博　士　論　文

Providing an Experimental Platform for Interfaces that Apply Electricity to the Human Body

（身体に電気入力を行うインタフェースの実験基盤の提供）

河野 通就

ABSTRACT

The border of computer technology and human beings have become ambiguous, where they are integrated and merged with each other. The human body is being modified and even artificial components are implanted inside the body. However, we often face fear or anxiety in such approaches, due to the unclearness of safety and threat of social acceptance. There has been an interest in using surface electrodes and electricity to modify the body without direct implants to the body. I consider this approach to be positioned between wearables and implants, where artificial electrical signals are applied inside the body from the outside surface. In this thesis, I call this approach "*Electrical Body Hacks*." This thesis aims to bridge the gap between wearables and cyborgs (implants), by practice through electrical body hacks, and to increase the acceptance of such attempts by developing an experimental platform.

However, electricity is not completely safe for the human body. The knowledge required for such consideration is spread throughout a large number of research fields. Therefore, I start by reviewing previous research pertaining to HCI in which users come into contact with electricity, as well as safety consideration and guidelines.

As a practice for my approach, we present a multi-channel electrical muscle stimulation (EMS) toolkit, in order to ease the access of users for electrical body hacks. We organized a workshop and found that multi-channel EMS has a significant demand for human augmentation purposes. To explore cognitive understandings of EMS on an unacceptable body part, I present studies of EMS applied on a human face. EMS may stimulate the face to express emotions through the facial muscle actuation, which may work better for negative emotions. Furthermore, a user study was performed to explore the effect of our approaches with combinations with virtual reality (VR) contents, which was found effective to enhance the experience. Finally, we present an approach which allows a human body to activate low-power electronic devices by touching them, and to present application domains that overlap with wearable and cyborg approaches.

Consideration for the acceptability of such systems are key issues, and discussions are required. Therefore, I present a careful discussion to address this issue, and to help increase the acceptability of the research area and future work. I envision future development and research of body modification to be more safe and acceptable for human augmentation.

論文要旨

人間とテクノロジーの境界はますます曖昧なものとなってきており，それらは相互に統合されてきている．人体は改変され，さらには人工的な機構が体内に埋め込まれることもある．しかし，このような手法において，手法の安全性や社会的受容性の欠落に伴う恐怖や懸念が存在する．一方で，人体に直接的に機構を埋め込むことなく，人体を改変する手法として表面電極などを用いることによる人体に対する電気入力を行う手法が注目を浴びている．この手法はウェアラブルと埋め込み型機構を用いる手法の中間に位置付けられると考え，筆者はこれを “Electrical Body Hacks（電気的ボディハッキング）” と呼ぶこととした．本博士論文では，Electrical Body Hacks の実践を通して，ウェアラブルデバイスとサイボーグ（埋め込み型手法）の境界の橋架けとなるように，手法の受容性を向上させ，実験基盤の構築を行う．

しかし，人体は電気に対して完全に安全であるわけではない．安全性について検討を行うために必要な知識は，ヒューマンコンピュータインタラクション（HCI）のみならず，多くの研究分野に散乱している．したがって，本博士論文では，人体に対して電気入力が行われる HCI 及び関連分野に関する研究，ならびに安全基準について明らかにした．

本研究の実践として，多チャンネルの出力・制御が可能な電気的筋刺激（EMS）ツールキットを開発し，ユーザが Electrical Body Hacks を簡単に行うことを可能とした．このツールキットを元に，ワークショップを開催し，多チャンネル EMS が人間拡張のために大きな需要があることを確認した．さらに EMS の受容性の低い身体部位への応用を確認するため，人間の顔に EMS を適用した．EMS を用いて，顔面の筋肉を作動させ，感情を表現するように顔を刺激することが可能であり，ネガティブな感情に対してより大きな効果が確認された．これにより，EMS が感情表現に影響を与えられることがわかった．さらには，この知見を応用し，EMS をバーチャルリアリティ（VR）コンテンツと組み合わせることによってもたらすことができる体験への影響について実験を行い，VR 体験を向上させられることを確認した．最後に，人間が手で触れることによって低電力の電子デバイスを稼働させる手法について提案を行った．これは既存のウェアラブルデバイスとサイボーグの応用事例との重複領域を示すための実践であった．

人間に対して電気入力を行うシステム開発には，システムの受容性を検討・配慮することは重要であり，考察が必要である．したがって，この問題に対応するために，本研究領域に関して受容性の向上手段について考察した．本博士論文が身体改造の安全性と受容性の向上に貢献し，さらなる発展がより円滑に行われていくことに期待している．

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My acknowledgments also go to all of my co-authors. Dr. Hiromi Nakamura participated in two of my published works. She gave great support to arrange my papers and to improve our work. I will never forget her help when I got sick just before the submission deadline. Takumi Takahashi contributed to our great journal article. He was so cooperative and helped smoothened the publication process. His contribution was not just limited to this co-authored article, but helped me with other technical issues that I faced during my research. Assoc. Prof. Yoshio Ishiguro and Keisuke Shiro advised me for some technical aspects of my circuits. Their advice helped me improve and smoothened my research procedure. Natsuki Hamanishi is a co-author of my other projects that are not included in the thesis. However, his contribution was significant, since I thought that managing multiple research projects in parallel was very important for my carrier as a researcher. I am excited about my future projects with all my great collaborators.

It is great for me to come to the end of the Ph.D. course. But I will have to give my special thanks to Assoc. Prof. Yasuaki Kakehi. He was my advisor during my

Master course, and strongly encourage me to proceed to the Ph.D. course. He has also advised me for my Ph.D. thesis, and I will not be here finishing it, if I had not received his advice and encouragement. Dr. Keita Higuchi, was a senior of me at Rekimoto lab. He was always helpful with my research and advised me about my carrier, and continued keeping in touch even after he had graduated.

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Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Body Modification

Technology and human beings have been interacting with each other, in order to strengthen their ability beyond the nature. In 1665, The idea of augmenting human senses was first introduced by Robert Hooke, in his book “Micrographia” [97]. Now there is a growing interest in augmenting human beings in various research fields, including human-computer interaction (HCI), psychology, neuroscience and artificial intelligence [1]. We often refer to them as human augmentation [1], cyborgs [13], enhancement [71], or empowerment [279]. The border of human and computers is becoming more ambiguous, where researchers and artists are attempting to “hack” the human body for augmentation purposes. For this purpose, researchers and artists have always been contributing to human development by using their own body as a subject [43]. Stelarc, who is one of the pioneering artists that work on body hacking and it’s art, describes the presence of the human body and cyborgs as follows.

> *The body is an evolutionary architecture that operates and becomes aware in the world. To alter it’s architecture is to adjust its awareness. The body has always been a prosthetic body, one augmented by it’s instruments and machines. There has always been a danger of the body behaving involuntarily and of being conditioned automatically. A Zombie is a body that performs involuntarily, that does not have a mind of it’s own. A Cyborg is a human-machine system. There has always been a fear of the involuntary and the automated. Of the Zombie and the Cyborg. But we fear what we have always been and what we have already become.*
> *(Stelarc, 2012 [22])*

Human has always coexisted with machines, which has augmented/supported its body. Although there may be some fear for the automation or the involuntary interaction, we should understand that the relationship has always been in this way. Furthermore, he describes that "*The body is a convenient location of experimentation [57],*" which I think is a common motivation for many body modification practitioners.

The term "cyborg" was first described as "*The cyborg deliberately incorporates exogenous components extending the self-regulatory control function of the organism in order to adapt it to new environments [31].*" However, it is now general to understand the term as the following definition. "*A cyborg is a human being with an electronic device implanted in or permanently attached to their body for the purpose of enhancing their individual senses or abilities beyond the occasional use of tools [225].*"

My understanding of the evolution of human augmentation and the relation of human and machines, is the matter of depth of implementation to the body. Typical machines exist outside the body, which usually has interfaces where the human can touch and interact with. Then the machines became smaller, which allowed human to carry or wear the machine through their daily lives. The *cyborg*, is an approach that goes further from wearables, in which the machine is implemented inside the body. Figure 1.1 is an illustration of this concept. Note that I follow the definition of "wearables" as "*Electronic technologies or computers that are incorporated into items of clothing and accessories which can comfortably be worn on the body [140],*" and examples are shown in Figure 1.2.

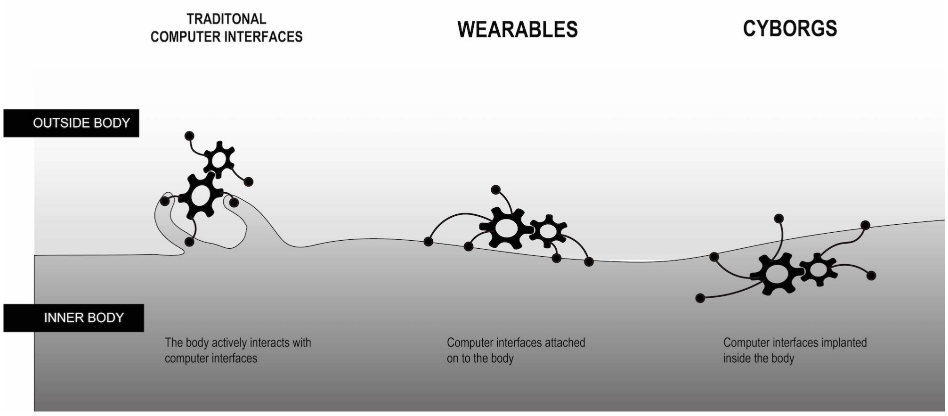

Figure 1.1: Wearables towards cyborgs. The depth of implementation has become more deeper into the body. Cyborgs are expanded approaches of wearables, which has deeper integration of human and machines from both physical and time aspects.

Figure 1.2: Example of Wearables. (a) Computer on an eyeglass [111]. (b) An interactive tattoo [336]. (c) A smartwatch with a projector [348]. (d) An armband for electromyographic (EMG) sensing and interaction [309]. (e) An interactive clothing [244]. (f) An exoskeleton for walking assistance [361].

Beyond wearables, towards cyborgs, the body is becoming hacked for human augmentation. I define the term "Body Hack" as "Affecting the body by means of engineering with external artifacts to augment human beyond nature." I do not intend to cover "Biohacking," which I define as body hacking including artificial manipulation at genetic levels, e.g., genetic modification.

The movement of body hacking with implants has significantly developed after the Kevin Warwick's project "Cyborg 1.0 [329]," where he implanted a radio frequency identification (RFID) tag to his arm in 1998, and his motivation was to consider a way to help human go beyond technologies that are becoming more intelligent than human [330]. Now there is a growing interest in becoming cyborgs at personal levels. Regarding cyborgs, there is an increase of interest in body hacking in HCI and related fields [96, 141, 91], and international conferences have been held, such as BDYHAX[1], which is described as "*BDYHAX is a Human Augmentation, Transhumanism, and Biohacking conference held annually in Austin, TX. ... Topics covered include wearable tech, body modification, life extension, implants, prosthetics, personalized healthcare, nootropics, ethics and legislation regarding human augmentation, and more!*" Companies such as Dangerous Things[2], distributes tools for body hacking as well as magnets and integrated circuits for wireless communication. Furthermore, the company estimates that there are already 50,000–100,000 individuals with chips implanted

[1] https://bodyhackingcon.com/
[2] https://dangerousthings.com/

in them, and Figure 1.3 illustrates notable attempts of body hacking.

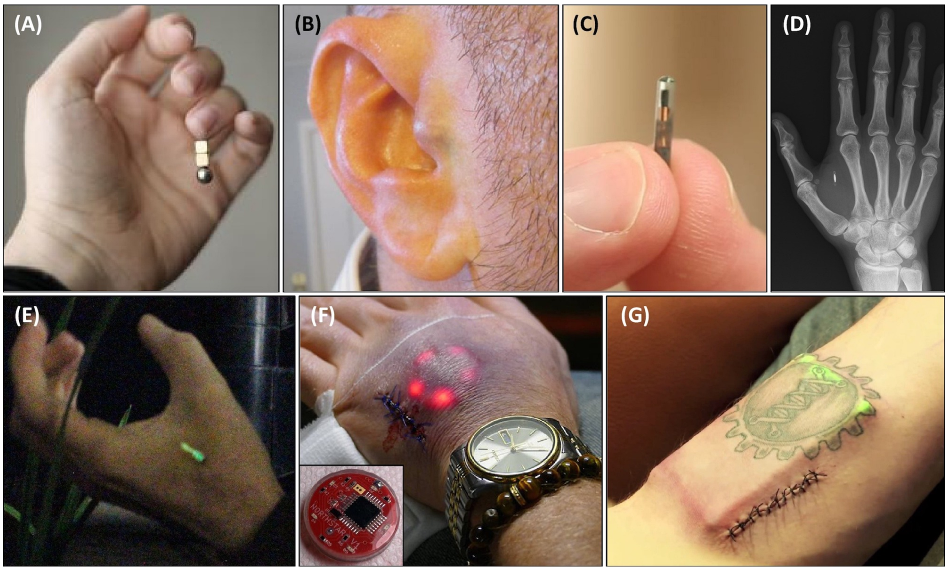

Figure 1.3: Implants Used by body hackers. (A) A neodymium magnet in a finger. (B) Magnets in the tragus of an ear. (C) A RFID tag. (D) RFID tags implanted in the webbing between the metacarpal bones of the index finger and thumb, positioned parallel to the index metacarpal. (E) Tritium lighting implants. (F) LEDs in hand. (G) Continual temperature sensor in forearm. (This figure is adapted from Yetisen, 2018. Figure 1 [356].)

However, we may encounter several issues for cyborg body hacking [225]. They include safety and ethical issues, as well as technical issues. There are also concerns of conflicts with other technologies in our life, e.g., magnetic resonance imaging (MRI). Graafstra et al. [79] stated that implantees are faced with health, safety, privacy, security, regulation and societal perceptions. As like Stelarc stated about the "fear" of the body hacking, the art of body hacking may be influenced by the anxiety or ethics.

To address these issues, I attempt to explore the potential benefits of body hacking through non-implanting methods. For the approach, I paid attention to the unique electrical characteristics of the human body, which can be influenced by artificial electrical signals. The interest of this thesis is to go beyond traditional wearables and to work on "Electrical Body Hacks," which I position as a middle domain between "wearables" and "cyborgs." I define the term "Electrical Body Hacks" as "Body hacking via artificial electric signals that pass inside the body by means of wearables." The approach has been considered through prior work by Sterlarc [285] in 1995, where he used FES (Functional Electrical Stimulation) for body-computer interaction. I attempt to augment the area by covering a larger topic for interaction purposes by applying electricity to the human body.

1.2 The Electric Machine

The human body has various electrical characteristics; it is fundamentally an electric machine. The body can perform as a conductive line, resistor, capacitor, antenna, and ground. These characteristics are relevant to various applications and connect and interact with each other as parts of an electric circuit. Further, tissues transport electricity and sensory signals throughout the body, actuating muscles and stimulating perceptions. A neuron is a specialized cell that processes and transmits information through electro-chemical signals. Neurons are core to many functions in the human body, e.g., motor neurons may innervate muscles to cause contractions. Researchers have taken on the challenge to develop systems and techniques based on these characteristics in the fields of human-computer interaction (HCI) and ubiquitous computing (UbiComp) and related fields, contributing to the growing number of sensors and ubiquitous computers [337]. There is a significant interest in this area, by utilizing the unique electrical characteristics of the human body, by means of electrical body hack for human-computer interaction.

One major example that is already used by consumers is touch panels. In 1995, Zimmerman et al. [370] presented a technique for applying electric field sensing to human-computer interfaces. The proposed technique enables the sensing of human interaction via an external electric field (EF) grounded by the user. Dietz et al. proposed DiamondTouch [46], a technique that expanded the EF sensing method to two-dimensional surfaces, in 2001. Furthermore, in 2002, Rekimoto developed SmartSkin [263], which enables users to input gestures such as grasping and zooming by recognizing the relative positions of blobs detected on the surface. The method has been incorporated into various devices, e.g., smartphones and tablets. As these types of devices have become more pervasive, it has become obvious that people have external electricity passing through their body in their daily lives. In addition, people's bodies are electrified by electrical and radio waves from commercial power supplies or network equipment. Today, it is not unusual for people to have electricity applied to their body in their interactions with computing systems. In addition to touch-sensing applications, there have been many notable studies in which some kind of electricity has been applied to the human body. As electricity on the body plays an essential role in it's functioning, it follows that electricity can be applied to affect the body's functioning.

With the varying amounts of power and signal types that are being used, safety considerations have become critical [305, 14, 148]. How much and what kind(s) of electricity can be applied to the body safely? What types of risks are involved, and in what ways can they be dangerous? Safety considerations are required for researchers conducting studies in which electricity is applied to the human body. However, the basis for these considerations may be difficult to discuss, as the safety knowledge underlying such systems is spread across various fields. Such knowledge is found in fields spanning engineering, physics, biology, physiology, medical science, and electronics, making it difficult for HCI researchers to comprehensively understand safety concerns. Addressing safety issues in the field is important and will enable researchers to develop systems that are safer and more acceptable to users.

Figure 1.4 illustrates the main principles used in research on the application of electricity to the body. Note that we focus on phenomena such as electrostatics and signals below 110 MHz rather than electromagnetic waves and radio-wave propagation and use the terminology *electricity* for our domain of focus, especially paying attention to the effect of current and potential electric shocks. An understanding of the objective safety issues and levels for applying different types of electricity to the human body will facilitate the discovery of design spaces for future development in body hacking research.

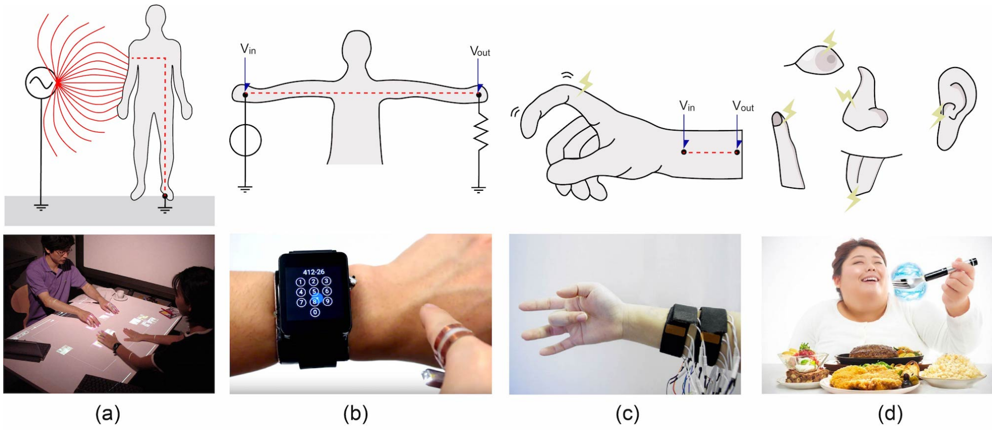

Figure 1.4: Main principles in research that apply electricity to the human body. (a) *Sensing*: Human body and gesture sensing by EF. An external source applies and monitors signals on the human body. The image shows an example of EF sensing for multi-touch interaction [263]. (b) *Transmission*: Human body as a conductive lead. Power or signals are transmitted through multiple points of the body. The image shows a technique for interaction via electric signals transmitting through the hand [365]. (c) *Actuation*: Activating human muscles and movement. Power and signals are applied to a body part. The image shows an example of electrical muscle stimulation (EMS) for hand gesture manipulation [305]. (d) *Perception*: Activating and Stimulating human organs. Power and signals are applied to a body part. The image shows an example of electric gustatory to control saltiness [113].

1.3 Advantages and Problems

UUsage of electrical signals and applying them to the human body (*electrical body hacks*), may have several benefits over other technical methods when building interactive systems. In general, the approach has a great benefit from the aspect of *mobility*. Furthermore, in cases for some applications, the method also has a high *scalability* and/or *wearability*.

As I noted earlier, the body is a convenient place that has many functions manipulated by electrical signals. When we utilize such features, the external systems can have some elements of its circuit omitted, and to be replaced by the human body. Therefore, the system configuration can be smaller than other mechanical approaches.

Since electrical body hacking systems are mobile, they can contribute to improving the resolution, or be applied to various body parts. In addition, because they are controlled by electrical signals, the parameters can be adjusted easily for various purposes (e.g., for electric gustatory, the waveform can be adjusted to stimulate various taste). The freedom of the size and the waveform contributes to the method to have a high scalability.

The body transmits electrical signals throughout the body, which sometimes allows us to avoid attaching direct elements to the body part of interest. For example, in the case of EMS, we can attach the electrodes to the forearm in order to manipulate the fingers. This does not require anything worn on the fingers, and they are left free to be used for general purposes. Electrical body hacks has a high wearability, where we can have the system worn or attached to a separate body part (or a body part nearby) for the interaction.

Resulting from such benefits, many systems and products have been deployed for social and personal use cases.

In contrast, work that applies electricity to the human body may account two problems. First, users may have potential fear and misunderstandings of safety. People may estimate that the technique may be dangerous or painful. This gives a negative impact on social and technology acceptance. Second, the availability of apparatus and systems for applying electricity to the human body can be low. Since comprehensive understandings for electrical safety is required to develop such systems, one may find difficulty or hesitation in order to develop them by themselves. This restricts the availability of systems that can be used for personal and research purposes.

1.4 Aim of the Thesis

This thesis aims to increase the acceptance of researches and applications that apply electricity to the human body. By practice through electrical body hacks, I will attempt to bridge the gap between wearables and cyborgs, and will provide an experimental platform for both developers and users. As I mentioned in the previous section, a human body is an electrical machine that can be affected by artificially designed electric signals. I will introduce several challenges that expanded the potential of electrical body hacks to a more complex area regarding safety and cognition. For the aspect of the acceptability, I present a careful discussion in order to maximize the potential acceptance of body hacking, by means of a consideration of safety, ethics and other elements of technology acceptance models. I also approach a body part that is said to lack social acceptance [90], and that have been previously avoided. It is important to share the value of the potential applications of such areas to affect the understandings of social acceptance. In order to encounter my goal, I attempt to explore the applications and acceptance of body hacking by means of electrical body hacking. Figure 1.5 illustrates the overview idea of this thesis.

