a non-driving task. Hence, we conclude that the immersive nature of EMS is well suited for nudging the user while they are physically and mentally engaged in a task.
RQ6	**How much control can we take over from the user?** In Chapter 10, we already established the possibility of using EMS to interrupt the user while they do a non-driving task. In another study (cf., Chapter 9), we used EMS to increase safety in VR. In a gaming scenario, in which the participants could move freely, we pulled the users' arms backward when they crossed a threshold. Thereby, we prevented the participants from hurting themselves by colliding with real-world objects. To answer our research question, as long as the actuation gives a clear benefit, the user is willing to share control with the EMS actuation.

Table 12.1: Overview of Contributions on Research Questions.

12.1.1 EMS Application Fundamentals

In the first part of our research, we focused on defining the underlying theory behind the integration of EMS applications in non-medical applications. We started by developing a better understanding of the nature of EMS applications (**RQ1**). In this part, we focused on differentiating the interaction of EMS from other conventional modalities, such as audio and visual. We established that EMS can influence human actions as well as human perception. This is unlike the other modalities, which can only have a direct influence on human perception. We used this influence to group the existing EMS applications based on a literature review. Our literature review further highlighted that there is another dimension that defines the EMS actuation type: augmentation or induction. The difference between augmentation and induction lies in the user's expectations and whether the system works with the user to reach a target. Based on a user study, we note further recommendations for using EMS actuation in fine-grained motions. We concluded this part by conducting online survey and interviews to determine the user requirements for EMS applications (**RQ2**). Based on our data, we emphasize that unfamiliarity with the technology and its potential creates a huge hurdle. This challenge, however, could be tackled by providing simple demos for use cases that the users deem necessary. Furthermore, the system should blend into the user's appearance and provide a clear emergency off switch.

12.1.2 EMS Applications

We used the two-dimension taxonomy (cf., Chapter 3) as a starting point for this dissertation. While there is a clear-cut definition for the augmentation and induction applications, we discovered that there is not such a clear-cut definition for the perception- and action-targeting applications. One main finding is that there is what we would like to refer to as a collaboration sweet spot. The collaboration sweet spot is the overlapping area between the action and perception where the impact of the system on the action is augmented by the user's perception. One example of the augmentation collaboration sweet spot is in Chapter 7, where the user is being actuated to execute a sign while receiving visual input about it. A similar example in the induction collaboration sweet spot is in Chapter 10, where the purpose of the actuation could only be fulfilled if the participant reacted appropriately to the takeover request.

12.1.3 Human Augmenting Applications

In the human augmentation applications, we first focused on influencing human perception. The nature of EMS is different from other haptic modalities since it flows inside the human body. To be exact, electricity flows into the muscle, triggering muscle contraction. We used this influence to manipulate weight perception in VR. Our results showed that EMS could manipulate weight perception by increasing the weight. Our participants further indicated that the actuation should not be focused on only one muscle for the whole actuation time, but should instead be distributed according to the movement mechanics. In another study, we used EMS to teach the participants ASL. In one condition, we used only EMS, and in the other, we used EMS along with a video that showed how to execute the sign. Our results show that EMS is practical for the collaboration sweet spot and that it could be used to correct a movement execution. However, in the condition in which only EMS was used, the participants could only recognize the movement direction. They were unable to form a mental image of how the movement should look. The results obtained from these two studies highlight two opportunities for using EMS technology to augment user perception (cf., **RQ3**).

We proceeded by exploring the potential of EMS to improve motor skill execution in the golf putting scenarios. The EMS system is used here to actuate the muscles responsible for the rotation of the hands. We explored two conditions. In the first, we blindfolded the participants and only actuated their hands. In the second, the participants were not blindfolded and could thus influence the rotation angle on their own. Our results showed that EMS could be used to augment the golf putting performance of novice users given visual input. The last, previously described, second two studies focused more on improving and enhancing motor skills. Here, our results show that EMS should not be used as stand-alone technology, but rather integrated with other input modalities (cf., **RQ4**).

12.1.4 Human Induction Applications

Using the unique nature of EMS, we communicated posture correction notifications during a game of crossminton. Our results indicate that in comparison to vibrotactile stimulation, EMS communicates clearer notifications. In another study, we used EMS to communicate a takeover request in autonomous vehicles. This was unlike the crossminton scenario, in which the notification result depended totally on the user's reaction. Here, the actuation initiates the action; however, the action itself should be continued by the user. So, to answer **RQ5**, EMS is a good modality to nudge the user, even in situations with high cognitive and physical demand.