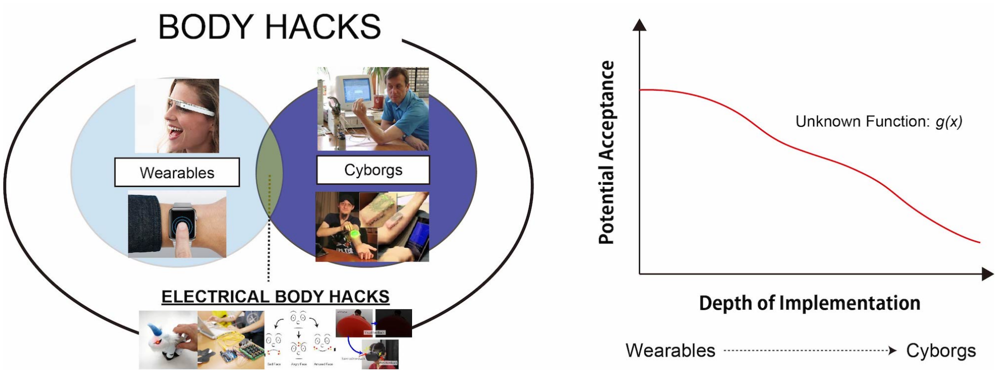

Figure 1.5: The focus of the thesis. Electrical body hacks is positioned between wearables and cyborgs. Currently, wearables tend to be more acceptable than cyborgs. This thesis attempts to increase the acceptance of electrical body hacks, towards cyborgs. Images for wearables are Google Glass[3], Apple Watch[4], is and Kevin Warwick[5], Tim Cannon (Founder of Grindhouse Wetware[6]) for cyborgs. The images for electrical body hacks are my works introduced in this thesis.

We assume that there are various parameters that influence acceptance, such as fear, safety concerns, usefulness, attractiveness.

Therefore, we attempt to challenge revealing the potential of electrical body hacks, and to provide as a literature for acceptable body hacks. We clarify safety, usefulness, attractiveness, and potential to reach into cognitive stimuli that influence the brain experience through non-implant body hacking. Chapter 4 is a practice to present the demands and the recent acceptance of EMS research. Chapter 5 and Chapter 6 is a attempt for working on a socially unacceptable body part. Chapter 7 works on an application where both prior wearable and cyborg approaches have been considered to be used, and to clarify the common features of electrical body hacks with them.

[3]http://www.google.com/glass/start/
[4]https://www.apple.com/watch/
[5]http://www.kevinwarwick.com/
[6]https://www.facebook.com/GrindhouseWetware/

1.5 Thesis Outline

The thesis starts by presenting a literature review in the field of HCI, where electricity is applied to the human body for interaction purpose (Chapter 2). Since considering and understanding safety aspects of electricity against the human body is difficult and are spread around various fields, in Chapter 2.2, we present safety issues and typical concerns for various signal patterns. Taking the review in Chapter 2, we give a design guideline for researchers to develop interactive systems that use electricity on the human body in Chapter 3.

After we have confident knowledge of related work in HCI and understandings of safety issues, we will introduce a toolkit for EMS in Chapter 4. The toolkit had multiple channel output, which contributed to novel outcomes related to human perception, in a conducted workshop.

By using our developed toolkit, we applied EMS to human faces, and studied the effects on emotion in Chapter 5. First-person and observer effects are studied and discussed. Due to the results revealed in Chapter 5, Chapter 6 presents an application of making use of the effects of facial EMS to the human emotional perception, which was a challenge to apply electrical body hack to a socially unacceptable body part.

A case for a practical application is introduced in Chapter 7, where the human body acts as conductive leads for power distribution. This was an attempt to work on an area where both wearable and cyborg approaches have been studied, in which technology is used to interact with daily interfaces.

Discussions of our research are presented in Chapter 8, where limitations and questions of acceptabilities are noted, and then concluded in Chapter 9.

To conclude the structure design of the thesis, I first share related work and the safety criteria of electricity on the body. Second, I will present a toolkit for developers to ease the access of developing/researching electrical body hacks. Finally, for users and consumers, example applications and design spaces are presented and discussed. Through these three processes, I attempt to improve the acceptance of electrical body hacks from both developers and users level, and to reach towards better assessment and development.

1.6 Contributions

This thesis contributes to the human-computer interaction field and body hacking domain from the following aspects.

- Review and categorization of existing studies in the field of HCI in which electricity is applied to the human body. The categories include EF sensing, transmission, and studies that incorporate the five human senses and the muscles (Chapter 2).
- Presentation of safety guidelines for designing systems that apply electricity to the human body based on information from research fields such as medical science and physiology. The current, voltage, frequency, time of conduction, the body part to which the electricity is applied, and route the electricity takes within the body must be considered (Chapter 2.2 and Chapter 3).
- Presentation of a multi-channeled electrical muscle stimulation (EMS) toolkit, and results observed from a workshop conducted with a theme of human augmentation. An expansion of easy-to-use multi-channel EMS, led to interesting use cases developed by novice users (Chapter 4).
- Presentation of a study for applying EMS on the human face and it's effect on emotions. Then we present use cases where users may find benefit for perceiving negative emotions through electrical stimuli. We used EMS to the eyelids to allow users to blink with external force, and a user study found effects for simulating realism, fear, and pain (Chapter 5 and Chapter 6).
- Presentation of a method for power distribution utilizing the body tissues as conductive leads. The practice was to present functional use cases via electrical body hacking (Chapter 7).
- Discussion of the potential of electrical body hacks, and consider strategies to clarify the acceptability of future body hacking (Chapter 8).

Through the above contributions, I will provide an experimental platform for developers and users to work on electrical body hacks, and ease the access to the method.

1.7 Statement on Multiple Authorship of Publications

Some of the contents included in the thesis have already been published as papers. For the prior publications, there were some collaborators working with me. Takumi Takahashi was a co-author of the article published in Transactions on Computer-Human Interaction (TOCHI) [149], where he took responsibility for high-frequency safety included in Chapter 2.2. Dr. Hiromi Nakamura collaborated for the guideline paper [149] and the work named Intentiō [148]. For the guideline, she contributed to the content related to electric gustatory in Chapter 2. For Intentiō [148], she contributed to the experiments as well as some of the application design. In addition, some figures were designed in collaboration with her. Therefore, I will use the term "we" to describe our work in the thesis (faculties of Jun Rekimoto Lab. are also co-authors of my publications). However, I was the primary author of all the publications included in this thesis [149, 146, 147, 148], and all work was conducted under my management and responsibility.

Chapter 2

Literature Review

This chapter presents a review of related work and safety knowledge to work on electrical body hacks.

2.1 Applying Electricity to the Human Body

Here, we first present a literature review of studies in which electricity is applied to the human body.

2.1.1 Categorization

Many approaches that utilize the electrical characteristics of the human body, such as its conductivity, resistance and/or impedance (Figure 1.4 (a,b)), capacitance (Figure 1.4 (a,b)), and/or stimulation of muscles and/or organs (Figure 1.4 (c,d)) have been proposed. Electricity has been applied to the human body to facilitate sensing and to actuate human interaction. We categorize these prior studies from three meta-levels, *application*, *circuit model*, and *quantity*. The purpose of the categorization is to help readers to find appropriate information related to their interest.

Application The *application* level is categorized into four main topics, and then categorize them into nine categories, including EF sensing (Figure 1.4 (a)), transmission through the body (Figure 1.4 (b)), and studies that incorporate muscles and the five human senses, i.e., haptic, gustatory, visual, auditory, and olfactory (Figure 1.4 (c,d)). Here, we categorize the studies by observing the technique used and the objective of the study without consideration of any side effects that may occur. However, there are some examples that may fit multiple areas of categorization (e.g., [167, 164]). The following in this chapter shows the details of the *application* category.

Circuit Model Figure 2.2 represents the *circuit model* level, which is categorized from 7 circuit models. The details are informed in the latter section (Section 2.1.7). The category mainly focuses on the path and the circuit model used for the design. Electric signals may pass through the body in many ways, and safety criteria may differ among them. Therefore, it is important to distinguish them by the used circuit model as presented in Figure 2.2.

Quantity Finally, the *quantity* level discusses the most detailed elements for developing practical systems. This category discusses the actual values of signals used for the application/circuit model. We start by presenting examples in Table 2.1, and then discuss safety criteria from current, voltage, frequency, time, and paths in Chapter 2.2.

2.1.2 Method of Survey

We primarily examined relevant papers presented in the ACM Symposium on User Interface Software and Technology (UIST) and the ACM Conference on Human Factors in Computing Systems (CHI) after 2011. This was managed by searching through the conference program with keywords such as "electro" and "electric" (these two keywords were chosen because they can cover words like electrostatic and electricity etc.). After collecting relative recent work, we referred to the cited references in the papers and the papers citing the work to cover prior and relative significant papers from other HCI conferences and journals. As we realized that this would not cover all of the categories we attempted to manage, we conducted further surveys of related work that in the perception category (visual / auditory / olfactory). As our goal was to find various types of work involving the application of electricity to the human body in the HCI field, due to our experience and relative survey methodologies [83], we searched the ACM Digital Library[1] and IEEE Xplore Digital Library[2]. We used *visual / vision*, *auditory / sound*, and *olfactory / smell / odor* with combinations of *electro / electric* (plus wildcards) as the keywords. The searched result was sorted in relevance, and then we checked the title, conference / journal name, and the abstract or keywords for at least the top 100 results for each keyword search to check the relevance to our objective. Furthermore, as we found that work in these categories was rare, we used relevant techniques from other fields to discuss the potential of the application. These procedures were taken in January 2018. Note that there are some additional references included beyond the introduced survey procedure, however, these were not found

[1] https://dl.acm.org/
[2] http://ieeexplore.ieee.org/

through the same survey procedure, but were selected with my personal interest.

2.1.3 Sensing

Application of electricity for EF sensing is a very common approach for recognizing human input into human-computer interfaces. The signal strength of the EF for such interfaces tends to be weak; however, we included it in prior work because it is a major approach in the application of electricity to the human body. EF sensing and capacitive sensing have a history of more than two decades, and a detailed survey can be found in a paper by Grosse-Puppendahl et al. [83] and Wilmsdorff [340]; therefore, we give only a brief overview in this section.

Following the application of EF sensing to human interfaces by Zimmerman et al. [370], many researchers took on the challenge of finding innovative ways to apply the technology. DiamondTouch [46] expanded the technique to two-dimensional surfaces, and SmartSkin [263] enabled additional gesture recognition for interactive surfaces.

The EF sensing technique is not limited to surface interfaces. Field mice [284] presented a non-contact three dimensional mouse based on measurements from the EF. Sensing devices can be designed to be wearable [72, 262, 367] or incorporated into other types of input devices such as gamepads [264]. FingeRing [72] is a ring sensing system allowing input by fingertip actions. GestureWrist and GesturePad [262] is a wristband and a module to interact with gesture based commands. Aurasense [367] enabled interactions around smartwatches. TriTap [78] identifies finger touch by implementing machine learning techniques in the application of capacitive electrodes on smartwatches. Manabe et al. [183] introduced a technique by using series-connected electrodes by simplifying the wired connections. Carpacio [324] distinguishes the user interacting with a car screen by capacitive coupling between the touchscreen and the electrode in the seat. Electrick [364] recognized touch inputs by EF tomography on conductive materials or painting objects with conductive paints. Capacitive sensing is popular to be used for touch input in HCI work, e.g., TableHop [267], a haptic display, and SkinMarks [336], an on-body interaction technique by electrodes on the skin.

Electric power supplies and sources can spontaneously induce varying electric potentials into the human body. Such potential changes result in capacitance changes of magnitude dependent on the contact condition with the ground [68]; thus, EF sensing can be carried out via passive sensing approaches. This means that the body acts as a kind of antenna, a feature that has been utilized by researchers for human motion and gesture sensing [34, 32, 33]. For example, Mirage [198] is a small sensor that recognizes the capacitance changes of the wave value resulting from the influence of commercial power supplies on the body. The signal wave value changes depending on the grounding condition of the body, which enables Mirage to detect movements such as jumping, walking, and various gestures.

2.1.4 Transmission

As the body is conductive and acts as a resistance and/or impedance against electric signals and power, researchers have developed techniques for gesture recognition, communication, and power distribution.

Capacitive Fingerprinting [89] and Touché [272] identify human gestures and interactions by sweeping frequency waves through the body and detecting the various changes that occur. Tomo [363] uses electrical impedance tomography to monitor and recognize gestures. SkinTrack [365] uses the body as a waveguide to conduct finger tracking on the body. Zensei [273] allows a variety of objects to recognize users by detecting bioimpedance related to the users' electrical properties.

Several notable studies in which body tissues were used as conductive leads have been conducted. RedTacton [6] and Personal Area Network (PAN) [369] transmit signals through the body for use by communication networks. Conquer it! [319] was a playful application based on this technique. Post et al. [243, 242] proposed techniques for PAN and power distribution. In EM-Sense [154], the electromagnetic noise from electromechanical objects that passes through the body when the user makes contact is measured to classify the objects. EM-comm [352] is a touch-based sensing technique transmitting signals from electronic devices to a wristband. In addition, intra-body communication (IBC) is another technique for sensor networks. A model called galvanic coupling is used to transport signals through the body for data transmission [334].

The strength of the signals used for communication and sensing does not have to be high and is therefore usually considered safe for the human body. However, when body tissues are being used as a conductive lead and for power distribution, care must be taken to ensure that the amount of power applied is safe. Intentiō [148] is a framework that distributes power through the human body to low-power electronics. The challenge in this research is to safely enable more power to pass through the body than has occurred in prior HCI and UbiComp studies. A consideration of the current and frequency values is a significant aspect of this research.

2.1.5 Actuation

Recently, in the HCI field electrical muscle stimulation (EMS) technology has been used to computationally manipulate the human body [278]. The technique, also known as transcutaneous electrical nerve stimulation (TENS) [323], is rooted in the field of medical rehabilitation [292] and is used for training or other medical treatments. However, an increasing number of studies based on EMS technologies have been conducted, and it has been used in various HCI applications.

PossessedHand [305], in which the user's fingers are manipulated to enable learning how to play musical instruments, is one of the pioneer studies applying EMS. EMS plays a significant role in applying force and in actuating the user to assist with interactions. Pointing-interaction-based research in which EMS technologies are applied is also popular, such as guidance of a finger [235] and wrists [175]. Muscle-plotter [175] assists users in drawing activities; for instance, it can help users plot charts or draw lines through data points. Pfeiffer et al. [234, 136] presented a study of a comparison of EMS and vibration feedback.

Haptics is one of the major areas in which electricity is applied to the human body. (Studies in this area are discussed in the next section.) However, EMS is also applied in haptics. Researchers have designed force feedback [152] and even food textures by applying EMS to the user's masseter muscle [211]. Lopes et al. applied EMS to mobile devices to create force feedback [164]. Impacto [167] simulated physical feedback to users such as impacts like being punched. Lopes et al. [174] also used EMS to provide haptic feedback for mixed reality experiences.

Zap++ [53] allows 20-channel EMS outputs with biphasic signals to create a wearable force-feedback system. Lopes et al. [173] utilized 8-channel EMS to provide haptics to walls and objects in virtual environments. Knibbe et al. [144] proposed an automatic calibration method by using 60 electrodes. An increasing amount of channels and electrodes are observed in recent HCI, as well as novel calibration techniques, e.g., using spacial interaction [240].

EMS can be applied as an output actuator for applications that require both input and output interaction. Proprioceptive Interaction [168] enables eyes-free interaction by users. In this technique, a wearable device comprising EMS and accelerometer sensors enables users to interact with both input and output. BioSync [213] is a platform that creates a synchronizing kinesthetic experience for multiple users by enabling them to interact bi-directionally via a wearable EMS system. Wired muscle [212] used EMG and EMS among multiple users to allow faster reactions to kinesthetic experiences. UnlimitedHand [303, 86] is another research project and product that allows both input and output hand gestures. MuscleIO [54] used EMS and EMG to recieve and react to notifications, and developing systems that share both input/output features are gathering interest [214].

The stimulation generated by EMS can be applied to obtain information or to provide notification to the user. Schneegass et al. [277] conducted a study based on this usage. Another interesting application involved a study by Lopes et al. [169] dealing with affordance to objects, in which they objects were allowed to communicate their dynamic usage to users. By stimulating the user's arm, the system actuated the arm to use the object or even perform movements required for using the object. Pfeiffer et al. [232] proposed a technique for assisting and controlling pedestrians' walking directions via EMS. Emotion Actuator [90] was a work to connect emotional expressions with body movements designed by EMS. Fortin et al. [69] proposed using EMS for reflex responses against heat. EMS Painter [35] allowed co-creation by using EMS and a tablet interface, which was manipulated by audiences.

Although a major approach in applying EMS in HCI is to actuate the user's arms or fingers, researchers have also attempted to actuate other body parts. Vibrat-o-matic [74] attaches the electrodes to the throat or stomach to vibrate the body part, enabling users to perform vocal vibrato. Yen-Chin et al. [354] applied EMS to the user's face to lift up the cheek to explore whether EMS can increase happiness.

In recent conferences, EMS has been featured in various ways. In the 2016 ACM Conference on Human Factors in Computing Systems (CHI 2016), a course was arranged in which participants created their own prototypes [171]. Furthermore, in the 2016 ACM Symposium on User Interface Software and Technology (UIST 2016), EMS was featured and used for the Student Innovation Contest (SIC) [172]. Ebisu et al. [60] considered using EMS for learning rhythm, and provided an opportunity for conference attendees to learn using the system [59]. It is now easier for researchers to explore EMS applications thanks to the contributions of Pfeiffer et al. [231, 55], Lopes et al. [176], and others [146] in developing open source toolkits.

In general, EMS supplies a larger amount of current to the human body (e.g., 100 mA at maximum [305]) than do other techniques. However, the route through which the electricity travels is limited. Signal delivery is generally based on pulse-driven signals whose pulse width is very small, approximately 30–800 μs [231]. The signals can be either DC or AC; however, the use of AC signals might avoid skin irritation [53].

2.1.6 Perception

Haptic

Applying electricity for haptic sensing is also common in the field. An electrotactile display [294] was proposed in 1970. Human welfare is another major area of application, where researchers attempted to support users with visual impairments [122, 306]. Electrostimuli has been applied to various parts of the body, which includes the forehead [122] and the tongue [51]. As mentioned in the previous section, EMS has also been applied for haptic sensing [123, 152]. In addtion, the techniques have been applied for notification purposes [239]. Takahashi et al. reported that electrical stimulation to the tendon can be used to present proprioceptive force sensation by stimulating receptors or sensory nerves, instead of stimulating motor nerves [299, 298]. However, researchers are faced with the challenge of designing richer sensations by considering and carefully managing the electricity that is applied to the user.

Researchers have applied electrostatic [349] and electrovibration [15, 14] methods to human interfaces. TeslaTouch [15] and REVEL [14] induce various haptic sensations to the finger dependent on the frequency and waveform of the electricity input. In these approaches, the haptic perception is generated mechanically by the electrostatic force deforming the skin. Kato et al. [135] proposed a method for both electrostatic forces and electrostimuli by inkjet printing with conductive ink. Kajimoto et al. proposed a method called the tactile primary color approach [126, 125] for designing rich haptic feedback. In their proposed approach, visual information is perceived by RGB sources, and the electrotactile sensation is designed using pressure, low-frequency vibration, and high-frequency vibration that stimulate different elements of the skin. This kind of technique was further applied for tactile displays on smartphones [127] and with combinations with mechanical approaches [353]. PinPad [120] is a high-resolution touchpad for tactile feedback from arrayed electrodes.

In the above examples, stimulation occurs as a result of the perception of current or electrovibration; however, high voltage (HV) has also been used in haptic design. For example, Corona [197] is a wearable device that provides a haptic sensation to users by applying HV to the body and observing the corona discharge that occurs when the user interacts with a grounded object. Fukushima et al. [73] used a maximum voltage of 20 kV to generate electrostatic force applied to the user's arm for piloerection, which elicited feelings of surprise from the user. Sparkle [288] used HV and electric arcs to induce haptics in users' fingers.

Using electricity to deliver haptic feedback to users requires safety precautions in order not to harm the user. A number of systems are designed to allow electricity to pass through the body from the finger; thus, the use of large amounts of power needs to be carefully considered. On the other hand, designing stable feedback to users is also challenging owing to unstable body impedance and other factors. Research geared towards solving this issue is actively under way. These include usage of anodic stimulation [124], PWM (pulse width modulation) [121] and current sensing and feedback [14].

Gustatory

Research on electric gustation dates back to 1754, when Sulzer [322] placed two types of metal on his tongue and experienced this phenomenon. Volta [322] subsequently hypothesized that this taste is induced by an electric stimulus from one metal to another. There are several hypotheses on how humans perceive taste; however, these have yet to be confirmed [322, 134, 238]. Nevertheless, Tomiyama et al. [313] reported that voltage threshold increases with age and is not significantly influenced by sex, history of smoking, artificial dentition, or metal dental crowns.

Researchers have also investigated numerous variations in output patterns for changing taste. Bekesy [17] reported that four taste classes and qualities (sweetness, saltiness, sourness, and bitterness) can be presented by changing output frequency and pulse duration. Hettinger et al. [92] discovered that cathodal current inhibits our perception of taste (especially salty taste) via experiments on animals and human psychological experiments.

Before HCI focused on this area, this phenomenon was utilized for taste testing in which taste functions were examined by researchers. Krarup [150] proposed the first electrogustometer prototype in 1958; its circuit and electrodes were subsequently improved by various researchers in ensuing studies. Feldmann et al. [67] changed the signal from DC to AC and used tuning-bar-shaped electrodes. Pulec et al. [248] proposed an oval-shaped electrode made of silver. Tomita et al. [94, 95] proposed an improved constant-current electrogustometer with a log-scale visualization of output current.

In recent years, HCI researchers have utilized electric taste techniques in virtual reality (VR) and augmented reality (AR) applications, as changing taste quality by electricity has been found to be easier than controlling the gustatory substance chemically. Nakamura et al. [202, 203] proposed a fork/cup that enables the application of electricity through food to change the taste. A saltiness control device utilizing

Hettinger's phenomenon has been proposed. Interactive methods for synchronizing electric taste with visual content, as well as methods allowing interaction among multiple users, have also been proposed [201]. Ranasinghe et al. [254, 252] proposed a system that employs an electric taste stimulus to digitally stimulate the sense of taste via an electrode placed directly on the tongue. They utilized Bekesy's [17] result and thermal control to output sweetness. The work by Ranasinghe et al. was further studied in depth, and they modulated the experiences of flavor tasting [256]. Aruga et al. [10] and Sakurai et al. [270] also proposed utensils for applying electricity to the tongue. Sakurai et al. [270] demonstrated that cathodal DC stimulation to the tongue inhibits salty and umami perception. They discovered a relationship between current value and the effect of taste suppression. Furthermore, Vocktail [255] proposed a virtual cocktail for multisensory flavor experiences with electric taste stimuli. Since the required power for electric gustation is low, Ooba et al. [223] proposed a method to harvest energy from chewing and piezoelectricity.

Visual

Various products in which electrical signals are applied to the eye to create visual information have been developed. In simulated prosthetic vision (SPV), electrical stimulation is applied to the user through electrodes implanted in the eye [100, 49, 99]. The visual information is usually captured by a camera and then downsampled to a low resolution to match the electrode array. Denis et al. [44] proposed a design that helps SPV users detect human faces even with low-resolution vision. The design is a computer vision (CV) solution in which a camera image is pre-processed with an object recognition algorithm. Although HCI researchers can contribute to the technology of such CV-based implementations, it may be difficult to gain access to the hardware as surgery is required to implant such systems, which are therefore usually considered to be under the purview of the medical field.

As a result of the difficulty of implanting electrodes or systems in the human body, research contributions to visual perception or augmentation remains rare in the HCI and UbiComp fields. Nevertheless, a method called galvanic retina stimulation (GRS), in which a flash sensation is perceived when electrical stimulation occurs around the user's eyes, has been developed [130, 128]. Higuchi et al. [93] also proposed a system in which GRS is applied to a lightweight visual feedback system. The system generates and controls the flash sensation of the user for AR and can be considered an alternative to head-mounted displays (HMDs).

Furthermore, a technique called galvanic vestibular stimulation (GVS) has been studied over an extended period [328]. The stimulus is known to produce stereotypical automatic postural and ocular responses in humans from electrodes on one or both ears. This technique has been used to stimulate visual perception by Nagaya et al. [200].

Auditory

In addition to SPV, cochlear implants are another notable used for mechanically supporting users' hearing. Johns et al. [119] reported that there are three mechanisms of hearing based on electrical stimulation. These mechanisms result from the perception of current passing through different parts of the ear. Much research has been conducted on cochlear implants [163], and the quality has improved considerably [47, 257]. However, the method requires implanting systems inside the ear.

Hearing aids that do not require implantation in the ear are also being developed to enhance audio support to users [218]. The approach and the target of hearing aids differ; in addition, they do not usually apply electricity to the body.

Ishin-Den-Shin [297] is a project in which the human body is employed as a sound transmission medium. In the project, an audio signal is turned into an inaudible electric signal that is then passed through the user's body to communicate with multiple users. The finger of one person and the ear of another form a speaker, allowing an audible signal can be perceived from the vibration of the ear lobe. Using electrical signals to augment hearing is still a minor area of study; however, there are other phenomena, such as the microwave hearing effect [160], which may have potential application to the HCI and UbiComp fields.

Olfactory

Olfactory perception plays a significant role in human sensing activities. In the HCI and UbiComp fields, many researchers have sought to design olfactory interfaces [138, 12]. For example, a display that produces olfaction was designed [351]. However, a majority of these approaches are based on air flow.

Researchers have found that olfactory perception can be generated by electrical stimulation [194, 157]. Ishimaru et al. [112] conducted a study on electrical stimulation of the human olfactory mucosa by inserting an electrode into the nose. Unlike electrical stimulation of vision and hearing, there is no need for electrodes to be implanted into the body with this method. This may make it easier for HCI and UbiComp researchers to develop novel interfaces and systems. In fact, Ranasinghe et al. [253] indicated the possibility of electrical stimuli for smell perception and Hariri et al. [88] have designed a digital smell system by inserting electrodes into the nose to stimulate the olfactory receptors. Although further studies are required, an initial prototype has been proposed to galvanize future HCI and UbiComp research.

Other Applications

Recently, the GVS technique has been applied to generate virtual acceleration in VR environments [180]. In addition, Aoyama et al. [8] enhanced the effect by applying a countercurrent to the user. Such stimulus is expected to alleviate the sickness that commonly occurs in virtual environments. With an increasing number of HMDs being developed and an increasing number of studies being performed, this approach could become one of the key solutions ro virtual sickness. GVS RIDE [7] was presented as a means for providing an augmented experience through the use of GVS for virtual reality.

In addition to the techniques we have described in the previous sections, another significant technique related to the application of electric signals on the body is electromyography (EMG). EMG is used for sensing users' gestures [219, 191], and there are now EMG products available for consumers [309]. However, instead of applying signals, EMG extracts signals from the body. Therefore, we do not discuss EMG further in this thesis. EMG techniques are compatible with EMS techniques; thus, some studies combine these methods for both input and output purposes [144, 213].

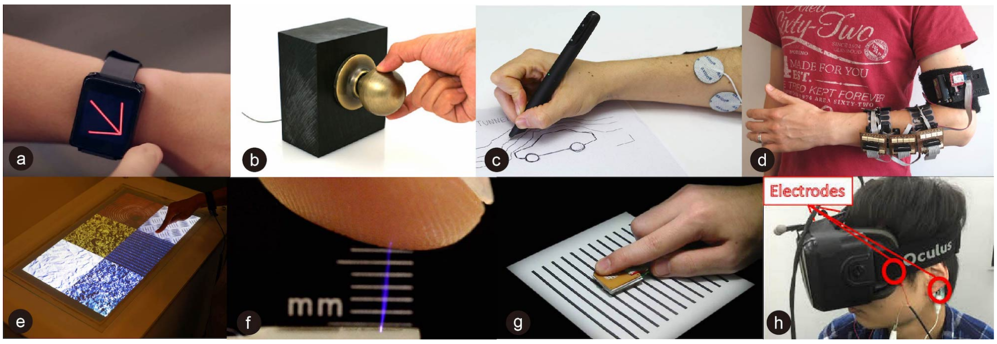

Figure 2.1: Images of Research in the topic. (a) AuraSense [367]. (b) Touché [272]. (c) Muscle-plotter [175]. (d) Zap++ [53]. (e) Teslatouch [15]. (f) Sparkle [288]. (g) GVS [8].

2.1.7 Summary and Discussion

Various notable applications involving the application of electricity to the body have been developed. However, they are based on different types of power and circuit models developed on various bases, various features of the human body, and various amounts of electricity (Figure 2.1).

Research Accomplishments

A number of accomplishments have been achieved in the development of EF sensing techniques, electricity transmission through the body, EMS, techniques built on the five human senses, and other methods associated with perceptual illusion. At present, EF sensing is one of the most popular techniques deployed for HCI and UbiComp and is very familiar to the public. However, research on haptics is expected to significantly increase as a result of the growth of VR and AR systems. In addition, an increasing number of studies that aim to augment the five human senses are being conducted, and it is hoped that they will enhance human interfaces [220]. EMS for HCI is also experiencing notable growth. For example, a wearable has been deployed for VR and AR that can be used by the public [86].

Circuit Model and Value

To successfully accomplish various kinds of applications, many variations of electricity and circuit models are studied. The human body has many electricity-related characteristics, including resistance, impedance, capacitance, and behavior similar to that of an antenna. Researchers have made use of such characteristics in various ways. Different applications utilize different types of circuit models. Figure 2.2 displays the major circuit models that are used for research associated with the application of electricity to the body. In the case of Figure 2.2 (a), signal or power is supplied to the body when the user makes direct contact with the source. The human body functions as a good ground, allowing robust signals to be applied to the body or signal changes to be observed for sensing purposes. In Figure 2.2 (b), the body acts as a kind of antenna allowing electric signals to be supplied to the body from a distance, i.e., without direct contact. In Figure 2.2 (c), a wearable source is worn by the user, typically in his or her shoe, supplying signals through the body and distributing them to an external object via direct contact. By contrast to the method shown in Figure 2.2 (a), that in Figure 2.2 (c) offers human-centered applications that can be carried freely by the user. The model in Figure 2.2 (d) is a combination of those in Figure 2.2 (a) and

Figure 2.2 (c); the source is worn by a user, who distributes signals to other users who act as a good ground to create a closed-circuit model. The model can be applied for communication purposes and interaction among multiple users. Figure 2.2 (e) shows the application of a signal to a specific body part, stimulating muscles or organs. Because the signal passes only through a specific body part, i.e., through a limited area, stronger signals (more watts or joules) tend to be applied. In Figure 2.2 (f), a signal is applied to the body and passes through multiple parts of the body; this technique enables the creation of a closed-circuit model that is completed within the user's body. This is applied for sensing purposes and the stimulation of organs. In Figure 2.2 (g), a signal is applied to the body, where galvanic coupling is used for data transmission.

Figure 2.1 and Table 2.1 shows typical research and proposed systems along with their power requirements and circuit models. As can be seen, there are a number of types of signals and circuit models applied for various research purposes. Thus, even if a researcher has specific knowledge about the application of electricity to the body, it is not necessarily the case that their knowledge will cover all types of research related to the application of electricity to the body. Different applications have different requirements, e.g., different signal types, power, frequency, and circuit models.

Table 2.1: Overview of related research (selected), and the signals applied to the body

Research	Objective (Fig. 1.4)	DC AC	V, A, W, J	Frequency, Pulse	Model (Fig. 2.2)	Body Part
Fish [370]	a	AC	60 V	10–200 kHz	b	Hand / Body
DiamondTouch [46]	a	DC	5 Vpp	100 kHz square wave	a	Finger / Body
AuraSense [367]	a	DC	3 Vpp	115 kHz square wave	a	Arm
Touché [272]	b	AC	6.6 V	1 kHz–3.5 MHz	a, f	Finger / Body
Intentiō [148]	b	AC	250 V, 2 mA, 5 mW	30 kHz	c, d	Finger / Body
SkinTrack [365]	b	AC	1.2 Vpp	80 MHz	f	Finger / Arm
Zensei [273]	b	AC	± 3.3 V	1 kHz–1.5 MHz	a	Hand / Body
IBC [334]	b	AC	± 1 mA	100 kHz–1 MHz	g	Arm / Leg / Body
PossessedHand [305]	c	DC	17–42 V, 100 mA	40 Hz, 0.2 ms	e	Arm
Muscle-Propelled Force Feedback [164]	c, d	DC	50 V, 100 mA	25 Hz, 290μs	e	Arm
Cruise Control for Pedestrians [232]	c	DC	13–33 V, 38–67 mA	120 Hz, 100μs	e	Leg
Muscle-plotter [175]	c	DC	8–10.3 mA	200 Hz, 20–500μs	e	Arm
Zap++ [53]	c	AC	87 V, 0–104 mA	30–120 Hz, 10–300μs	e	Arm
TeslaTouch[15]	d	AC	80–120 Vpp, 0.5 mA	80–400 Hz	a	Finger / Body
REVEL [14]	d	AC	200 V, 150 μA	50–80 Hz	c	Finger / Body
Corona [197]	d	DC	-4.5 kV, 1 mJ	–	c	Finger / Body
Sparkle[288]	d	AC	12.75 kV, 0.21 mA	450 kHz	a	Finger / Body
Smarttouch [126]	d	DC	100–300 V, 1.0–3.0 mA	10–50 Hz, 0.2 ms	a, f	Finger
Saltiness [203]	d	DC	-5.1 V, 250 μA	–	d, f	Tongue / Body
Olfactroy [88]	d	DC	1–5 mA	50 Hz–10 kHz, 0.5 s	e	Inside Nose
GVS [8]	d	DC	0.3–3.0 mA	0–2000 ms	e	Face / Eye

Note: The values in this table are based on those reported in the papers cited under “Research.” They are typically the maximum values indicated in the paper.

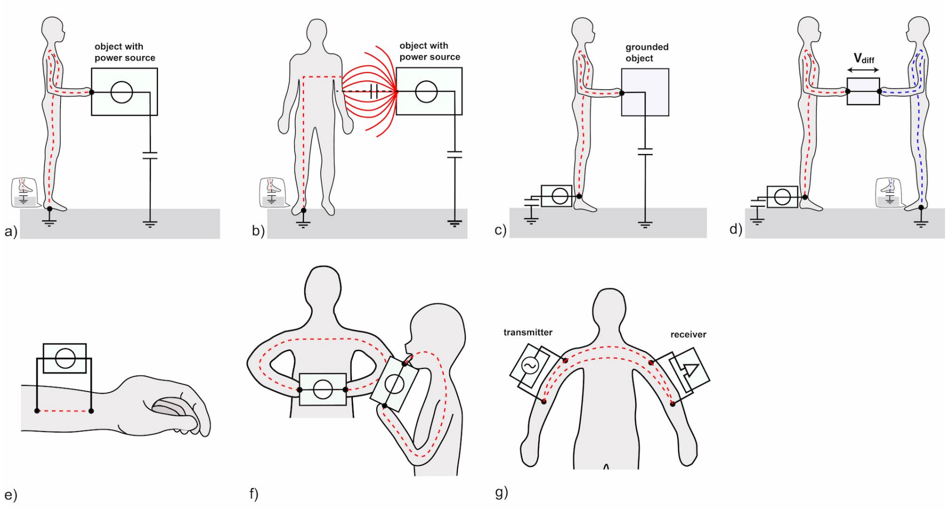

Figure 2.2: Typical circuit model variations. (a) A signal and/or power is supplied to the body from an external source, via direct contact. The body acts as a good ground. (b) A signal is supplied to the body from an external source, via capacitive coupling. The body acts as a good ground or an antenna. (c) A signal is supplied directly to the body (e.g., through a wearable), through which the signal is applied to the other media via direct contact with the user. The body acts as a conductive lead. (d) A signal transmitted from a different user is supplied directly to the userand creates a difference in potential between the media as a result of contact. The bodies of the users act as a conductive lead and a ground. (e) A signal is supplied to a typical part of the body via an electrode, with the signal collected through a paired electrode attached to the body (normally on the same body part). The body acts as a conductive lead enabling electricity to stimulate muscles or organs. (f) A signal is supplied directly to the body and the signal passes through other parts of the body, which creates a closed-circuit model within the body. The body acts as a conductive lead for transmitting signals and/or stimulating organs. (g) A signal is supplied to the body from an external source. The body acts as a conductive lead, which passes signals to a receiver. This is known as a technique called galvanic coupling.

2.2 Designing Safety

It is not completely safe for the human body to conduct electricity; therefore, consideration of safety issues in studies in which electricity is applied to the body is essential. Although many researchers have attempted to apply electricity to humans and have discussed safety concerns in the HCI and UbiComp fields, the elements that must be considered differs depend on the type of power that is applied. The magnitude of the current, voltage, and frequency, along with the duration of conduction, the body part where the power is applied, and the route taken all need to be considered. Therefore, we present information below on each element as well as the risks that exist when they are handled inappropriately.

2.2.1 Electrical Hazard

The main hazards when electricity is not handled appropriately are shocks and burns. There are two types of electric shock: macroshock and microshock [4]. Microshocks occur inside the body when a current is applied directly to the heart. They occur at 100 μA, a value that is much lower than the current required for macroshocks. However, microshocks are not expected to arise in HCI or UbiComp research as they require direct stimulation to the heart (as occurs with, e.g., Cost-Volume-Profit Analysis (CVP) or pacemakers [196]). By contrast, it is important for researchers in these fields to understand the risks associated with macroshocks, which occur when electricity is applied through the skin or when current is applied externally and spreads through the body at a reduced concentration. In general, there are three levels of macroshocks. The first level is the perception threshold: signals above this threshold are perceived by humans but do not necessarily pose any serious health risk (although the shock may be uncomfortable). Accordingly, HCI and UbiComp researchers tend to stay below this threshold to avoid disturbing the user. The second level is the let-go threshold, above which paralysis occurs and the user finds it difficult to detach from the medium without outside help. Continued contact at this level increases the risk of further harm. The third level is the most serious, with contact above this threshold leading to ventricular fibrillation as well as the possibility of asphyxia, respiratory arrest, and/or asystole [80].

Electricity passing through any resistance will cause joule heating, which can be expressed as $H = I^2Rt$ (where H is the heat expressed in joules (J), I is current (A), R is resistance (Ω), and t is time (s)). Therefore, when electricity passes through the body, there will be noticeable joule heating and a risk of electric burns [290]. Electric burns anc result in harm to health in the form of ulcers, coagulation necrosis, and/or electric marks. Protein is known to degenerate at temperatures over 60°C [286, 187]. In addition, even at lower temperatures there are risks of moderate-temperature burns when continuous heat is applied [296].

2.2.2 Current

According to the International Electrotechnical Commission (IEC) [104], the important element in considering electric shock is the amount of current passing through the body. With a 15–100 Hz AC signal (such as in commercial power supplies collected from plugs [106]), humans do not perceive less than 0.5 mA of current (Figure 2.3). In fact, currents of to 10 mA do not pose a serious risk to humans. However, although they may be safe, currents from 0.5 to 10 mA are perceptible. Different threshold values have also been reported. For example, some researchers have reported that, at 60 Hz, the threshold of perception is 0.2 mA [80]. In addition, 0.5 mA is the stated threshold for the occurrence of a startle reaction. Eales [58] stated that the threshold of perception is above 0.1 mA. It is also known that the value of the threshold varies according to individual characteristics including gender; thus, the design of offsets is important to ensure safety.

However, the perceptible current changes with the frequency conditions. According to Dalziel [38], the perceptible current decreases at higher frequencies. Therefore, designing a system that can carry a larger amount of current through the body requires the use of higher frequency AC signals. Table 2.2 lists the values of current that should be considered for safety at various frequencies.

Although higher frequency electrical signals tend to have a higher threshold for safe usage, the characteristics of DC power and its safety differ. According to IEC 60479-1, the threshold of perception in the case of DC is 2 mA; however, the perception only occurs at the beginning and termination points. In addition, it should be considered that there is no let-go current less than 300 mA [302]. To cause ventricular fibrillation, DC requires approximately four times the current required by AC power; thus, AC power is considered to be more dangerous than DC. However, as mentioned by Prasad et al. [245], the threshold at which a tingling sensation is felt is 1 mA. Therefore, as with AC power, it may be necessary to consider offset values for DC power. In cases where AC power contains DC features, it is necessary to consider the peak-to-peak value and the time duration [104, 302]. For time durations exceeding the beat cycle of the heart, the waveform of the current becomes unrelated.

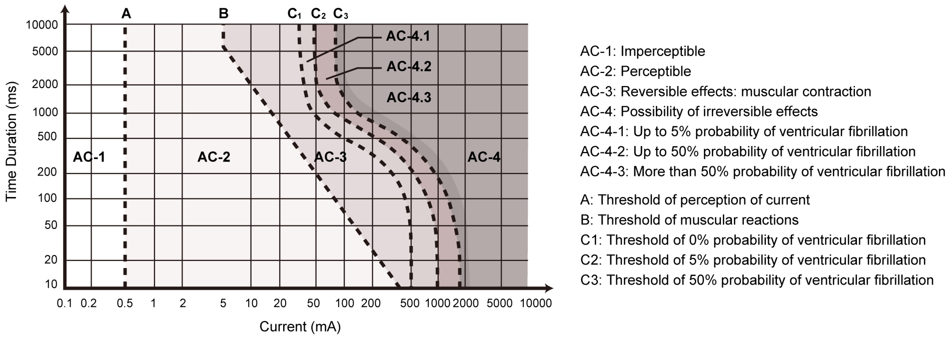

Figure 2.3: Effects of AC current (15–100 Hz) on the human body when it passes from the left hand to the feet. (The figure is referenced from IEC TS 60479-1 ed.4.1 [104].)

Table 2.2: Reference levels of time-varying contact currents from conductive objects. (The table is referenced from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [107], Table 8.

Exposure Characteristics	**Frequency Range**	**Maximum Contact Current (mA)***
Occupational Exposure	up to 2.5 kHz	1.0
	2.5-100 kHz	$0.4f$
	100 kHz-110 MHz	40
General Public Exposure	up to 2.5 kHz	0.5
	2.5-100 kHz	$0.2f$
	100 kHz-110 MHz	20

* f is the frequency in kHz.

2.2.3 Voltage

The main cause of danger from electric shocks to the human body is the amount of current. However, with reference to Ohm's law it is sometimes useful to alter the voltage to regulate the current. The impedance of the human body varies and is influenced by many elements; hence, estimating a precise value for the impedance is difficult. Therefore, safety indications are usually based on estimates and assume typical situations. According to IEC 61200 [102], the agreed-upon voltage allowed for continuous contact is 50 V [300].

The impedance of the human body is a significant element for consideration, especially when dealing with HV. The impedance of the skin is negligible when dielectric breakdown occurs. Different reports present different values at which this occurs; for example, Grimnes [82] provides values in the range 300–500 V, Mason et al. [188] provide 600 V, and Yamamoto et al. [350] provide 450 V. These values may have been measured under different conditions, but it is obvious that it is difficult to provide an exact value.

However, use of HV power can cause electrical discharge on the skin that can be painful and cause burns. This can occur when an HV electrode is held close to the skin with a small gap in between. Reilly [258] reported that a stimulus is perceived at voltages above 330 V. Risk factors include wrinkles and any other interruption of the skin. Turning on the power after attaching the electrode firmly to the skin will help to eliminate this risk. Care must also be taken that the electrode is not detached while the power is activated.

Mason et al. [188] developed an equation that can be used to calculate the electrical stimulation that occurs from thermal effect:

$$I_{pain} = \sqrt{\frac{k\theta_\tau A_e}{R_e t_p f_{rep}}} \tag{2.1}$$

where f_{rep} is the pulse repetition frequency, k is a constant equal to 4.184 J/cal, A_e is the electrode area in cm^2, R_e is electrode resistance in ohms, t_p is pulse width (in seconds), and θ_τ is the threshold thermal energy density for pain resulting from radiant heat stimulation with the value of $\theta_\tau = 250mcal/cm^2/s$.

The Electronics and Electrical Engineering Laboratory (EEEL) from the National Institute of Standards and Technology (NIST) suggests a guide when treating voltage exceeding 1000 V [209]. They recommend the current to be under 2 mA for AC and 3 mA for DC, or 10 mJ for an impulse voltage generator with a stored energy. These values are slightly below the startle response threshold indicated by Delaplace et al. [42]. When considering HV discharge, it is common to use a human-body model (HBM). Electrostatic Discharge Association (ESDA) defines the human-body capacitance to be 100 pF in this model [64], and researchers have attempted calculations by using the value [358]. However, Jonassen [118] indicated that the capacitance can vary depending on the measurement method, which varies from 100–400 pF. A person may be naturally charged up to more than 30 kV [185].

2.2.4 Frequency

The frequency of the electric signal significantly influences the safety threshold of the current value. As stated above, the safe current value above which harm can occur to the human body is higher at high frequencies. However, different effects are observed depending on the frequency conditions. We therefore present separate safety guidelines according to the various frequency ranges.