We proceeded by using EMS in a VR setup to pull the users' arms backward in case of a potential collision with real-world objects. There are two main differences between the three mentioned scenarios in this part. The first difference is the level of decision-making involved. In the crossminton scenario, the users need to execute the posture correction on their own. This involves determining what should be corrected and then executing the correction. In the takeover request, the initiation of the action depends on the system, but the coarse of the action is determined by the user. In the last scenario, EMS is used for both action planning and execution, as the user is just an object controlled by the system.

The second difference between all three scenarios is the potential influence of EMS on muscle contraction. In the crossminton scenario, EMS could not induce a movement because nearly the whole body weight was resting on the calf muscles. This is distinct from the other two scenarios, in which the influence of the EMS signal could be observed when actuating the biceps of a relaxed arm. In conclusion, to answer **RQ6**, the amount of control an EMS system can take over from the user depends on the muscles involved as well as the level of decision-making granted to the users.

12.2 Future Work

> *"The more you know, the more you know you don't know."*
>
> **–Aristotle–**

Throughout the writing of this dissertation, the more we researched the topic, the more we discovered aspects that were either out of the scope of this dissertation or were unexpected elements that we encourage future research to explore.

12.2.1 Actuation Limitations

In this dissertation, we often employed manual calibration. This approach depended on finding the muscle and adjusting the stimulation intensity for each participant. Also, we often opted for simple movements that could be achieved via shallow muscle actuation to ensure that we could conduct studies. However, we imagine that there are actuation limitations yet to be discovered. For example, actuating fine-grained motions is still an open challenge, which could limit the technology's integration in many scenarios. Furthermore, no clear limit has thus far been set regarding the extent of actuation that may be used. Should the limit of the actuation movement be the same as the natural human limit or should it be less? Further studies should work to answer this question from the system side and provide guidelines for limitation.

12.2.2 Testing Environment

Based on our studies as well as previous work (cf., literature survey – Chapter 3). The different application scenarios are mainly evaluated in a lab setting (65 out of 68 user studies – Subsection, cf., 3.5.2). While this is a decent first step, going out into the real world is necessary to understand the true benefit of EMS (similar to mobile computing [203] or smart textiles [362]). Also, aspects such as a sense of agency and social acceptability are not easy to explore in a lab setting, but are crucial for a technology to move from research to application in the real world.

12.2.3 Body Location

Currently, EMS is mainly used on the lower arm to actuate movement of the hands (cf., Figure 3.5). While the hands can be used in a range of application scenarios, the application scenarios for the other body locations also showed that they can be beneficial (e.g., redirecting walking [319]). One reason for this is the use of self-adhesive electrodes in combination with manual calibration. The electrodes have to be relocated if the EMS signal does not result in the desired actuation, which is most convenient on the lower arm. With integrated electrodes [206] and automatic calibration [207], the attachment and calibration to other body parts could be eased up. This could result in more diverse usage of different body locations and more variety in targeted muscles and actuations.

12.2.4 EMS for (Good) Health

Previous work has used EMS for health-related applications. To be exact, the majority focused on medical and sports applications. Technology has been shown to be greatly beneficial to both fields, yet the integration of this technology into everyday life is rarely considered. Therefore, we recommend integrating EMS technology into a health monitoring system. We envision using the system in two cases. The first is to induce physical activity whenever the user is detected to be physically inactive. The second case is to use it for posture correction. In our daily lives, we find ourselves in many different positions, such as lying while watching TV or sitting while working. In many of these positions, however, we have poor posture, which can negatively impact physical health. Here, EMS could be of great benefit to improve posture. While the use of EMS in these two cases may seem limited, there are several relevant and crucial aspects. The first aspect is the hardware design. It is quite challenging to implement one system that fits all use cases. Therefore, to obtain such a system, the design for the different use cases ought to be thought through thoroughly to ensure user acceptance. The third and last aspect we consider is the user and social acceptance of this system. To implement a monitoring system that actively actuates the users according to a certain design is quite challenging. Since users are different and have different requirements, would the aim of such a system be to adapt to each user's lifestyle, or would the users be active participants in creating a targeted aim according to their own needs?

12.3 Concluding Remarks

Throughout the years in which I worked on this dissertation, I have been frequently asked the following question by fellow colleagues and researchers:

> "Do we really need this technology?"