Up to 100 kHz

Low-frequency AC signals can cause electric shock. For low-frequency AC signals, especially signals up to 100 Hz, the allowed current is shown in Figure 2.3. In general, the value considered as the threshold in most studies is 0.5 mA. However, Dalziel [38] reported that the threshold increases in high-frequency conditions. The guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [107] include equations for calculating the reference levels. Table 2.2 shows the electric current values that should be considered. Up to a threshold of 2.5 kHz, they recommend a maximum of 0.5 mA. For frequencies between 2.5 and 100 kHz, the maximum current is expressed as 0.2*f*, where *f* is the frequency in kHz.

In cases of signals comprising multiple frequencies with exposure occurring simultaneously, the following equation should be applied [107]:

$$\sum_{n=1Hz}^{110MHz} \frac{I_n}{I_{c,n}} \leq 1 \tag{2.2}$$

where I_n is the contact current value at the frequency n, and $I_{c,n}$ is the reference level of the contact current at frequency n as displayed in Table 2.2. However, it should be noted that these assume the worst cases, and therefore it is recommended that thresholds at lower levels should be considered.

Up to 110 MHz

In applying high-frequency signals to analyze human behavior, particularly at a short range, it is essential to consider risks of electric shock as well as thermal effects.

High frequencies of up to 110 MHz can cause shock or burn hazards to the human body [107, 24, 308, 18]. For example, the current perception threshold is 25–40 mA at frequencies of 100 kHz to 1 MHz. The ICNIRP guidelines set the maximum value of contact current to 40 mA for occupational exposure and 20 mA for general public exposure at frequencies of 100 kHz to 110 MHz (Table 2.2) [107]. Multiple-frequency signals should be treated the same way as lower frequencies, i.e., using equation (2.2), by calculating the sum of the rate of the value against the reference level for each frequency [107].

Furthermore, it is reported that, for frequencies in the range of 100 kHz to a few GHz, EF can lead to temperature increases of more than one degree Celsius [24, 25, 98, 75, 312]. Temperature increases of more than 1–2°C result in adverse health effects such as heat exhaustion, heat stroke [2], and heat stress [251]. This level of heating in the skin and tissue is caused by exposure to a whole-body specific energy absorption rate (SAR) of approximately 4 W/kg for about 30 min [107]. The ICNIRP guideline therefore has a whole-body average SAR of 0.4 W/kg at 100 kHz to 10 MHz as the basic limit for occupational exposure. For general-public exposure, ICNIRP stipulates a whole-body SAR limit of 0.08 W/kg, which is one-fifth of the occupational safety level.

Up to 300 GHz

Some studies [159, 326, 250] in the fields of HCI and UbiComp apply radio frequency (RF) sensing technology in the development of radar-based sensors, which capture human behaviors and gestures at short distances. Soli [159, 326, 355] is a radar-based sensor for sensing gestures of the user at short distances. Soli is designed to work at 60 GHz; hence, it should be noted that it may affect the human body depending on the power density or when used on sensitive body parts. DoppleSleep [250] uses a 24 GHz Doppler radar sensor for tracking human sleeping behavior at a two-meter distance. Health considerations based on federal regulations have also been discussed [65]. However, further analysis is required with regard to the long-term usage of DoppleSleep. High-frequency-radar-based techniques can be applied to recognize user input at short distances in many ways.

Between 10 and 300 GHz, the basic restrictions in the ICNIRP guidelines are given in terms of power density; these give the basic exposure limit as a power density of 50 W/m^2 for occupational exposure and 10 W/m^2 for general public exposure. It is known, for example, that for 2.5 GHz signals the penetration depth in muscle tissue for a plane model is approximately 1.7 cm and that a linear dimension of approximately 2.15 cm^3 is equivalent to 10 g of muscle tissue [161].

Over 300 GHz

Signals over 300 GHz include far infrared rays (300 GHz to 3 THz), infrared rays (3–370 THz), visible rays (370–790 THz), ultraviolet rays (790 THz to 30 PHz), x-rays (30 PHz to 300 EHz) and gamma rays (over 3 EHz) [269]. Whereas the ICNIRP guideline covers frequencies up to 300 GHz, frequencies over 300 GHz are covered by the International Commission on Radiological Protection (ICRP) [108]. As these types of signals are known as electromagnetic waves, we do not give a detailed discussion of these conditions in this paper, as our focus here is on *electricity*.

2.2.5 Time Effects

For low-frequency power, continuous current passing through the body for a few seconds may be risky. Figure 2.3 displays the effects of time and current value. For example, when a 10 mA current passes through the body, the risk is AC-2 per instance of use; however, the risk becomes AC-3 if the current is applied for more than 2,000 ms. Although current under 0.5 mA will not result in an electric shock, when the current passes through the body continuously the heat generated must be considered. In the case of EMS, moderate-temperature burns resulting from continuous use have been reported, and the effect from electrodes has been studied [226, 227]. As the skin and tissues create resistance, Joule heating of $H = I^2Rt$ will occur. Suzuki et al. [296] showed in a study conducted on a rat that continuous warming of the skin even at 38°C can result in burns.

By contrast, the main risk of continuous usage of high-frequency power is heating. For example, high-power and high-frequency currents are used for electrosurgery [283]. However, this phenomenon is usually considered for frequencies over 100 kHz, and studies report that no established effects are found at lower frequencies [274, 283, 107]. Nevertheless, they also state that further studies are required and that the effects of long-term usage are unknown.

Fig. 3 is useful when we consider treating currents of more than 10 ms. However, in case of a shorter duration, currents up to 1000 mA has a low risk of fibrillation (up to 5 % possibility) [105]. Furthermore, current with pulses requires an additional consideration. For pulses that have intervals greater than 300 ms, they can be considered individually as if they were non-repetitive pulses. On the other hand, pulses with intervals less than 300 ms have more risk of ventricular fibrillation. According to IEC 60479-2 [105], The threshold for ventricular fibrillation of the seventh current pulse is 10 % or even less than the threshold value of the first current pulse. This means that continuous input of repetitive pulses (pulses with intervals less than 300 ms) leads to more danger.

2.2.6 Path and Body Parts

The threshold for harm that can occur as a result of electricity passing through the body depends on the route of the flow. In IEC 60479-1, the heart current factor is defined with respect to the values on the path from the left hand to the feet, as displayed in Figure 2.3 [104, 302, 109]. The risk of ventricular fibrillation for current paths other than that from the left hand to the feet can be calculated using $I_x = I_r/F$. In the equation, the heart current factor is F, the current for a given path is I_x, and the reference current (the current from the left hand to the feet) is I_r. Various values of F are given in Table 2.3.

In the case of DC, it is known that ventricular fibrillation is unlikely to occur when current passes through the heart horizontally [302]. In addition, the polarity influences the threshold significantly for cases in which the current passes through the heart vertically. For example, when the cathode is on the hand and the anode is on the feet, the threshold value for ventricular fibrillation will likely be approximately two times greater than for the opposite case.

As we have shown that the threshold for safety current is related to the path through the human body, and paths that affect the heart directly tend to be more dangerous (Table 2.3), some body parts are more sensitive than others. For example, eyes have poor heat removal capacity, which may pose risks such as cataract formation [281]. Some researchers claim that the human brain is the most electrically sensitive organ and that the locus at which the brain is connected to the rest of the body can be considered the most electrically active organ [28]. Some reports indicate risks of brain tumors for long-term electrical workers [311]. In addition, there are some concerns about cancer; however, the evidence for such a linkage is still not clear, and there are several causation hypotheses [107, 28, 345]. Therefore, we will not discuss details or attempt to present precise guidelines of these aspects of electrical safety at this time.

Nevertheless, some researchers are working on transcranial direct current stimulation (tDCS), in which the brain is stimulated as a treatment for depression and other phenomena (GVS is a variant of tDCS) [318, 216]. It is believed that a current of 1–2 mA and duration of 20 min is safe for usage in tDCS [318]. However, there are still unknown issues pertaining to such applications; thus, care is required when these techniques are used [347].

Table 2.3: Heart current factor for various current paths, corresponding to Figure 2.3 (The table is referenced from IEC TS 60479-1 ed.4.1 [104]).

Current Path	**Heart Current Factor F**
Left hand to left foot, right foot, or feet	1.0
Both hands to feet	1.0
Left hand to right hand	0.4
Right hand to left foot, right foot or feet	0.8
Back to right hand	0.3
Back to left hand	0.7
Chest to right hand	1.3
Chest to left hand	1.5
Seat to left hand, right hand or to both hands	0.7
Left foot to right foot	0.04

Examples: A current of 200 mA from one hand to the other has the same effect as a current of 80 mA on the reference path from the left hand to the feet. A current of 100 mA from left hand to the feet has the same effect as a current of 2500 mA from left foot to the right. Note that this value is a calculation for risks of ventricular fibrillation, and not a value to ensure safety. Currents exceeding 100 mA may lead to heat generation [104]. Note that the table was adapted from the IEC [104], however, the statements in the footnote are not from the original text.

2.2.7 Resistance / Impedance

The main threat of electric power application is from shocks occurring as a result of current passing through the body. Low-frequency AC power tends to be the most dangerous to humans; however, high-frequency or HV DC power can also cause shocks, heating, and burns. The magnitude of power delivered must be handled carefully, and it is recommended that circuits be designed with limitations on current output or even offset values to ensure safety. Nevertheless, controlling the magnitude of the output onto the body is difficult. This is because the impedance of the human body varies depending on various parameters.

Therefore, in attempting to design a safe and stable system it is important to consider the impedance and resistance of the body. An equivalent model of the human body can be represented using a resistor R_b (Ω) and a capacitor C_b (F). There are generally two types of equivalent circuit models, series and parallel.The impedance of the series-equivalent model can be expressed using equation (2.3), while the parallel-equivalent model can be expressed using equation (2.4). The choice in deciding how to apply these measurements is a matter of convenience; however, the parallel-equivalent model describes the properties of tissues more naturally.

$$Z_i = \sqrt{R_b^2 + \frac{1}{(2\pi f C_b)^2}} \tag{2.3}$$

$$Z_i = \sqrt{\frac{1}{1/{R_b}^2 + (2\pi f C_b)^2}} \tag{2.4}$$

The equivalence models displayed above do not contain all elements required to consider the whole-body impedance, which is given as Z_b is $Z_b = Z_{si} + Z_i + Z_{so}$, where Z_{si} and Z_{so} are the impedances of the skin for current passing in and out, respectively. Estimating the whole-body impedance is difficult because it is a function of numerous elements (e.g., voltage, frequency, current duration, contact area, contact pressure, skin condition, moisture level, and current route) [80]. Skin impedance is the most difficult to characterize because it is nonlinear, time-varying, and dependent on environmental and physiological factors [259]. However, studies have shown that, under high-frequency conditions, skin impedance decreases and the total body impedance approaches the internal body impedance [265, 260]. In addition, it is necessary to be aware of how the voltage can affect the impedance, as the impedance tends to be lower under HV conditions. Nevertheless, it remains difficult to estimate impedance, and it is therefore recommended that the design of systems with stable output involve the use of techniques that can adapt to varying impedance. For example, in REVEL [14] the system monitors the current output and adjusts it for stability, and in Kajimoto [121] pulse width modulation feedback was used to monitor the impedance in real time.

2.2.8 Summary

In the design and application of electricity in HCI and UbiComp systems, the main threat of harm is electric shocks occurring from current passing through the body. AC power tends to be much more dangerous than DC power; therefore, it should be treated carefully when one manages the power, especially for low-frequency signals. For high-frequency signals and HV power, heating and burning risks are present. Developers must be careful of lightning burns resulting from discharges from electrodes and burns caused by continuous usage of systems.

We categorized electricity studies from nine perspectives. We started by introducing research based on EF sensing. EF sensing is a significant method for input recognition and has been deployed in devices such as smartphones and tablets. Such devices are based primarily on the characteristics of the body, which acts as a good ground. We also described studies dealing with the transmission of power or signals through the body. These studies utilized signals that varied according to the body condition or, as the body functions as a conductive line, apply power to the body for power distribution. EMS is now a very prominent method for actuating human muscles computationally and is applied in learning or for other purposes such as notification. Electric signals are also applied for VR haptics and gustation or to augment human senses. However, research on vision, hearing, and olfaction is still ongoing. Other applications based on GVS have also been developed for VR and augmentation.

We showed that applying electricity to the human body can aid in the development of applications based on the unique characteristics of the body. The human body can act as a resistor, capacitor, or antenna. Its senses and muscles can also be stimulated. Each application requires a different set of knowledge for safe handling, and an understanding of the appropriate features is important because of the presence of hazards. However, such hazards differ by type of power used and the circuit model employed, and each type of research requires its own discussion founded on a unique basis.

Chapter 3

Guideline for Designing Safe Systems that Apply Electricity to the Human Body

This chapter presents a guide for following researchers to work on electrical body hacks.

3.1 Design Guideline

As we propose setting forth this guideline for research on the application of electricity to the human body, we first review related safety discussions and guidelines. We then discuss a generic guideline for research followed by a discussion of its limitations.

3.1.1 Related Discussions and Guidelines

In the previous chapter, we referred to the IEC and ICNIRP guidelines in discussing safety. When a researcher discusses the safety of their work, these guidelines are often cited in addition to other objective evidence. For example, in Corona [197] their work is compared to EMS systems, IEC 60065 [103] and 60479-2 [105] Guideline and National Aeronautics and Space Administration (NASA) terms. REVEL [14] cites Teslatouch [15] and introduces Webster's paper [333]. In Digital Lollipop [252], the paper by Dalziel et al. [39] is cited. Post et al. [243] compare the functionality of the system used in their work to that of a personal microwave machine. Aoyama et al. [8] explain that the use of electricity in their work was conducted under the advice of a medical doctor, and Higuchi et al. [93] follow the standards in the Declaration of Helsinki [346]. Zimmerman [368] discusses his work following standards from the Federal Communications Commission (FCC) [66]. In fact, although it is a good idea to follow information in related work or consumable products, the current, frequency, route through which the electricity passes, etc., must be strongly related to what is discussed in the reference, which the worker/reader is planning to follow. Furthermore, in Section 2.1.3, we outlined proposed EMS toolkits for use by researchers in the field [55, 176]. In these toolkits, safety guidelines are also proposed. For example, the guide proposed in the Let Your Body Move ToolKit [56] and openEMSstim [177] includes the following points.

- Electrodes should never be placed on the front torso near the heart. Do not place two electrodes across the heart, and do not place electrodes from the same channel onto different sides of the body.
- EMS devices should not be used by users with pacemakers or heart disease, and people with the following conditions are strongly recommended not to use EMS or to use it only with the permission of their doctor: pregnancy, epilepsy, cancer, recent surgery, sensitive skin, or skin disease.
- The use of EMS signals involves the risk of pain, injury, and even death. The thresholds for these differ by individual.
- Do not use EMS for an extended period of time, as no studies have yet been conducted to examine the associated risks.
- EMS should be never used by people that do not know or do not understand the safety issues or how EMS works.
- Always follow guidelines from Ethics in HCI [195], the ACM Special Interest Group on Human-Computer Interaction (SIGCHI) [282], and the American Psychological Association [3].

In addition to the guidelines proposed with regard to research-purpose toolkits, standards may be provided by countries. For example, in the Japanese Industrial Standards (JIS), JIS T 2003:2005 [116] and JIS C 9335-2-209:2007 [117] are provided for low-frequency electric therapy equipment such as EMS devices. The standards include the following remarks.

- A timer is necessary to limit the maximum time of use (the time must not exceed 60 minutes).
- The device must be designed to be unusable by multiple users.
- The power and the output statuses of the device should each be visibly noticeable.

- The current must be lower than 20 mA (with 1 kΩ resistance).
- The frequency must be lower than 1,200 Hz.
- The voltage must be lower than 200 V (with 1 kΩ resistance).
- Pulse waves must not use sinusoidal AC signals with frequencies under 60 Hz.
- The pulse energy must be lower than 120 mJ (with 1 kΩ resistance).
- The accuracy (frequency, voltage, pulse width) must be $\pm$ 30 % of rated values.

Industrial standards such as these can provide strict regulation, which can be useful. However, to make our guideline more general, we primarily refer to international standards (IEC and ICNIRP), although we are aware of other standards and norms. For example, as in Zimmerman's discussion of PAN, when considering electromagnetic compatibility (EMC) it may be valid to follow norms such as FCC [66], Canadian Standard Association (CSA), European Norms (EN), etc. [139]. For the time being, we do not provide further discussion on these types of norms, as we focus on human bodily safety under electricity-based research that does not involve electromagnetic waves.

3.1.2 Proposed Guideline for Researchers and Practitioners

The guidelines mentioned above give rigid limitations, as they assume third party usage, including usage by novices. However, in considering researchers and practitioners developing systems with related or new signals, it is important to understand the electricity type being used and to follow an appropriate guideline. For example, electrodes may be attached to both arms, allowing signals to pass through the heart if the signal is designed appropriately for the purpose, even this is restricted in EMS guidelines. Note that it may still be dangerous to apply EMS electrodes to both arms and, of course, in general no benefits are gained by applying EMS in this way.

The following points are significant elements that a researcher must consider when applying electricity to the human body.

- The conditions of current, frequency, and the path through which the power passes are strongly related. It is important to consider these elements comprehensively. The threshold of safety becomes serious when the electricity passes across the heart. Therefore, it is recommended that electricity not be allowed to pass through the heart without a reason for doing so, in which case researchers and practitioners should follow Table 2.2 and 2.3.

- There are still unknown risks in applying electricity to the body, especially when the signal is applied for an extended time period. Therefore, it is recommended that no signal be applied continuously without a reason for doing so. Researchers and practitioners should be aware that some risks exist even if there is no immediate noticeable harm.
- It is essential for researchers and practitioners to take responsibility for the user's state of health, including injuries, diseases, pain, etc. When an artificial signal is applied to the body, there is a risk that the signal will disturb electronics (e.g., pacemakers) or exacerbate a heart condition. All users must understand that there are risks, both known and unknown.

(1) Signals

(1.1) *Sensing / Transmission*

The literature on *sensing* does not generally provide discussion on safety. Such studies typically involve the use of high-frequency signals ranging from 1 kHz to 60 GHz, which have a low risk for electric shock. In the use of electric signals for *sensing*, low current magnitudes are needed (typically, a few micro-amperes). As long as the signal does not exceed 0.1 mA, the current is considered to be safe [58]. However, most currents up to 0.5 mA can also be considered safe in many conditions [104, 107].

(1.2) *Actuation*

When EMS electrodes are treated appropriately, they do not pose a serious hazard risk. However, incorrect or high-power signals can cause pain or fatigue. Typical electrode parameters include pulse widths of 30–800 μs [231], frequencies of 1–150 Hz [231], and currents of 10–30 mA (currents above 40 mA can stimulate pain receptors) [231], and the maximum recommended current output is 100 mA [305, 169].

(1.3) *Perception*

To stimulate organs, currents of up to 3 mA are typically used [8, 93, 318, 126]. These values are applicable to stimulation around the face and for haptic applications. Note that, in such applications, the signal does not pass through the heart.

When applying electricity to the tongue for gustatory purpose, different treatments should be considered. The tongue is a damped area of the body and therefore has lower impedance and requires more careful treatment. Stimulation of taste sensation appears at 4–400 μA [204]. For example, currents of 20–200 μA [252] and 250 μA [203] have been used in prior work.

(1.4) *Other Challenging Applications*

In applying electricity to the human body for the purpose of new and/or challenging research, the electrical signal must be treated carefully. The current value and frequency are essential elements for consideration. Acceptable contact currents can be found in Table 2.2 and equation (2.2), in which the minimum value is 0.5 mA, i.e., currents of up to 0.5 mA are thought to be safe independent of the frequency. When a larger magnitude of current is required, the frequency must be increased. In addition, researchers should follow Table 2.3 with the understanding that different current path have different risks, e.g., electrodes placed near the chest will be more dangerous.

(2) Testing on the Human Body

(2.1) *Health Concerns*

When researchers conduct user studies or examinations, they must pay careful attention to health concerns (e.g., heart conditions). There are known and unknown risks in applying signals to the body. In cases involving people with conditions such as pregnancy, epilepsy, or cancer, it is recommended that the researcher obtain permission from the individual's doctor. In addition, skin conditions can influence electric signals applied to the human body, and therefore obtaining permission from the doctor is also recommended in cases involving individuals who have had recent surgery or who have sensitive skin or skin disease. In the initial and development stages of research, external oversight can help support confidence in the safety of the procedure.

(2.2) *Agreements and Responsibility*

Generally, it is good practice to collect agreements from users in cases of third person usage. This ensures that the state of the users' health is clear and that concerns about system safety are understood. Furthermore, requiring an agreement for a liberty waiver is recommended to clarify the responsibilities in demonstrations. Such agreements are generally required to control the risks for both the researcher / developer and the users.

A simple way to ensure the safety of an electric system is to limit the maximum output current. It is also important to know that the body's electrical characteristics differ from person to person, and thus the application of offset values should be considered in common use.

We hope that this guideline will help researchers to find information appropriate for their studies and to easily find reference materials relevant to their signal output type.

3.2 Limitation

It is necessary to state that these guidelines will need to be updated in light of the results of future research. The guidelines from the IEC, ICNIRP, and other organizations are updated every few years; thus, the foundation of this guideline is expected to undergo minor changes in the future. Readers of this guideline are urged to consider such updates. In addition, we are aware that criticisms have been leveled against the previously published guidelines [28]. Therefore, readers should be cognizant that the values presented here are simply for reference. In addition, readers must bear in mind that some concerns (e.g., health risks for cancer or of long-duration exposure) still require further research for an accurate determination of the factors influencing the application of electricity to the human body.

Chapter 4

Multi-Channel Electrical Muscle Stimulation Toolkit

This chapter introduces a toolkit for users to ease the access towards electrical body hacks, and a workshop study based on the toolkit.

4.1 Introduction

Electrical muscle stimulation (EMS) has attracted many interests to researchers in the human-computer interaction (HCI) field. EMS has enabled computational manipulation of the human body by stimulating muscles directly.

An increasing number of workshops and/or panels are arranged in HCI related conferences, which are performing as great introduction for researchers to use the EMS technique. One initial workshop using EMS was organized by Manabe et al. [182] at the 4th ACM International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10). In recent years, more workshops are being arranged (e.g., in 2016 [171, 170] and in 2017 [166]). Furthermore, EMS toolkits are introduced, which are contributing for following researchers to walk into the field. An important toolkit for EMS is released by Pfeiffer et al., known as the *Let Your Body Move Toolkit* [231]. Lopes et al. developed an extended version of the toolkit (openEMSstim [176]), which was used for the 29th ACM User Interface Software and Technology Symposium (UIST '16) student competition[1]. The development and diffusion of EMS work have introduced many researchers to control the human body with a mobile and safe way. Figure 4.2 shows the growing interest of EMS research in HCI.

[1]https://uist.acm.org/uist2016/contest

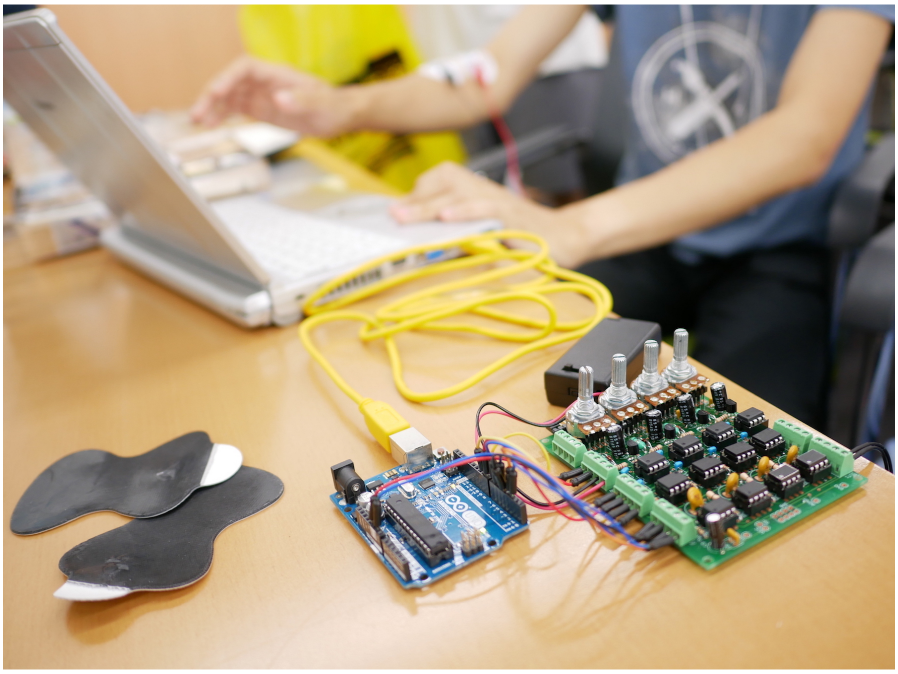

Figure 4.1: The EMS toolkit with multiple channels used at a workshop. The toolkit is controlled by combinations with typical prototyping tools.

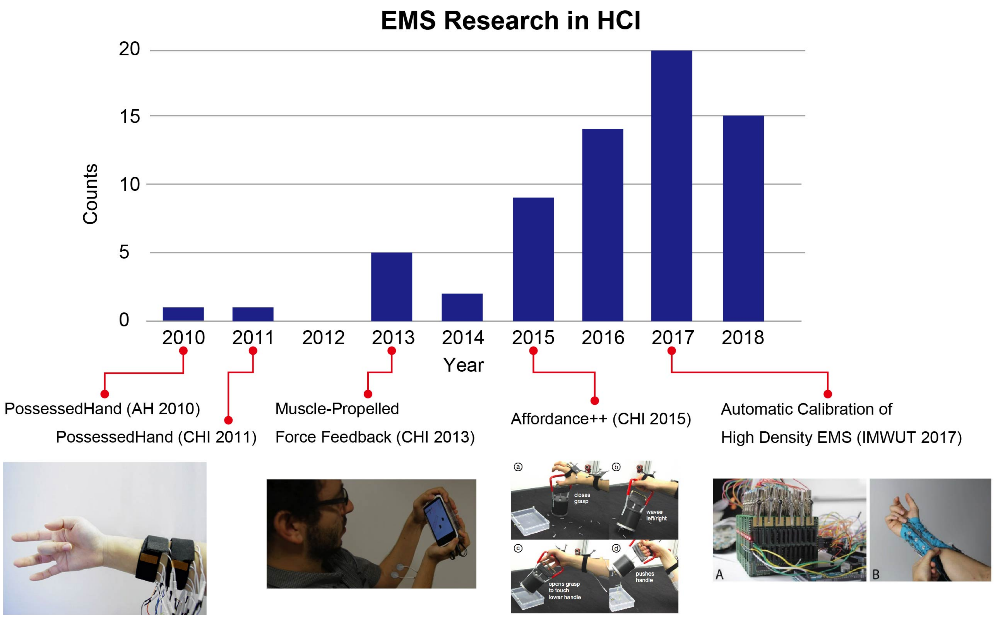

Figure 4.2: Papers on EMS that refer PossessedHand (2010 [304], 2011 [305]), data retrieved from Google Scholar (Oct 18, 2018). Other images are extracted from [164, 169, 144]. Note that these are not the exact numbers of papers that work on EMS, and our motivation here is to provide a basic idea of the increase of EMS interest.

Taking these significant demands for EMS techniques and toolkits, in this chapter, we introduce an advanced toolkit beyond prior EMS toolkits. We also introduce a study through an organized workshop, which was conducted with a theme of *"Human Augmentation."* The success of the workshop enabled us to explore demands of EMS for human augmentation purpose. The participants of the workshop successfully managed to use our toolkit effectively and safely, and presented several interesting works.

The contributions and the results of our work are concluded as follows.

- A multi-channel EMS toolkit was developed. The toolkit enables users to control the pulse width, frequency, output duration, and intensity. Both analog and digital controls of the intensity was provided for convenience. A single board has 4 output channels, however, the number of channels were designed to be scalable and easy to increase.

- A workshop was conducted, where we explored the demands of EMS. Even though the usage of EMS was not compelled through the workshop, several groups came up with ideas using EMS for their work. Our toolkit was successfully utilized by the participants for interesting outcomes. Multiple channels were used for these outcomes. Furthermore, an application for multiple users with simultaneous EMS output was developed.

4.2 Related Work

In this section, we introduce related work for toolkits in HCI, and we focus on toolkits for haptics. This is because we are aware that major application of EMS was for haptics [231].

Toolkits have performed as helpful tools for researchers and developers to explore new experiences and to follow the topic. Therefore, various toolkits have been developed in the HCI field and a workshop has been organized to discuss them [184]. Although HCI toolkits vary and cover many types of technologies, we are aware that there are many prior toolkits that are designed for haptics.

TECHTILE toolkit [193] is a toolkit for non-professional users based on audio information using microphones and voice-coil actuators. Stereo Haptics [366] is also a toolkit for haptics based on audio tools. TESSA [268] is a toolkit for sensory augmentation, consisting of a range of sensors and actuators. The hardware and software enhance a sense from information collected from another sense. Touch Toolkit [241] consists of a graphical user interface and four interactive surfaces that contain actuators. The toolkit was used as a method to convey touch-based design knowledge and skills to the users. The HAPTICTOUCH toolkit [156] is a toolkit to develop haptic tabletop applications. There is a rod manipulated by motors to generate height, malleability, and friction as haptic information.

One of the main purposes of EMS toolkits [231] is considered to be haptics. Toolkits designed for haptics are related strongly, however, EMS is not always limited to haptic usage. An example can be found by a work developed by using Lopes's toolkit, which produced vocal vibrato by EMS [74]. Our toolkit is for haptics and for researchers and developers to explore new design space by using multi-channel EMS.

4.3 The Toolkit

A toolkit was designed for researchers and developers to use EMS easily to their work. We considered the toolkit to enable adjusting various parameters of the signals, which are controlled through typical prototyping software. The toolkit allows multiple channels to be used simultaneously that are isolated from each other.

4.3.1 System Overview

We are aware that prior research has developed multiple channeled EMS (Let your body move toolkit [231] with 2 channels and others with 6 or more channels [293]). Zap++ [53] is a system enabling 20 channels of EMS output with a similar implementation of ours, which the electrodes are in a layout of two sleeves assumed to be worn on the arm. We refer to implementation designs presented in Zap++ and other presented designs [26], however, we allowed the system to be used as a toolkit by simplifying the design and by using major prototyping open-sources.

The overview of the system is presented in Figure 6.5. The channels and the output signals are controlled through a graphical user interface (GUI). Then the signals are sent to a microcontroller (Arduino[2]) which is connected to each circuit board to control its pulse width, frequency, voltage and the time duration. The circuit board consists of a booster circuit and a relay for each channel, which allows the output to be controlled individually. In our current design, each circuit board is capable for four output channels, however, the number of channels can be extended easily.

For the design of our toolkit, we considered the following features to be included in the implementation of development efficiency.

[2]https://www.arduino.cc

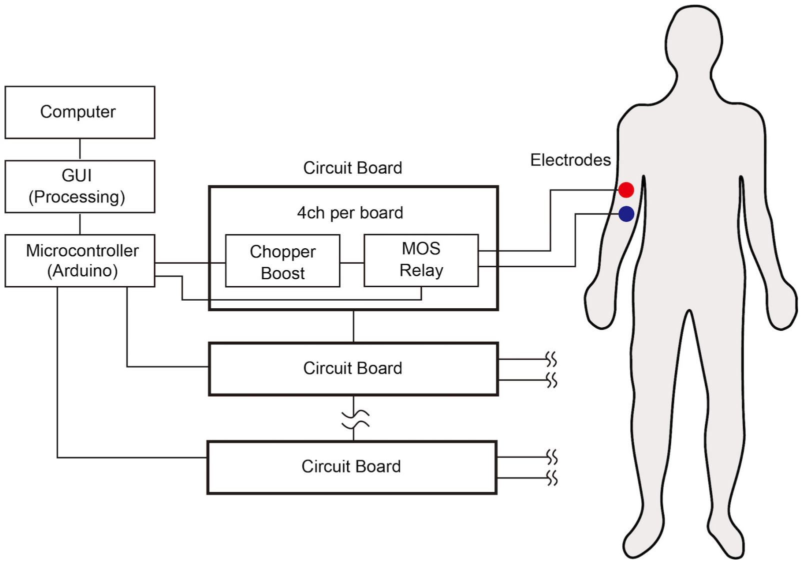

Figure 4.3: Overview of the system configuration. The system is controlled by a GUI and a microcontroller, which sends signals to the circuit boards that allow multi-channel output.

- Allow users to use multiple channels (more than four) with ease. This was to prevent restricting the ideas of users by considering the limitation of the number of available channels.
- Allow users to develop systems by typical prototyping tools (e.g., Arduino, Processing). This was to reduce the threshold of gaining access to EMS prototyping.
- Allow users to control the intensity from both analog and digital controls. Using analog nobs may be faster and easier that are appropriate for simple prototyping, however, using digital control can be useful for dynamic and advance usages.
- Not to restrict the connecting cable, and maintain scalability by using alligator clip etc. EMS electrodes have various types of cables, therefore, for generalization, we did not want to restrict the cable form to a specific one.

4.3.2 Implementation

Hardware

If the channels and the electrodes share a common ground, signals can pass through unintended routes between the electrodes. Therefore, enabling multi-channel simultaneous output is a challenge. The channels are required to be isolated from each other and to be controlled independently. For our system, we chose to control the channels by time multiplexing (Figure 4.4). As we assume the frequency of the electric stimulation to be $50 < f < 150$ (Hz) and the pulse width to be $40 < \tau < 240$ (μs), the maximum number of the channels N_c is calculated as $N_c = 1/f\tau - 1$ where N_c will be 26 in our case. However, if a lower frequency and a short pulse width is used, the maximum available channels will increase. In our current implementation, as the relays have a slight rise time and fall time resulting to have a delay from the signal manipulation, the system is recommended to be used in a less amount of channels than the theoretical limit. In our current time multiplexing method, the frequencies of the channels are required to be set at the same value, while other parameters (pulse widths etc.) are able to be controlled individually.

The design of the circuit board is shown in Figure 6.8. Each output channel consists of a chopper boost circuit with a photo-MOS relay. The boost circuits were powered by 3 V batteries, boosting the voltage up from a range of 30–100 V. The output voltage is independently controlled by adjusting the switching frequency of the chopper boost circuit. The voltage can be adjusted digitally or by analog knobs. In case of digital manipulation, the switching frequency is applied through the Arduino signal. Analog control of the voltage is more easy and safe, which is designed by an LM555 Timer IC and a 2MΩ variable resistor. Digital/Analog controls are selected by a jumper on the circuit board.

Another important technique of EMS circuits is galvanic isolations of the electrodes and other signal generating elements. We use AQW210 (Panasonic) for the relay (Photo MOS Relay), where the pulse width and the output frequency is controlled by an Arduino. This isolates the EMS signals from the signal generating elements (computers and the Arduino). On the other hand, the time multiplexing technique is used to realize isolation among each active EMS channel. The galvanic isolation of the circuits is required for safety, which will prohibit unintended conflicts of signals and allow multiple channels to be activated among multiple users and locations of the body. The design of one channel of the circuit is displayed in Figure 4.6. The circuit board can be easily connected to increase the available channels; i.e., we have designed the circuit to have high scalability.

In our current implementation, we use mono-phasic waveforms. Although some prior work suggest using bi-phasic pulses [53, 192], it is known that bi-phasic stimulation results to sharper sensation and many machines use mono-phasic pulses to deliver stronger and comfortable stimulation [323].

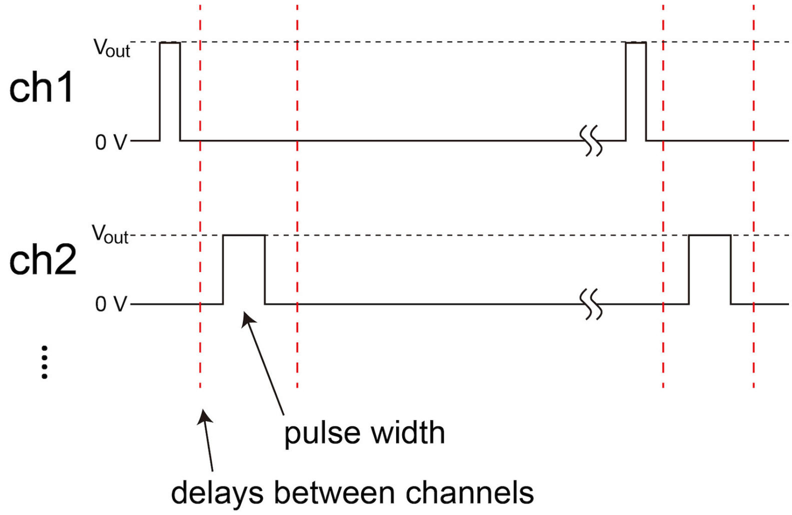

Figure 4.4: The theory of multi-channel output of our system. The output of each system has a delay. Therefore, the system never allows pulses to be produced at the same time. This will allow us to have EMS signals to be produced simultaneously and safely.

Software

The software is developed by Arduino and Processing[3]. The Processing code communicates with the Arduino via serial communication, sending the adjusted output values. Figure 4.7 is the GUI interface to control the multiple channels of EMS. The user can control the pulse width, frequency, and the time duration of output for each channel. The voltage can be controlled through this GUI when the user wants to control the intensity digitally. Furthermore, for convenience to manipulate a large number of channels, these values and the state of each channel can be controlled all at once.

We are aware that the Arduino supports functions like *millis()* and *micros()* to control the time, however, in our current implementation, we use the *delayMicroseconds()* function to control the pulses and the timing. EMS signals require pulse widths to be designed in microsecond order, but through our test, the function *micros()* did not perform precisely, which could lead to unintended output signals. Instead, the *delayMicroseconds()* function helped us to control the signals safely, which ensures pulse signals not to be released simultaneously among channels. Furthermore, this method prevents risks of toolkit users to accidentally modify the source code in an unsafe way.

[3]https://processing.org

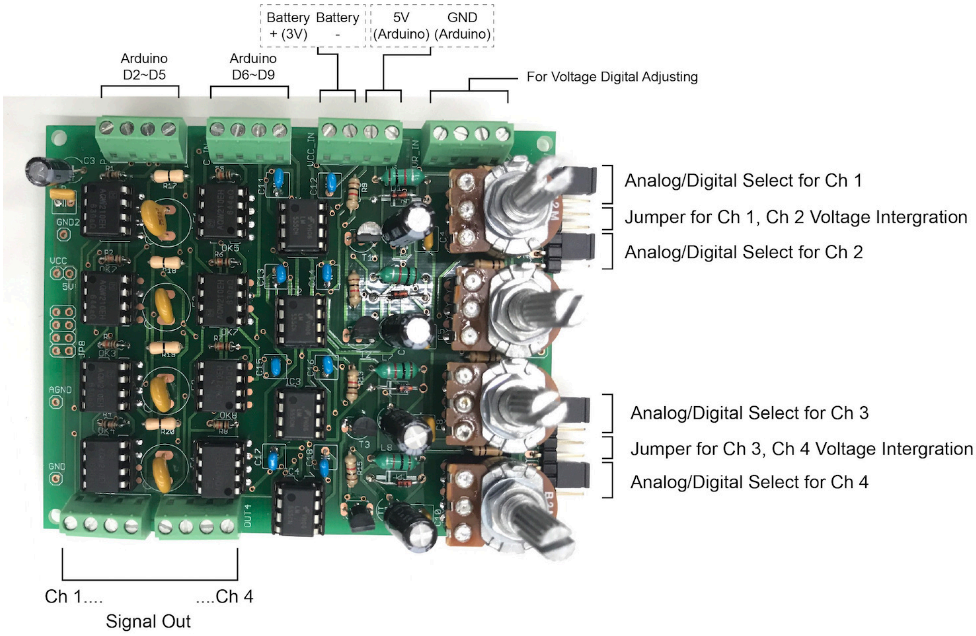

Figure 4.5: The circuit board of the toolkit. Four output channels are available for each board. The board is connected to the micro-controller and the electrodes.

4.3.3 How to Use

The toolkit is prepared for the user to control their desired EMS signal via Processing and Arduino. The GUI enables adjusting the signals for each channel, which is triggered by a confirmation button. However, the toolkit is not restricted to be used by the original GUI. Users may arrange the output signals of all the channels by managing a function that sends the signal information to the Arduino by serial communication.

We do not focus on using our toolkit on a certain part of the body. General placement of electrodes are supposed to be along the muscle and the pair of the electrodes should be placed on both ends of the muscle fiber to be contracted. Users should find the appropriate position of the electrodes. It is also a good idea to follow successful prior work using EMS (e.g., [173, 232, 231]). In fact, we observed the participants in our workshop to successfully develop their work, by referring to prior work in order to find the appropriate electrode placement.

Before using the system, a calibration process is required. As like other research based on EMS do, it is necessary to gradually increase the current output until there is a movement notable at the corresponding muscle. Then the signal should be increased

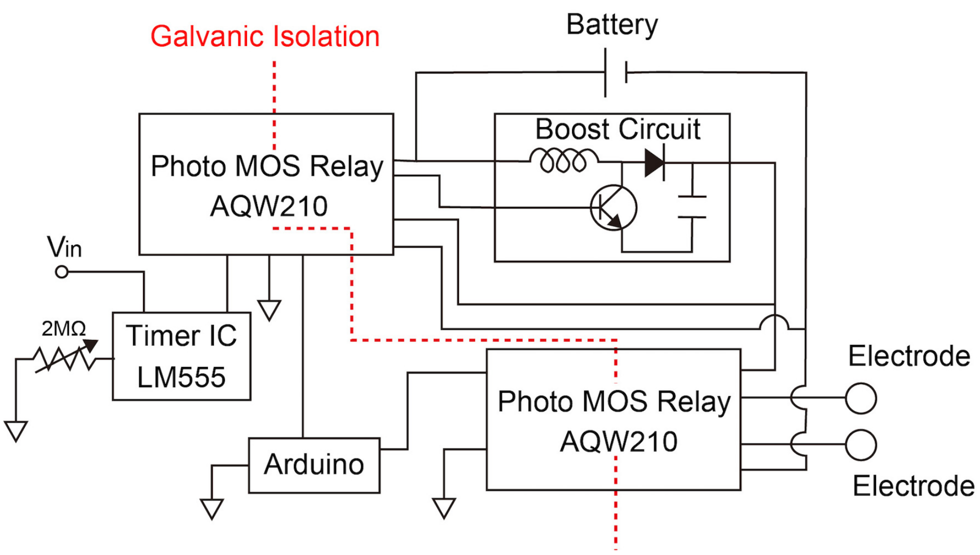

Figure 4.6: Design of the circuit board for one EMS channel. Note that detailed resistors and capacitors are removed from the figure to maintain the readability.

to a level where the user perceives a comfortable stimulation. This procedure should be repeated for each active channel. Through the calibration process, users must be aware of pain or any uncomfortable stimulation. Users should test with short output duration first. In addition, it is required to be aware of any fatigue or temperature rise. These are required to prevent risks for damaging the body. We are aware of automatic calibration techniques for gestures [144], however, our toolkit does not focus on a specific body part, so we leave the signals to be calibrated manually. It was also important for us to develop the toolkit simple as possible. This was to allow a novice third-party user to reproduce and use the toolkit. The toolkit is open to the public and provided on GitHub[4].

4.4 Workshop

To explore the potential of our EMS toolkit, we offered the toolkit for a workshop. Since the workshop was based on group work (5 groups), we prepared several of our toolkits, so that it could be used by multiple groups. However, the usage of our toolkit and EMS were not compelled.

[4]https://github.com/rkmtlab/multi-ems

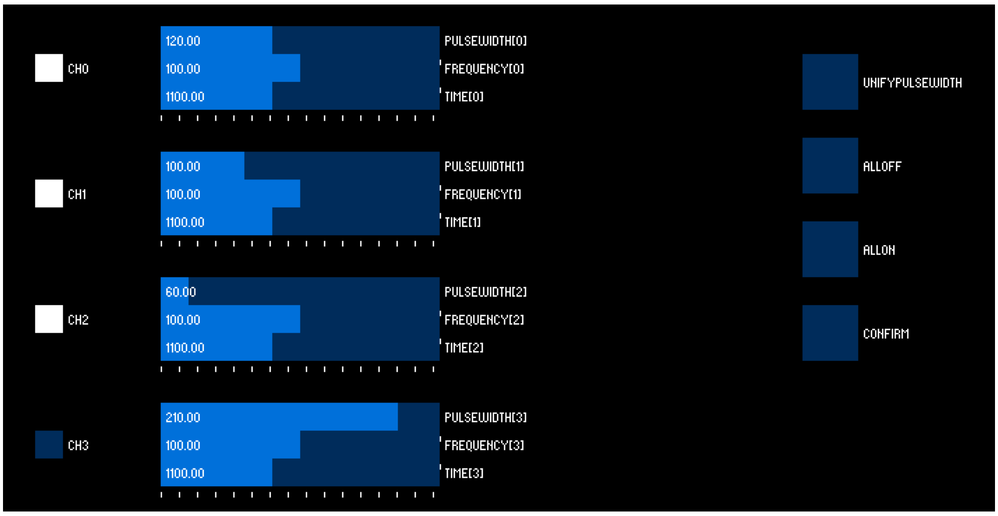

Figure 4.7: The GUI interface of the toolkit for 4 channels. The user can control the pulse width, frequency, voltage and the time duration of output for each channel. The interface can be modified if more channels are used.