The aim of this dissertation is to provide an in-depth understanding of EMS technology and its capabilities. Based on many research studies exploring the theory as well as the practice, my conclusion is that ***just because we can, it doesn't mean we should***.

As previously described, EMS technology holds great potential, but also faces many challenges. Nevertheless, overcoming these challenges and reaching the maximum potential of EMS doesn't mean that we should rush to push the technology into the market. While research should proceed in exploring new use cases, other research should focus on evaluating EMS systems in terms of how they benefit society and users. Throughout history, there have been many failing technologies. A similar result can be observed for many smartphone applications: although a wide range of options exists, not all successfully meet users' needs. One way to deal with this is to better understand what the users want, what they can generally afford, and what the technology can provide. In conclusion, to make EMS a success, the most crucial factor is to give people a reason and motivation to adopt the new technology.

VI

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VII

Appendix

Appendix A

Semi Structured Interview Sample Questions

Interviewer: [welcomes participants, asks for consent, explains the purpose of the interview and the link to the conducted online survey, and explains (again) the basic principles of EMS]. We had 8 scenarios [interviewer presenting the photos as in Table 4.1 as well as photos of the two baselines]. Please always refer to the EMS technology in general. If one of the scenarios differs from the others, please let us know!

A.1 Social Value

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. When would you use such a system? Does the location influence your willingness to use? Why?
Q2. How would you think of people wearing such electronic devices (think about playing games, interacting with a system, health, and sports)? Why? When/where would that be acceptable in your point of view?
Q3. What if such a device is embedded in clothing or smartwatch – would that change your opinion and make it more acceptable?

Q4. How important is appearance for you in general? How about such a device?

A.2 Perceived Usefulness

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. What application scenario would you consider useful?
Q2. When would you agree to use EMS?

A.3 Perceived Enjoyment

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. Can you indicate what you expect as perceived enjoyment?
Q2. What benefit would you need so that you would enjoy using it?

A.4 Anxiety

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. Why are you afraid to hurt yourself/others? Does the fact that you can override the technology help that you feel safe?
Q2. What about receiving feedback vs. feeling being actuated why?
Q3. What needs the system to do in order to provide a higher security level or more assurance for you? Would a safety switch or communication of intent help to trust the computer?

A.5 Trust

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. Why or why not do you trust EMS? If wearing EMS would convey a better experience, performance, or treatment, for which scenario/experience would you be certain of using it? (Which not?) Why?
Q2. Would you trust being actuated with EMS for each of sports, action,

perception, and health? Why this specifically?
Q3. EMS provides the control over parts of your body to a computer. This rarely happens in other occasions. What would you need to accept that a computer partly controls your body?
Q4. Is it different in health? Why? What about Doctor prescribing for example the navigation system to let you walk a longer way home to have a healthy and active lifestyle?

A.6 Intention of Use

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. What negative implication do you expect? How to overcome them?
Q2. Do you think in general there is a scenario where you would like/can use EMS in your daily life? How would it look like? How should one of the scenarios change so that you would use it?
Q3. Does the location of the electrodes influence your rating? Would putting them on your head differ from limbs or from rest of the body?

A.7 Functionality

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. Why do you (not) think that EMS could provide realistic functionality? More details?

A.8 Compatibility

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]
Q1. What everyday task you do might benefit from EMS?

A.9 Attitude

Interviewer: [reading items from the original survey as in Table 4.2, then proceeds]

Q1. What would you make using the EMS technology? How should technology be/not be? Would you rather use perception or action scenarios?
Q2. Do you have experience with EMS? What? Did your opinion towards EMS change after trying it out?

Appendix B

Consent Form Example

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UNIVERSITÄT DUISBURG ESSEN
Offen im Denken

Thank you for your willingness to participate in Investigating Gesture learning via Electrical Muscle Stimulation (EMS). Please read the following sections carefully. Below we present the course of the study, your participation rights, the data we have collected and the health exclusion criteria that would prevent you from participating in the study.

Exclusion criteria

In the study, electrodes are placed on your forearms, arms and/or shoulders. Currents of variable intensity are used to generate muscle activity. If any of the following points apply to you, please let us know as you will not be able to participate in the study.

Disclosure of the applicable criterion is not required.