4.4.1 Workshop Procedure

We organized a workshop with a theme of *human augmentation* and *"Extension and Substitution of Perception."* We had 26 students (a mixture of bachelor, master, and Ph.D. course students) as participants from various expertises (e.g., HCI, robotics, design, VR, natural language processing, machine learning, fabrication, chemistry etc.). The participants were grouped in 5–6 people, for a total of 5 groups (Group A–E, mentioned as GA–GE). The workshop consisted of 3 days with 4 phases. The 4 phases were *introduction phase*, *brainstorming phase*, *implementation phase* and *presentation/demo phase*. Day 1 was for the *introduction phase*, day 2 was for *brainstorming phase* and *implementation phase* and day 3 was *implementation phase* and *presentation/demo phase*. For the workshop, various products and technologies were prepared for use (e.g., VR headsets, Raspberry Pi[5], cameras, Arduino and various actuators and sensors). EMS was not compelled for use. In case of EMS usage, we prepared UnlimitedHand [86] (a consumable EMS output device mainly for VR) and our EMS toolkit.

In the *introduction phase*, some related work for human augmentation was introduced. There were examples of vision sharing contents among multiple players [132], usage of EMS [212], and general information about neural network and

[5]https://www.raspberrypi.org/

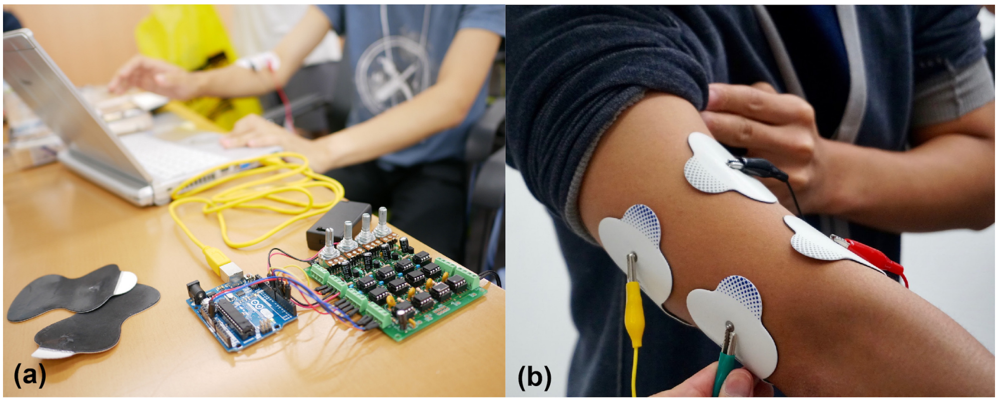

Figure 4.8: Pictures from the workshop. (a) The toolkit under use by a participant. (b) Example electrode placement for an application by the participant.

recent trends/tools[6]. Although an example of EMS was introduced, this was just one of the many examples introduced, therefore we believe that this did not encourage the usage of EMS stronger than other introduced works. In the *brainstorming phase*, an interim presentation was required to introduce some ideas of their group. We then had a total of approximately 8 hours for the *implementation phase*, which the participants actually developed prototypes of their proposed ideas. At the end of the final day, *presentation/demo phase* was held. The participants gave a talk of their built work, and then all the participants were given time to experience the demonstrations of them.

4.4.2 Example Usage

Application Ideas

At the interim presentation of the *brainstorming phase*, 4 out of 5 came with ideas using EMS. The abstract of the ideas are concluded as follows.

- Substitute visual information with haptic information. EMS was considered as a method for inducing the haptics, as well as vibrators (GB).
- Exchanging emotional information by usage of EMS to the body (GC).
- Sharing haptics or emotional perception with vibrators or EMS. An idea where goosebumps like feeling (due to surprising or fear) to be shared among multiple users was presented (GD).

[6]https://dl.sony.com/

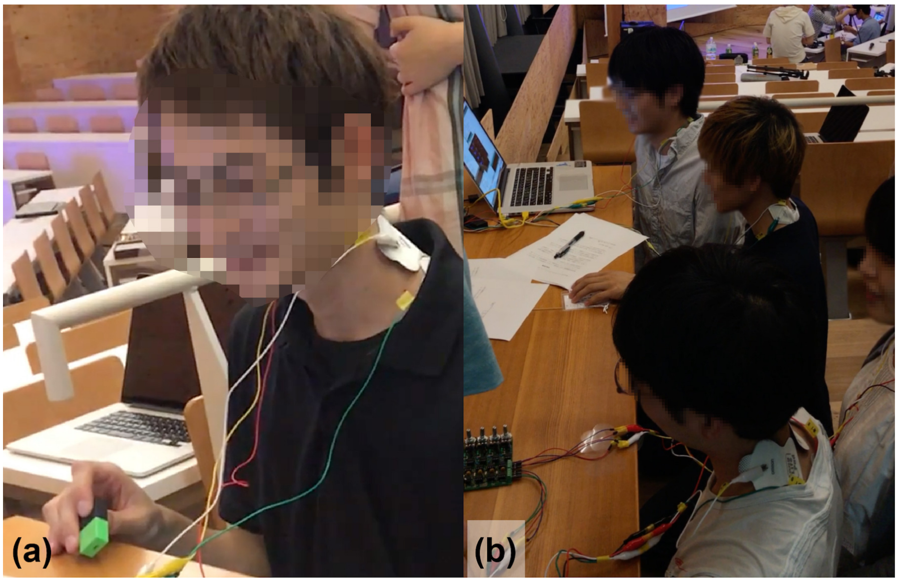

Figure 4.9: An example application developed at the workshop (GD). (a) One participant pushes the MESH button. (b) The stimulation is shared among four participants.

- Connecting physical objects and it's deformation with the human body. EMS was considered as the method to deform the human body accordingly with an object (GE).

As a result, 2 groups actually used the EMS for their implementation (GD and GE, Figure 4.8). The two ideas were "sharing perception (goosebumps) among multiple people (GD)" and "connecting object deformation with the human body (GE)." In case of the groups that did not decide to use EMS, GB used vibrators and GC used voice conversion techniques for their work.

Implementation and Outcomes

We had all the participants who used the toolkit agreeing to a liability waiver form both in the *implementation phase* and *presentation/demo phase*.

For GE that attempted to link an object with the human body, a doll with sensors (e.g., bending sensors) was created. The sensors detect the deformation of the doll, which was sent to a computer through an Arduino. According to the detected deformation, the user with EMS had his body deformed relatively to the posture of the doll. The electrodes were used on the arms, and the participants referred to Lopes's work [173] to find the appropriate position of the electrodes. However, in this chapter, we will rather give details of the work by the other group that used EMS (GD).

The other group that attempted to share goosebump like perception among multiple people (GD), utilized the EMS toolkit for multiple users (Figure 4.9). Two pairs of electrodes were attached to the neck for each people. Then they were stimulated one by one, where the stimulation traveled through multiple points of the body to design some kind of fear or emotional effects. The experience was kind of related to Fukushima et al.'s work [73] that utilized high-voltage on the arm, however, the group developed their work by EMS and stimulation around the neck. The placements of the electrodes were explored by the participants by themselves. For a trigger of the stimulation, MESH[7] (SONY) buttons were used. A maximum of four participants can join the experience. All of them holds a MESH button and have the electrodes attached. When one pushes the button, the stimulation occurs on all of the participants. The developers of the group said that they wanted to allow people to share their experience with others. For example, when one feels some kind of fear and/or shivers, the stimulation would be shared with others. The work was to notify others of emotional feelings through physical perception. It was also interesting to induce anonymity of the triggering person. Instead of visualizing or notifying the person who pushed the button to trigger the stimulation, this was left anatomized.

For the groups that decided to use our EMS toolkit for their work, it was interesting to have both groups to use 8 channels at maximum and to use our toolkit instead of products like the UnlimitedHand. In this case, our toolkit was a success to be designed for multiple channel output. Another issue of the UnlimitedHand was that the placements of the electrodes were limited to a single form on the arm. It was required for the participants to have the electrodes placed freely around the body for their work. Furthermore, the participants successfully modified the code for their own usage. Successful combinations of our toolkit and other prototyping tools like the MESH was a good example to see.

We observed the *presentation/demo phase* of GD, and heard a number of interesting comments. Many participants agreed that the stimulation of the work was similar to the sensation of when they shiver or tremble. One participant said that "I think I really have goosebumps after the stimulation finishes." This was an example where the virtual stimulation evoked the participant's real stimulation and sensation. Furthermore, the EMS stimulation on the back of the neck seemed to be an interesting stimulation for those who have previously experienced EMS. The novice developers of

[7]http://meshprj.com/en/

EMS found new boundaries of applying EMS to new body parts and number of users.

In the meantime, other groups came out with outcomes by using systems and tools like HTC Vive[8], Unity[9], voice changing techniques, and motor vibrators.

Our workshop successfully managed the participants to create outcomes to substitute, exchange and or enhance perceptions such as vision, auditory and haptics. The outcomes for *human augmentation* were developed by using various techniques and technologies. As well as other technologies such as HMDs, EMS had a significant demand for developing these human augmentation work.

4.5 Discussion

We now discuss the potential and demands of our EMS toolkit, as well as the limitations and safety issues.

4.5.1 Multi-channel EMS for Multiple Users

Typical EMS research is based on EMS for one person at a time. However, we are aware of rare cases that use EMS for multiple users. BioSync [213] was an example where devices are attached to two users. The device detects one's movement by electromyogram (EMG), which is then copied to the other user's arm by EMS output. EMS is applied for multiple users that copy movements or encourage communication through their muscles.

On the other hand, our development of multi-channel EMS toolkit encouraged a further study beyond this example. Instead of one-to-one communication, the work by GD was developed for four people to communicate (Figure 4.10). We believe that the work opened a novel path for multiple user communication through somatosensation. The muscular actuation and the haptic perception revealed a potential for further application of EMS.

4.5.2 Electrical Stimulation for Human Augmentation

There is an increasing number of EMS research for human augmentation purpose in the HCI field. For example, in the 8th Augmented Human International Conference (AH '17), several research based on usage of EMS were presented (e.g., [74, 60, 307]).

We consider that the two main applications for EMS are thought to be *actuation* and *perception*. *Actuation* is where EMS enables the human body to move dynamically for

[8]https://www.vive.com/us/

[9]https://unity3d.com/

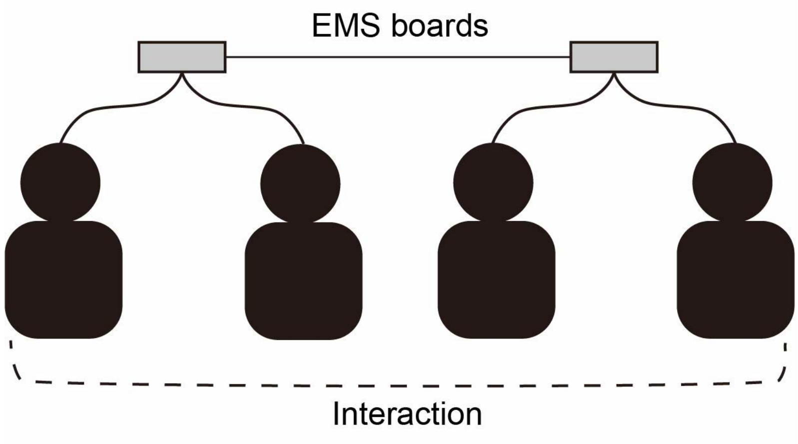

Figure 4.10: Overview of EMS applied to multiple users. The principle was used for GD's work. Four users share the same perception/stimulation. Two of our EMS toolkit was used, where two channels were used for each user.

physical purposes. These kinds of work have been explored by the usage of techniques such as exoskeleton. EMS has been utilized for such purposes due to the mobility of the technique [165]. Although there are still limitations in the strength produced by the stimulation, researchers and developers are finding values of EMS for actuation purpose. The work presented by GE fits this domain, which manipulates and actuates the human body through an external interface. *Perception* is where EMS stimulates the human body to induce haptic or emotional feedback. Looking at recent EMS work and ideas from the workshop, stimulation for haptics may be considered to be one of the significant demands of EMS (see Section 2). Previous researchers have worked on haptics by mechanical actuators like motor vibrators [315], which is now substituted by EMS for some demands. The work by GD was a good example for this domain. GB and GD both considered vibrators and EMS for their implementation. While GB decided to use vibrators, GD chose to use EMS. We can see from our workshop that the two techniques are highly related.

Since an increasing number of EMS applications are being explored, EMS is now used for a various purpose and to substitute some of the traditional techniques. EMS not only allows you to move the body, but it also allows you to stimulate one's perception. We also believe that the increase of EMS related work is contributing to the acceptability of electrical stimulation, which leads to the increase of users to think of applying EMS for their work.

Our workshop revealed application domains, methods, demands, and the acceptability of EMS for human augmentation purposes. Due to the demands found through our workshop, we believe that EMS will still perform a significant role in the HCI field, and development of EMS toolkits will help encouraging researchers and designers to work on studies based on EMS.

4.5.3 Limitations

We would like to note that one of our significant contribution of our work is where we designed our workshop without compelling EMS usage, while other related prior EMS workshops were accomplished with EMS usage only. However, in this case, comprehending all of the considerable conditions is difficult, where different conditions may result in different results.

Our workshop was conducted through a limited condition. The equipment and tools, as well as the participants, may have influenced the results of the outcomes. We made an effort to prepare equipment and tools to be fair and so that the participants will not have their brainstorming limited due to the prepared equipment and tools. The participants had various backgrounds, however, they were all students. The groups were arranged so that participants with the same expertise will not be concentrated on a single group. As we observed that groups with members having expertise in the VR field tended to use VR headsets for their work, technical backgrounds may have influenced the outcomes. However, there were two participants who had prior experience working with EMS. It was interesting to see the groups with these participants with EMS experienced members did not use EMS, but the groups with no members with EMS experience used EMS for their work. Some of the groups developed their work based on the equipment they were familiar to, while others tried equipment new to them. Therefore, we believe that the workshop was designed to be fair enough to discuss our findings.

4.5.4 Improvements and Alternative Implementations

After the workshops and other exploration of our toolkit, we improved our toolkit, and newer versions are currently available. We will introduce two variations of our development.

Development of multi-ems

Figure 4.11 shows the design of the new toolkit. The toolkit was improved from four aspects. First, we inserted audio connectors to the board. This is because, a

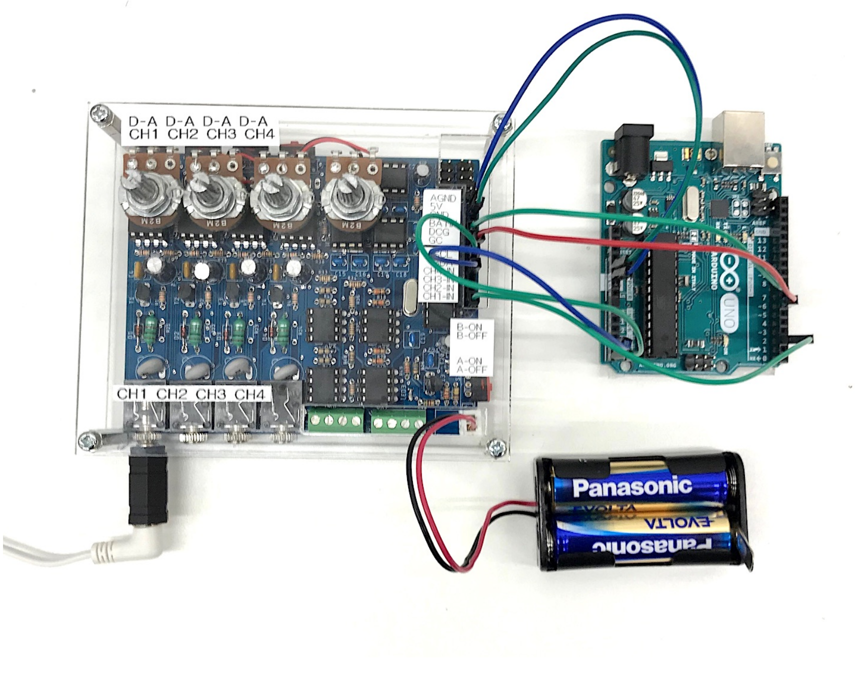

Figure 4.11: The design of the improved toolkit.

major apparatus of EMS, developed by Omron etc., uses audio connectors for the electrode connection. Second, while our previous toolkit required an additional microcontroller externally connected to the board for digital intensity controls, we loaded a ATMega328P microcontroller to the board. Third, we reduced the required cables for connection to the Arduino and simplized the design. Lastly. we included switches for on/off control and analog/digital intensity control switching. From these improvements, our new toolkit allows increasing the efficiency and usability beyond our previous design. The detail design of the circuit can be found in Appendix B.

We also prepared an acrylic case that can cover the circuit board. This may also improve the acceptance since it may prevent risks of electric shocks by accidentally touching the board.

wavEMS: Improving Signal Variation Freedom of EMS

One of the most important features of our original toolkit was the number of output channels. However, through our study, we found demands for testing variations of signal types. Therefore, the second toolkit was designed to improve the signal variation freedom. We named the toolkit "*wavEMS*," and the overview is shown in Figure 4.12.

The implementation consists of a Bluetooth module, piezo amplifier, battery, and voltage converters. RN-52 (Microchip Technology) allows the toolkit to connect to mobile devices or computers, and receives the audio signals. A 9 V battery is used, which is converted to 12 V and ± 5 V with DC-DC converters. The audio signals and the converted power source activates a PWM amplifier (IFJM-001, Marutsuelec Co., Ltd.), which outputs EMS signals to the electrodes (the current is limited to a maximum of 100 mA). For the software, we prepared a Processing program that can output typical EMS waveforms. However, for *wavEMS*, any type of audio can be used for stimulation output. *wavEMS* allows to output various waveforms including; sine waves, triangle waves, square waves, Russian current, and other desired waveforms. Waveforms of EMS can influence the experience in many ways. Some additional discussions will be noted in Appendix D. Another important benefit of *wavEMS*, is where it is controlled wirelessly. This helps improving the mobility of EMS prototyping.

One negative aspect of *wavEMS* is where it can output signals that are not usually used for EMS, and can be *dangerous* without knowledge. Therefore, when using *wavEMS*, understandings of our safety guideline (see Chapter 3.1.2) will be more strictly required. We recommend going through Chapter 2.2, and to check the considerable threats, especially the effect of the frequency. There is another issue of the current toolkit design regarding power efficiency, which is subject for future work.

4.6 Conclusion

In this chapter, we introduced the design and implementation of a multi-channel EMS toolkit. The toolkit enables users to control the pulse width, frequency, output duration, and intensity for each used channel. We conducted a workshop to explore the demands of EMS and our toolkit. In the workshop, the usage of EMS was not compelled. However, several groups came up with ideas using EMS, and some groups actually developed their work by using our toolkit. Our toolkit was successfully utilized by the participants for interesting outcomes. We have found that there is a significant demand for EMS for human augmentation purpose, and the main demands were for body deformation, haptics and to share dynamic elements among multiple users. Future work includes studies for effects of EMS to multiple body parts that have not yet been studied in HCI, as well as developing a more mobile toolkit with multiple functions and simple constructions.

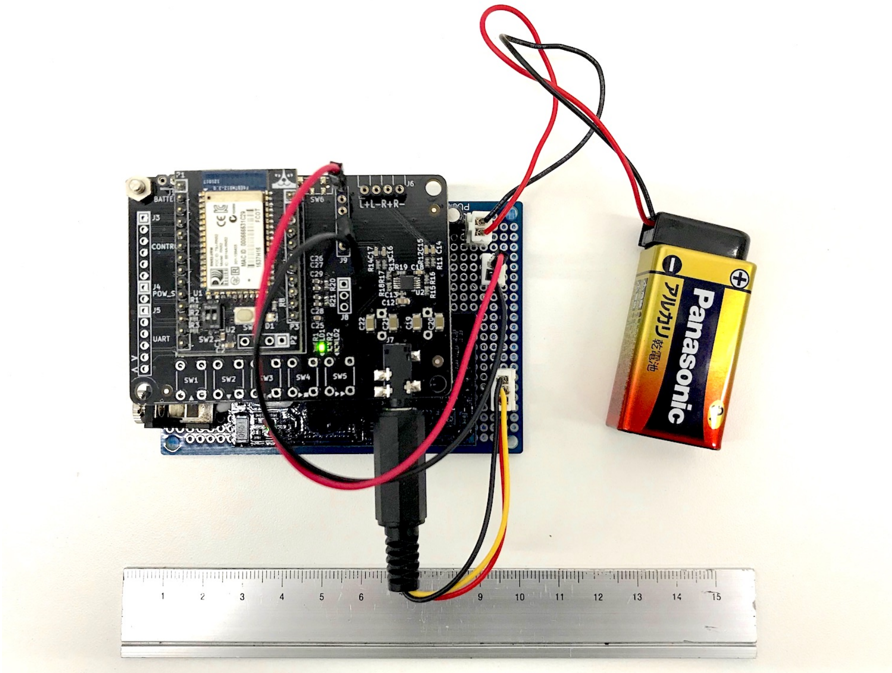

Figure 4.12: The design of the improved device that can output various types of waveforms.

Chapter 5

Facial Emotion Manipulation via Electrical Muscle Stimulation

This chapter challenges to affect the cognition through facial EMS, which has been challenged in cyborgs approaches by brain implants. Furthermore, this chapter is also important because we challenge to work on an unacceptable body part.

5.1 Introduction

Emotion, is an important information for communication [237]. Sharing one's emotion may influence the conversation or feelings perceived during communication. One can feel bright or even dull depending on the emotional condition of themselves or the opponent. While there are many ways and means to emit or observe emotions of a human, the human face can be thought to be commanding, due to its visibility and omnipresence [61]. Therefore, the facial expression is a significant interface for communication; they play various roles to share information [21, 151]. In this sense, one's face is an effective display and an interactive surface to represent affective information. This display is controlled by the body owner, who sends signals to the muscles around the face. However, the facial interface is not generally supported to be manipulated by an external user. Researchers have challenged to deform a human face by graphical approaches [310], mechanical approaches [186] and physiological approaches [314] in order to apply the results for graphical usage and to explore the effect to emotion. One impressive technique to manipulate a human body in the real world is the use of electrical muscle stimulation (EMS). In this technique, we can actuate users by applying electric signals to muscles and motor neurons. An increasing number of interactive systems based on EMS is now proposed due to their mobility and scalability [278].

However, general applications based on EMS are on the arms or on the legs.

The motivation of our work is to challenge and explore the potential of designing facial expressions by using EMS on the face. Manipulation of the human face with an external force can be important for many application areas. As like prior researchers have attempted to enhance communication by modifying facial expressions with image processing in video chats [295], a similar approach can be taken in the real-world face-to-face communication. One can get used or train to create a facial expression [314] in a more passive way. Sometimes people may enjoy negative emotions (e.g., fear) [5], therefore, these kinds of experience can be augmented by simulating or enhancing negative emotions.

In this chapter, we contribute to the field by presenting studies of facial EMS and its effect on emotion stimulation. We present a prototype to actuate and manipulate the facial muscles, and two studies to evaluate the effect of the facial stimulation, for both the body owner and an observer. The studies revealed the understanding of facial EMS for three emotions; sadness, anger, and amusement. The results suggest that users tend to understand negative emotions (especially anger) more efficient. We also discuss the potential of facial EMS, as well as application areas and limitations of our work. We conclude the chapter by proposing future directions of facial EMS. We expect our study to motivate researchers to consider using EMS to further emotional studies beyond prior work (e.g.,[90, 360]), and to apply the technique for domains such as affective computing, immersive experiences and communication enhancement.

5.2 Related Work

5.2.1 Emotion

The human face has been considered to have a strong relationship to emotion. More than a hundred years ago, Darwin [40] and James [115] exclaimed the two-way relationship between these two elements as the facial feedback hypothesis. Researchers have continued to explore this hypothesis. On the other hand of psychological research, researchers are now exploring computational methods to stimulate, sense, or to express emotions [236]. Social media can be used to share emotions [16], computer vision methodologies can be used for recognizing the emotion [36], or electric signals can be directly measured from one's body to recognize emotions (e.g., brain signals [229]).

5.2.2 Face Conversion

Researchers have attempted to convert a human face via image processing. Face2Face [310] was a research, which attempted to copy one's face to an external user. In the HCI field, researchers have used the image processing approach to explore human factors and the effects of one's emotion. In Smart Face [206], the creativity of the users was enhanced by facial deformation in a video conference situation. Yoshida et al. [359] explored the facial feedback effect through a mirror like a system for individuals.

Other than these optical approaches, some researchers have attempted to convert faces in the real world. FacialMarionette [186] uses strings and motors to control user's eyebrows, which is a more mechanical approach. Further, Face Visualizer [181] was an artwork that applied EMS to the face to control facial expression. These studies motivated our work to explore further details of the reactions of facial muscles against external actuation methods. We aim to use EMS methods to create a physical deformation of a face, and to study the effects against emotions.

5.2.3 Electrical Muscle Stimulation

Elsenaar's work [63] was a pioneering work to apply EMS to the face. The work has been followed to apply the method to other application domains. Niijima et al. applied EMS to the face to design textures of food when eating [211] and to enhance the contraction of limbs [210]. In 2009, Manabe [181] presented an art performance which he applied multiple channels of EMS to the face. He manipulated the face to control the facial expression or to apply them as an instrument and to copy the facial expression among multiple performers. There are examples where EMS is used to study and stimulate emotions. Emotion Actuator [90] was to study emotional feedback by using EMS on the body. Studies to explore facial EMS, and force users to smile have been proposed [360, 354]. Our work explores facial EMS and it's effect on emotional feedback, for multiple emotions and for both the body owner and an observer.

5.3 Designing the Facial Expression

It is known that there are more than 30 kinds of muscles on one's face and neck. When we consider stimulating muscles on the face, it is required to place the electrodes precisely to the corresponding muscle.

In our study, we followed the three emotional expressions (Amusement, Anger, and Sadness) evaluated by Hassib et al. [90]. These three emotions were selected since they are basic emotions and are well distributed in Russell's model [266]. In order to design these three facial emotions by EMS and to select the appropriate muscles to stimulate, we referred to the work by Elsenaar [63], who refereed to Dunchenne et al. [52] and Ekman's facial action codes [62]. Figure 5.1 displays the position of the related muscles for emotional expression.

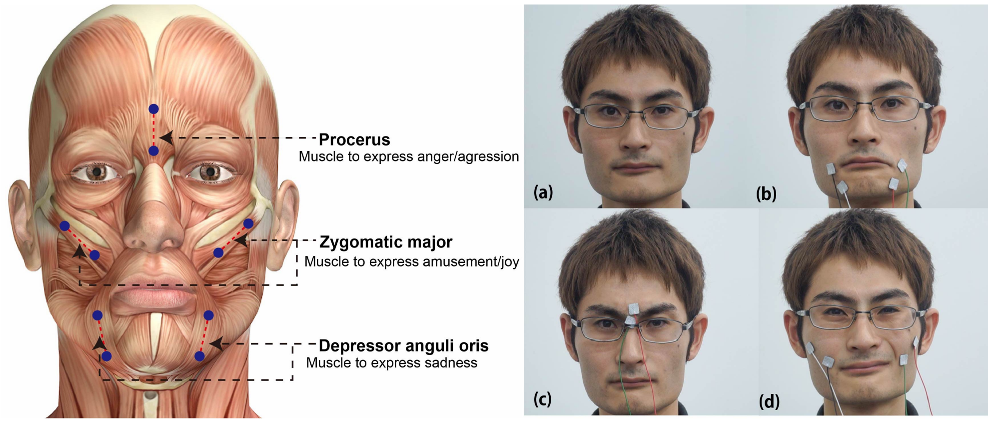

Figure 5.1: Left: The positions and examples of the muscles and the appropriate position of the electrodes are displayed. The blue dots are the electrodes, and the red lines indicate the route of the current path of the electrode pairs. Right: (a) Neutral (b) Sadness (c) Anger (d) Amusement

5.3.1 Sadness

A sad face is expressed by lowering the lip corner. The depressor anguli oris is stimulated to actuate the lip corner. The muscle should be stimulated simultaneously on both sides of the mouth.

5.3.2 Anger/Aggression

One's face can express an angry face by depressing the inner brow. The related muscle to move the brow is the procerus muscle, which is located in the lower part of the forehead, between the two eyebrows.

5.3.3 Amusement/Joy

To create a face that expresses amusement, the zygomatic major muscle is used. The stimuli of the zygomatic major allow the lip corner to be pulled up and the cheeks to bulge. The related muscle should be stimulated simultaneously on both sides of the face. The muscle is innervated by the buccal and zygomatic branches of the facial nerve.

5.3.4 Other Muscles and Emotion

We must note that the facial expressions that could be created are not limited to the three expressions used in our study. For example, a surprising face can be created by combinations of stimulation to the frontalis (raising the eyebrow) and the mylohyoid (opening the mouth). Furthermore, stimulation to the sternocleidomastoid can rotate one's neck. These kinds of expressions and movements may present other effects to people, and we will give additional discussion later in the chapter.

5.4 Study 1: First-Person Feedback

We designed a user study to explore how facial EMS can stimulate emotional feedback for the EMS user. Prior work that evaluated the facial feedback effect based on physical facial deformation [48] was based on participants own muscular action (the participant was asked to move his own face to the desired form) or to hold a pen in their mouth [287]. Our work was to explore how external stimuli that is not based on the face owners intention can stimulate emotion, especially when using EMS.

5.4.1 Apparatus

For our study, we used a earlier version of the EMS toolkit we introduced in Chapter 4. Electrodes typically used in other EMS research were not appropriate for our work. In order to actuate facial muscles, it was necessary to stimulate small muscles in a short distance. Considering the size of the electrode was important. If we use large electrodes, the electrodes may cover multiple muscles and result in an unintended stimulation. In contrast, small electrodes may increase the resistance and current density which can cause pain. Following the presumption of our consideration, we used "1025 EMG Disposable Surface Electrodes" (The Electrode Store) for our electrodes, which are 1.2 mm $\times$ 1.2mm each and are made with Ag/AgCl. The electrodes are designed for EMG, however, they were suitable for EMS usage as well.

5.4.2 Study Design

Procedure

We invited 8 participants aged 21-29 years (M = 23.9, SD = 2.3, 1 female) for our study. Through the study, the participants had the EMS electrodes attached to their face and had their face stimulated. 4 participants had some experience using EMS such as products like the UnlimitedHand [86], while the other 4 participants experienced EMS for the first time through this work. The participants were not allowed to see how their face was deformed and how it looked like during the stimulation.

For the evaluation procedure and the questionnaire, we followed the content of the study conducted in Emotion Actuator [90]. The participant's facial muscles were stimulated at random order. The muscles stimulated were, depressor anguli oris (Stimulation 1, S1), procerus (Stimulation 2, S2), and zygomatic major (Stimulation 3, S3). The relation of the stimulated muscle to the emotion was not described to the participant. Each of the stimulation was repeated 4 times to allow the participant to focus on the expression, proprioception and to get use to the stimulation. The duration of each stimulation was 3 seconds and there was a minimum of 2 seconds interval between the trials. We then asked the participants to rate the stimulation for three emotions on a 7-point Likert scale, if he or she agrees to the statement "The stimulation fits the emotion amusement/anger/sadness" (1 = strongly disagree, 7 = strongly agree). They were assumed to evaluate the emotion based on their proprioception. In addition, we referred to a questionnaire from Schaefer et al. [275] and asked them to rank how intense they felt an emotion in a 7-point scale by the statement "During the stimulation I felt..." (1) "no emotion at all" to (7) "very intense emotion." Finally, the study was wrapped up by an interview, discussing the experience through the facial EMS. The study was conducted after having the participants signing a form agreeing and understanding the safety/risks.

Calibration

As we have noted that there are about 30 muscles crowded around the face overlapping and related to each other, targeting the muscle for the study was a challenging task. A typical way to calibrate EMS for HCI research is to increase the output until a small movement of the targeted muscle is observed and then calibrate the upper bound of the stimulation that is pain-free [173]. In our study, we increased the output gradually and asked the participant to tell us about the perceived stimulation every time. We asked the participants whether they felt pain from the stimulation or feel comfortable and do not have any concerns. In addition, we asked whether they felt and deformation of their face.

According to the participant's feedback, we mainly adjusted the location of the electrodes and the intensity. Through an initial test by the authors, we experimentally found that the perceived face deformation of the participant and the actually observed deformation did not always equal. Since forcing the participant to allow an obvious deformation may cause pain, we took advantage of the participants comment based on their proprioception. In cases when no obvious deformation was observed from the outside but the participant felt deformation by themselves, we took that condition for a relevant stimulation for our study. The actual deformation result of the face was not noted to the participant. The total calibration time varied among the participants, which took 20–40 minutes. We made sure that the stimulation was set to a level where the participants do not feel uncomfortable.

5.4.3 Results

Quantitative Results

Figure 5.2 shows the quantitative results of our study. As well as the results of the Figure 5.2, following the work by Hassib et al. [90], we used the median of the rated results for the discussion. In all cases, the emotion of anger was rated the highest (MD = 4.5, MD = 5.0, MD = 4.0 respectively).

For the measurement of the intensity of emotional arousal, the stimulation of anger (S2) performed as the most effective emotion (MD = 5.0). S3 was found to have the weakest emotional arousal compared with other stimulations (MD = 3.5).

A Friedman test for the corresponding emotions to each stimulation (S1:sadness, S2:anger, S3:amusement) found a significant difference ($p < .05$). No significant difference was found for the intensity of the emotion from the three stimulations (Friedman test, $p > .05$).

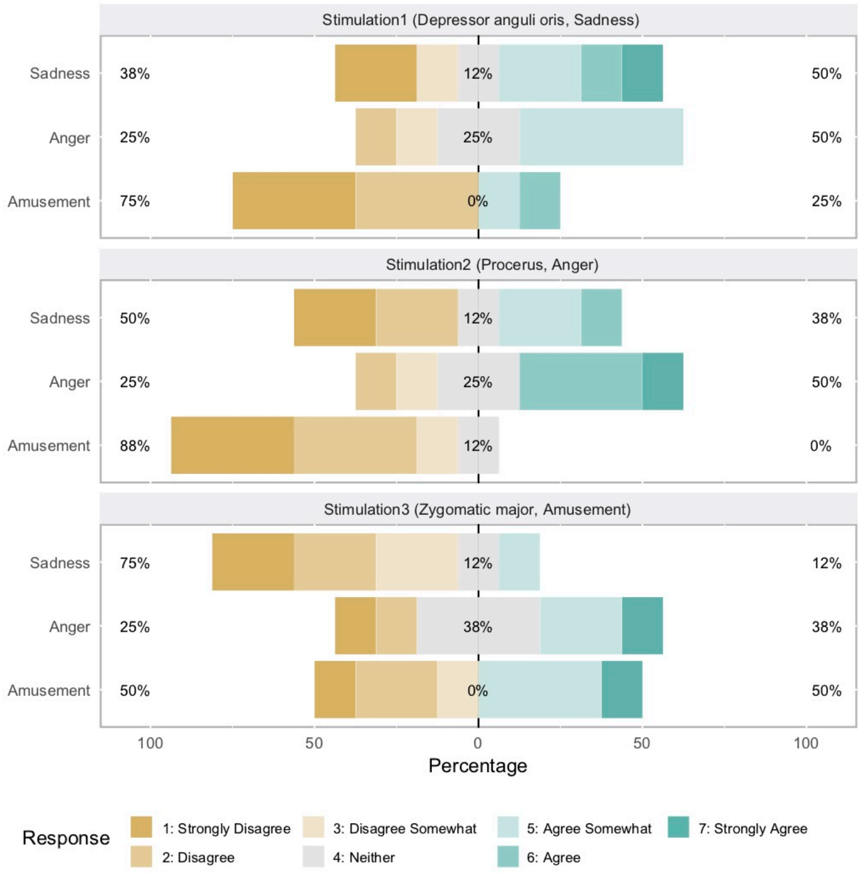

Figure 5.2: Rating results of how well the stimulation fits the emotion on a 7-point Likert scale. The percentage on the left indicates disagreements (rating 1–3), the percentage in the middle indicates neutral responses (rating 4), and the percentage on the right indicates agreements (rating 5–7).

Qualitative Results

We were also interested in how the participants felt the sensation from the stimulation and how they measured the relationship to the emotions. P7 said that *"The last one (the stimulation of zygomatic major) felt like eating something sour, and the first one (the stimulation of procerus) was like when I was thinking."* The deformation of the surroundings of the mouth reminded the participant an experience done in the past. P1 gave a comment, which can be thought as a basis for this discussion by saying *"The perception of the stimulation makes me easier to associate negative emotions."*

When we asked at the interview the reason and how the participants answered the questionnaire, four participants (P2, P3, P4, P6, P8) said that they associated the emotion from the perceived deformation of their face. P7 said that he answered to the questions by comparing the stimulation with the experienced movements of the facial muscles.

There were some interesting comments about the perception of the sensation from the participants. P6 and P8 described some of the stimulation as someone pinching them or twisting their face. In case of P5, the participant said that there was some enjoyment and found the stimulation interesting.

We also received interesting free comments from the participants at the end. P6 said that he wanted to see how the face was actually moving. Furthermore, P1 said *"The sensation of the stimulation remains after the study. And when I move the related muscles by myself, the sensation of the stimulation revives in my mind."* We assume that the sensation of facial EMS developed a link to the participants own muscular movements.

Emotion Response

The stimulation for expressions had some effects to emotion. However, the stimulation was not always described as the intended emotion, but as other emotions as well. P2 said *"The movement I felt from the third stimulation (stimulation for amusement) was small but the influence of my emotion was the easiest to perceive. This resulted from the relationship to emotions I feel in daily life. For example, for the other stimulation, I think I use the related muscles for various kinds of expressions so it was difficult for me to evaluate what kind of emotion the stimulation is related to."* Participants sometimes found difficulty to understand the effect of the stimulation, due to the complexity of human muscles and the relation to emotions. However, it was interesting to see the stimulation for the sad face to present a result to fit the *angry* emotion. This can be considered because the depressor anguli oris muscle may be used to express an angry face for some people. Overall, our recognition rate from the quantitative results was not high, however, in combination with the qualitative results, the results may suggest an advantage for negative emotions.

5.5 Study 2: Observer Feedback

As well as to explore how the facial EMS influences the emotion of the subjective, it was important for us to explore how a EMS deformed face is perceived by an observer of the face. In this study, we explore how people feel or think, when they see a face stimulated by EMS. The study was to make clear the effect of artificial EMS based stimuli for emotion.

5.5.1 Study Design

We had 14 participants (age: M = 29.7, SD = 11.8, 4 female) for our study. We asked to tell us about the expressions of the images shown. There were 9 variations of expressions displayed for the study. The 9 expressions were expressed by 3 people, which expressed anger, amusement, and sadness. The data was collected from Study 1 and were used under agreement (the 3 people did not participate in Study 2). We used images of multiple people since the result of the stimulation appearance varies among individuals. Therefore, 42 answers were collected for each stimulation. All the expressions were stimulated by EMS, however, this was not informed to the participants, and we did not use any terms related to EMS and/or electricity. The participants were consisted of a mixture of acquaintances and non-acquaintances with the 3 people used as images. We assumed that knowing ones neutral face expression might help rating ones facial expression. Therefore, in order to equalize the conditions for the participants, we attached an image that displayed a neutral face with electrodes attached to the face. The participant was informed to use this image as a basis, and it displays the person's neutral emotion. Making this clear, for each procedure, pairs of a neutral face and a stimulated face were displayed.

For each image, we asked the participants to rank the expression for three emotions, if he or she agrees to the statement "The expression fits the emotion amusement/anger/sadness" (1 = strongly disagree, 7 = strongly agree). As like Study 1, we also asked "From the facial expression I thought that he/she was expressing..." (1) "no emotion at all" to (7) "very intense emotion." These questions were corresponding to Study 1, and these were used to compare the results with Study 1. In addition, we asked "The expression looked..." (1) "very unnatural" to (7) "very natural." This question was included to see how the participants think about the artificially manipulated face. For each image, the participant was permitted to indicate any other kind of emotion that they thought will fit the displayed expression. The study was concluded by collecting free comments from the participant.

5.5.2 Results

Quantitative Results

Figure 5.3 shows the quantitative results of Study 2. The figure displays combined results for each stimulation from the 3 people. As like our study for subjective effects, the stimulation of procerus (S2) was found to be most obvious (76 % agreement, MD = 5.5). For S1 and S2, amusement was rated much lower than compared to the other two emotions (76 % disagreement, MD = 2.0 and 88 % disagreement, MD = 2.0 respectively). In case of S2, participants tended to find the expression quite intense and natural as well (both as MD = 5.0). S1 was also evaluated to have a good intensity (MD = 5.0).

A Friedman test for each stimulation found significant difference for S1 and S2 ($p < .001$), but not for S3 ($p > .05$). In addition, a Friedman test for the corresponding emotions to each stimulation found a significant difference ($p < .001$). A post-hoc Wilcoxon signed rank test with Bonferroni correction found significant differences for all three pairs ($p < .001$). For the intensity of the emotion, a significant difference was found by a Freidman test ($p < .001$). A post-hoc Wilcoxon signed rank test with Bonferroni correction found significant difference between S1 and S2 ($p < .001$), S2 and S3 ($p < .001$), but not for S1 and S3 ($p > .05$). A significant difference was observed for the naturality of each emotion as well (Freidman test, $p < .001$). A post-hoc Wilcoxon signed rank test with Bonferroni correction found significant difference between S1 and S2 ($p < .05$), S2 and S3 ($p < .001$). As like the intensity, S1 and S3 had no significant difference ($p > .05$). For all ratings, S2 (stimulation to express anger) was found to be the most effective.

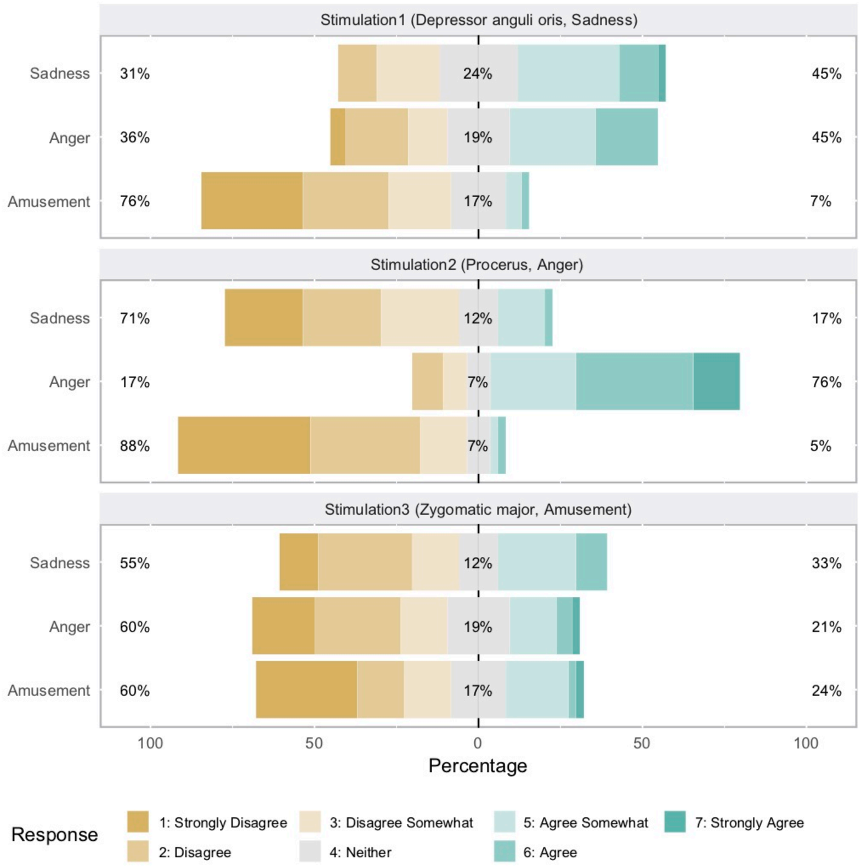

Figure 5.3: Rating results of how well the participant thought the expression fits the emotion on a 7-point Likert scale. The percentage on the left indicates disagreements (rating 1–3), the percentage in the middle indicates neutral responses (rating 4), and the percentage on the right indicates agreements (rating 5–7).