- You wear electrical devices in or on your body (pacemakers, insulin pumps, hearing aids, cochlear implants or similar)
- You have metal implants in your body
- You currently have a high fever
- You suffer from cardiac arrhythmia or other heart conditions
- You have seizure disorders (e.g. epilepsy)
- You are pregnant
- You have cancer
- You've had recent surgery on your arms or torso
- You suffer (current or chronic) from skin diseases or injuries at or near the target position of the electrodes (including inflammation, redness, allergies, rashes)
- You have recently consumed alcohol or drugs

Voluntary participation and right of withdrawal

Participation in the study is voluntary and without consideration. You have the right to cancel your participation at any time. If you wish to terminate your participation while you are already wired, please inform the study guide

Removal of individual electrodes without prior deactivation of the EMS module can cause damage to your health!

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Study Procedure

Participation in the study is divided into several sections across two weeks. For the first would take less than 20 minutes after the calibration part. The test persons are instructed by the study guide on the sequence of steps.

- Calibration of the electrode position / stimulation intensity
- Execution of the main study

The second week duration would be less than 20 mins.

Calibration of the electrode position / stimulation intensity (~ 10 to 20 minutes)

Due to differences in physique, the necessary positioning of the electrodes varies from subject to subject. Therefore, we perform a series of calibrations, during which the applied stimulation intensity is also slowly increased, starting from zero, until study participants perceive the stimulus. In this phase, probands are asked to inform the study guide,

- as soon as a stimulus is perceived (usually the first perception is a tingling in the hand and arm region) and
- once the stimulation becomes uncomfortable..

Main Study (~ 20 Minutes)

The aim of our study is to detect the effectiveness of different technologies to teach the users different unknown gestures. One main requirement is that you don't have any previous knowledge of the American sign language. The study is divided into two parts, with a span of two weeks. In this part, you will have several sessions randomly displayed and separated by a break of 3 mins. In each session, you will be standing with you hand palms facing the outside (i.e., projector side). We will display on our projection the ID of a gesture (e.g., Gesture 1). Then we will communicate with you certain gestures (i.e., movements) ten times. We will either show you a video of a mannequin doing the gesture, or actuate you with EMS, display an audio guide of how the gesture should be done and a combination between both EMS and video. The audio guide could be displayed in English or German according to your preference. For each condition there will be a specific movement. In the break, you will answer a questionnaire and provide us with any remarks you want to share.
In the second part in two weeks, you will come and we will just show you the ID and ask you to execute the same gesture as you did in part one for each condition. We will record mainly your performance in the two parts using Optitrack markers that you would put.

Anonymity and data protection

Your data is collected anonymously. An allocation of the data to your person is not possible. The evaluation and use of the data is exclusively within the scope of the research project. All data is processed without your name or any other direct means of identification. If results of the study are

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published, it is not possible to assign the data to your person. Due to the anonymous data collection, a subsequent deletion of your data on request is not possible.

The data and personal communications collected in the course of this study and described above will be treated confidentially. Thus, those project staff members who have personal data through direct contact with you are subject to the obligation of confidentiality.

The collection and processing of your personal data described above is carried out pseudonymously by the study management using an ID code and without giving your name. The declaration of consent with name and ID-code is only for the test management and the study management.

accessible; this means that only these persons can associate the collected data with your name. The declaration of consent will be kept under lock and key and will be destroyed after the data evaluation is completed. Your data is then anonymised. This means that it is no longer possible for anyone to associate the collected data with your name. The anonymised data will be stored for at least 10 years.

The data will possibly be made available to other researchers in anonymised form.

Right to results

If you wish, the results of the study will be communicated to you after it has been elaborated. If you make use of this option, your e-mail address will be stored beyond the period specified above until the elaboration is completed.

Investigating Gesture learning via Electrical Muscle Stimulation

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Participation form

ID-Code: ______________________________

Name, Last Name: ____

E-Mail: ____

Results: I would like to be informed about the results [ ]

I have completely read and understood the participation information for the study. By participating in the study, I agree to the above information and conditions.

Date, Signature: ____

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LIST OF ACRONYMS

EMS	*Electrical Muscle Stimulation*
HCI	*Human Computer Interaction*
VR	*Virtual Reality*
XR	*Mixed Reality*
TAM	*Technology Acceptance Model*
UTAUT	*Unified Theory of Acceptance and Use of Technology*
UAWD	*User acceptance of wearable devices*
AV	*Autonomous Vehicle*
DBC	*Dumbbell Biceps Curl*
ASL	*American Sign Language*
TOR	*Take-Over Requests*
TTR	*Time to React*
EMG	*Electromyography*
LYBM	*Let Your Body Move*