Qualitative Results

Some participants attempted to describe the image with other emotions expect from anger, sadness or amusement. For a face expressed by S1, some described the face as dissatisfaction (P1, P3, P6), disagreeable (P2, P3) or troublesome (P7). These were still negative types of emotions describing the expression. For S2, P4 mentioned one image as *no expression*, however, no other emotions were mentioned to describe the emotional state of the stimulation. S3 was described with other emotions most often, for example, painful (P3, P6, P8), discomfort (P1, P7) and no expression (P2, P5). P10 said that *"Looks like stimulated by sour food"* and P7 said that *"Looks like despis-*

ing someone else and feeling superiority." Although the angle of the mouth was lifted up, comments mentioning negative emotions were collected. P4 and P10, mentioned that the eyes are important evidence to evaluate someone's emotion. Furthermore, P4 said *"For some of the expressions, even though the facial muscles were deformed, the appearance around the eyes did not change. This made me feel the expression unnatural."* P10 said *"Expressions are majorly influenced by deformation of the stimulated face parts, but also affected by other parts."* From these comments, we can assume that creating different expressions by stimulating multiple muscles simultaneously, will achieve different understandings of emotion.

5.6 Discussion

5.6.1 First-Person and Observer Effects

There were some agreements as well as disagreements among the results of the two studies. The results for S1 and S2 were similar to our Study 1, where these negative emotions were found quite agreeing with the stimulation. However, objective results gave a slight advantage compared with Study 1, especially for S2, where the participants in Study 2 confidently observed the expression as displaying *anger* (76 % agreement, MD = 5.5, intensity at MD = 5.0). S3 in Study 2 had a slight advantage compared with Study 1, but still did not perform an obvious result. Stimulating and deforming the face to display a comfortable and amused expression was a difficult task, and the result of the three people used for Study 2 varied, where the deformation appearance was different. In Study 1, some people may move unstimulated muscles reacting to the stimulation. These kinds of unintended movements could have displayed or stimulated negative expressions.

5.6.2 Negative Effects

The results of the two studies suggest better results for negative emotions. This was suggested from both quantitative and qualitative results. Through the results and related discussions, we assume that one of the most significant factors that have influenced the result is due to the tactile sensation created by EMS. It is obvious that EMS will generate tactile feedback, and it has previously been studied for force and textile feedback [167, 233]. In our current study, it is difficult to distinguish the tactile and the deformation effect to the perceived emotion. This issue has also been questioned in prior work [360], which also revealed negative effects. They stimulated people's face with functional electrical stimulation (FES), and had the participants to perform a volunteering smile during the stimulation. Therefore, the stimulation is thought to be weaker than the EMS used in ours, and lacks the ability to deform the facial muscle by itself. However, even with this kind of stimulation, negative effects were observed. Nevertheless, the position of the EMS, tactile feelings (tingling feelings) are difficult to omit (e.g., on the arm [167]). Therefore, it may be necessary and inevitable to evaluate the effect of EMS on emotions by assuming the tactile feedback.

5.6.3 Application Areas

We are aware that EMS on the face has been used for medical and beauty usage [50]. In this section, we will highlight application for domains where facial EMS has not yet been deployed as products, and domains where emotional appearance are important.

Communication

One application domain is for communication enhancement. Our system can be applied to study the facial feedback effect and to alternate methods using image processing [359] for communication application to be used in the real world. The deformation and appearance of one's face may influence the quality of communication [295, 206]. Facial EMS can be used for face to face communication, as well as video conversations among distance.

Immersive Contents

Taking the characteristics where our methodology can benefit better for negative emotions, we may consider applications to intentionally increase and stimulate negative emotions. We consider this domain as a significant area where we can apply facial EMS techniques. This is because it is known that human can sometimes enjoy having negative feelings [5]. For example, people may actively see horror movies, or experience fearful things like roller coasters. Usage of facial EMS has potential to enrich these kinds of experiences. We did not study the effect for *fear*, however, we think of facial EMS as an effective method to increase the fear of immersive experiences (e.g., virtual reality (VR) contents), by designing interactions that create and warps the face, or closes the eyes.

Training for Natural Expressions

It is known that training or activating the facial muscles is valid to effect emotions [314, 48], therefore, usage of EMS on the face and to stimulating the facial muscles may also be effective. Tsujita et al. [314] designed a system to enhance positive emotions and to increase happiness. The system required participants to smile every day when performing a certain task. This allowed the participants to get familiar with smiling, which eventually allowed the participants to smile unconsciously and more natural. A repetition of self-muscular movement helped the user to express emotions. Facial EMS may contribute to users as a more mechanical way to induce such expressions by stimulating the muscles directly.

Other Domains

A further application includes usage for patients with facial paralysis. Electric stimulation is a method used for treatment for such patients [30], however, our system may have a possibility to help further muscular movement and expression displaying.

5.6.4 Limitation and Future Work

A limitation of our work is the limited number of participants for the studies. However, a possible tendency exists, which can be seen from both quantitative and qualitative results. This indicates that our approach is effective for negative emotions, especially for anger. However, the participants still found difficulty in distinguishing what kind of negative emotion it was that they perceived, and our studies are limited to the three emotions we have explored. In the meantime, we have to limit the number of emotions and stimulation because the calibration of facial EMS is still difficult and takes time, which requires effort for the participation. Our future directions include studying with a larger participant pool and other emotions to increase the generalization.

In our studies, we used the most related muscle, however, conducting further studies with combinations of multiple muscle stimulation can be expected. As eyes can also be a significant element to display an emotion [339], stimulation of the eyes can also be effective. Some muscles overlap each other, therefore, electrodes placements may have a conflict. This means that we cannot truly manipulate the whole face freely and simultaneous. It is important to consider the appropriate muscle for the purpose of the usage. In our current studies, we have attached the electrodes for the corresponding muscles, and removed other electrodes for other stimulations. However, when we want to create a face to display various expressions without replacing electrodes for each time, a multi-channeled EMS system will be required. This is why we build our system to be scalable and to enable multi-channel EMS output to the face. We considered our system so that it can be used for any other future work using facial EMS.

The electrodes used for our design are opaque, thus if we attach too many electrodes to the face, it may decrease the visibility of the user's face. It may disturb an observer to recognize the user's expression, therefore it is important to consider which electrode placements are necessary for each application. In addition, we may consider using transparent electrodes to increase the visibility. We are aware that there are some consumable transparent electrodes available for medical application and plan to consider using them in our future work.

5.7 Conclusion

This chapter presents a prototype to manipulate the human facial muscles, and two studies to evaluate the effect of the facial EMS. We explored the facial EMS effect for three emotion statements, sadness, anger, and amusement. The results show that facial EMS has a possibility to stimulate the face to express and understand emotions through the facial muscles, especially for anger. Both the body owner of the stimuli and the observer understood some emotion from the stimulated expression. Furthermore, the results indicate that facial EMS may effect negative emotions better than positive emotions. We presented application domains and limitations to discuss the potential of facial EMS, and proposed future direction of research using EMS for facial expression and emotion designs.

Chapter 6

Enhancing Virtual Experiences with Facial Electrical Muscle Stimulation

This chapter refers the results from Chapter 5, and explore an area for negative emotion stimuli and improvement of experiences.

6.1 Introduction

Virtual Reality (VR) has introduced many immersive and realistic experiences to users in many domains. VR is based on visual and auditory sensations, however, researchers are now exploring an additional sensation for VR, e.g., by designing immersive haptic feedback. Many mechanical approaches have been taken to create a haptic sensation and to present haptic feedback to the users. One of an interesting approach to this domains was the application of electrical muscle stimulation (EMS). Lopes et al. [167] proposed *Impacto*, a novel approach to design haptic sensation by combinations of mechanical actuators and EMS. The work successfully created an immersive experience for a user to perceive *impact* (a sensation of being hit). This approach was to reproduce a tactile and force sensation relative to a visual content. In an experience like being punched, you may feel the *haptics*, which is a force that hits your body. However, if the experience was real, you may feel *fear*, as well as some *pain*. It is interesting that human sometimes enjoys having such negative feelings [5], therefore, can be important factors to create richer and favorable virtual experiences, and various approaches have been considered (e.g., theater implementation [222], heartbeat feedback [317], electrostatic force [73]).

In this chapter, we present In-Pulse, a challenge to create *fear* and *pain* as an additional feedback for VR contents (Figure 6.1). Although generating a first-person view through a head-mounted display (HMD) may slightly simulate these aspects, it is still challenging to simulate this emotional feedback with additional components. Nevertheless, when we want to create an experience that causes *pain*, we cannot always use direct stimulating methods (e.g., PainStation[1]), which actually causes pain and damage to the user due to ethical reasons.

We hypothesized that a visual or an artificial blink reflex could induce fear or pain. This is because if you imagine an experience being punched in the face, people may react by closing their eyes (a blink reflex) that may result from the perceived fear [87]. We assumed that creating a facial reaction when a user feels fear or pain may allow users to perceive more fear or pain. Creating an experience that closes the eyes may recall an experience related to a blink reflex, which may also stimulate some fear and pain. To explore our hypothesis, we built a prototype HMD, which was combined with a mechanical actuator to simulate the haptic feedback and EMS on the face/eyes to manipulate the user's eyelids and to close their eyes. We then conducted a study to evaluate the effects of five conditions in VR.

Our main contribution is the concept of negative emotion simulation in VR. We present several scenarios to describe and demonstrate the benefits of In-Pulse and negative emotion simulation, where it influences the perceived realism, fear, and pain in VR experiences. The result of our study suggests that our approach can be effective to simulate emotional and emphatic VR experiences.

[1]http://www.painstation.de/

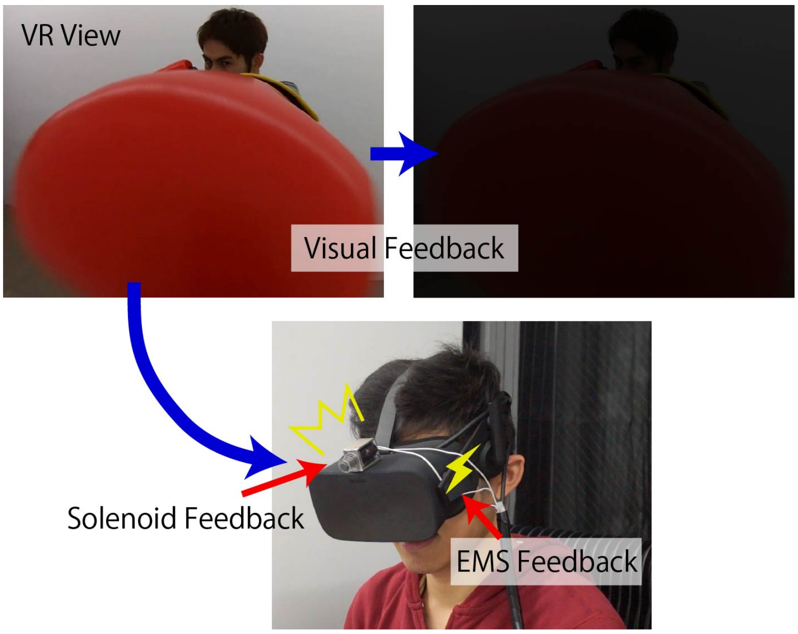

Figure 6.1: In-Pulse uses visual, mechanical and EMS feedback to simulate fear and pseudo pain for VR contents. We study and compare five conditions through a virtual boxing experience.

6.2 Scenarios

As we have indicated above, we think of In-Pulse and the concept of negative emotion simulation as a technique for enriching VR experiences. To emphasize and to clarify this point, here we present example scenarios which we consider by using In-Pulse.

6.2.1 Immersive Experience

Experiences like being hit can be designed and augmented. For example, a boxing game or a video can be more immersive with the In-Pulse system (Figure 6.2). The tactile stimuli or the electrical stimuli may induce fear and pain through the experiences. Feeling fear and pain can be important factors in such an application. Just when the punch lands on the user's face, In-Pulse stimulated the eyelids, which forces them to close.

In order to allow users to experience immersive video experiences, we analyzed the blur level of the video for estimation and detection of the impact. Figure 6.2 (a) is an example displaying the impact of the boxing video. We can see that a detectable blur (which is a jolt of the camera) occurs at the timing of impact. Observation of optical flows can be used to detect and analyze more complicated actions in videos.

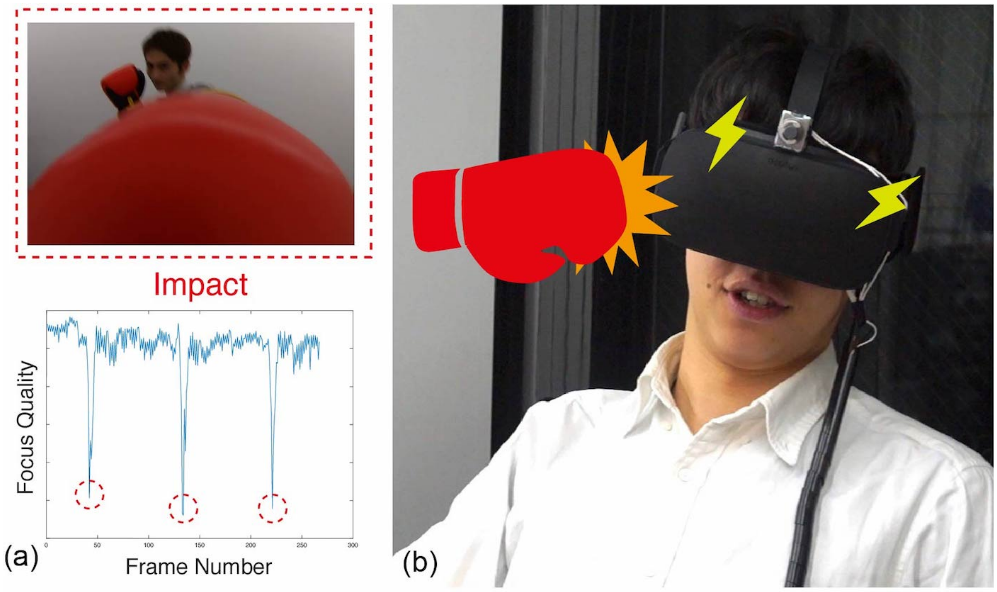

Figure 6.2: An experience being punched in the face. (a)A significant blur is recognizable at the timing of impact. In the video, 3 punches were performed in 9 seconds, recorded at 30 fps. (b) When the punch lands on the user's face, In-Pulse stimulates the user for feedback.

6.2.2 Horror Contents

The In-Pulse system can be used for horror games or video contents. The EMS can stimulate the user at the timing of a surprising or fearful point. Although some may feel fear from the visual feedback itself, combinations with EMS may increase the perceived fear of the experience. The added negative emotion may lead to more engagement.

Figure 6.3 is an example application using the In-Pulse system for a horror content. We embedded the electrodes to a PlayStation VR (Sony Interactive Entertainment) and used a purchasable horror content. The system stimulates the user's face at the selected fearful points from a sequence, which may enrich the experience of the video content. We developed an interface to record and send the fearful points with Processing, which communicates with the Arduino via serial communication. One technique to induce further fear, is to include fake fearful points. Stimulation at non-fearful points can confuse and fear the user, since they may assume something fearful to happen at the timing of the stimulation. In these kinds of VR contents, when the avatar of the user in VR gets damaged (e.g., shot or stabbed), the pain induced by In-Pulse main increase the empathic connection with the avatar.

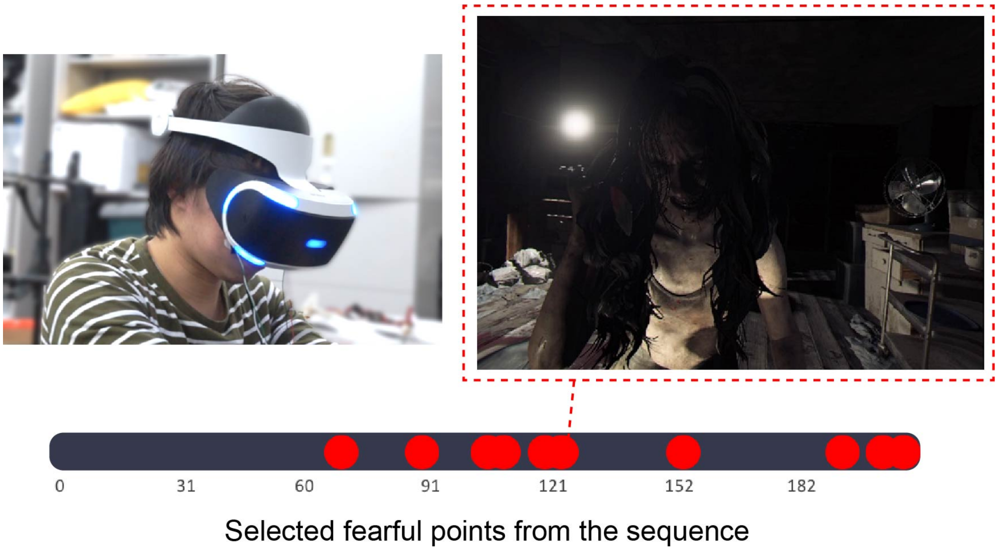

Figure 6.3: EMS stimulates the user at these points that may induce additional fear. Fearful points are selected from video sequences. The figure shows a screenshot of the fearful point from KITCHEN (CAPCOM Co., Ltd., approx. 3.5 minutes video content).

6.2.3 Extreme Conditions

One popular and typical experience in VR is an experience of a extreme content. Examples of extreme sports [133] and contents of roller coaster experiences are well known. Here we will provide a use case for a VR roller coaster experience. Figure 6.4 shows stimulation points of In-Pulse, which are typical fearful points. These include experiences where the user visually loses or feels strong gravity according to the ride.

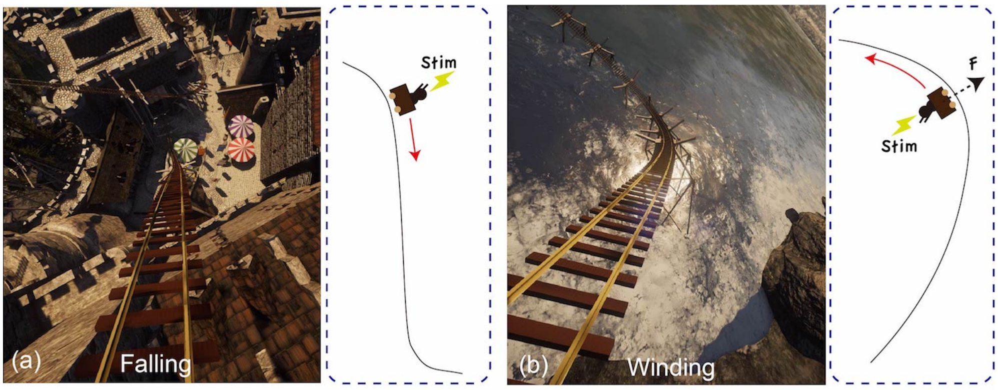

Figure 6.4: An example usage of In-Pulse in a roller coaster video. (a) The user perceives additional fear when the coaster falls down. (b) The user gets stimulated by In-Pulse at a winding point, where he/she feels strong gravity due to centrifugal-force.

6.2.4 Game Playing

We assume In-Pulse to be used when playing a game. As like the example of PainStation, designing risks in a game may influence the engagement and the gameplay of a player [189]. In addition, studies indicate that sharing of physiological states in games has effects on the emotional experience [45]. Therefore, designing some kind of risk like pain in game playing, may influence the players and to act more seriously, or simply to increase the engagement and immersivity.

6.3 Related Work

Various techniques have been used for haptic and perceptional feedback in VR. Grabity [29] is a wearable device that allows to simulate force, weight or grasping activities for virtual objects. Haptic Turk [27] uses humans as actuators to create feedback in VR experiences. Augmented reality flavors [207] is a technique using cross-modal effects to allow users to perceive pseudo flavors. Hapbelt [205] used vibration and skin deformation for haptic displays that can be applied to various body parts including the head. There are also other studies working on feedback generation to the head, for example, ThermoVR [228] provides thermal feedback directly to the users face. GyroVR [84] attaches a flywheel to the HMD to simulate motions such as flying and diving. GVS RIDE [7] uses GVS (galvanic vestibular stimulation, a technique to stimulate virtual acceleration) to produce tri-angular acceleration for VR applications. FacePush [23] used normal force for feedback to the face to improve HMD experiences, and Face/On [343] used combinations of multiple stimulation elements (including EMS) to the face to increase immersion.

In-Pulse uses solenoids and EMS on the face, which are integrated into an HMD. The main interest of In-Pulse is to work on the emotional effects of immersive experiences.

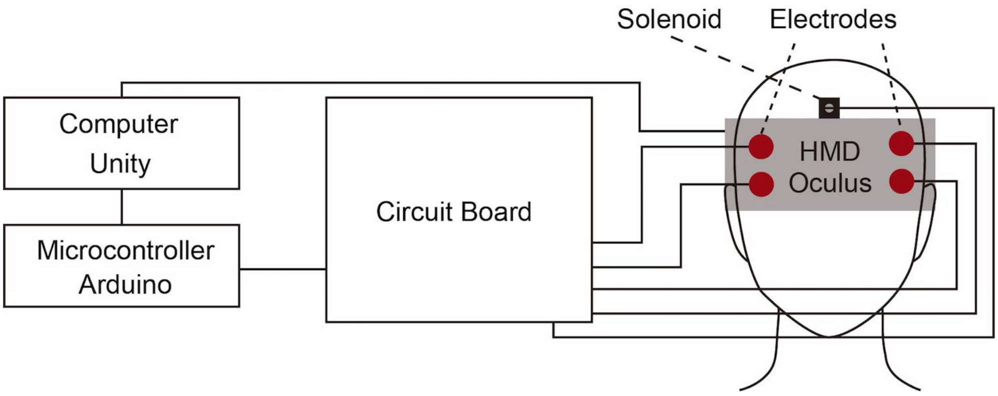

Figure 6.5: System overview. The system is developed by Unity, Arduino, Oculus, EMS, and a solenoid. The actuators are activated accordingly to the visual content shown in the HMD.

6.4 Design of In-Pulse

In-Pulse is a novel approach to use mechanical actuators and EMS on the face/head in order to influence the fear and pain perceived by the user.

Figure 6.5 displays the system overview of In-Pulse. We integrated the electrodes of EMS to the inner side of the HMD to stimulate the user's eyes and to close them artificially. In addition, a solenoid is fixed on top of the HMD, which produces physical impact. Oculus CV 1 was used for the HMD. An omnidirectional video was recorded and managed by using Unity. The Unity application sends signals via serial communication to an Arduino to activate the actuators (solenoid and EMS). The actuators are activated at the timing of impact or a selected point in the recorded video. Details of our designs are explained in the following sections.

6.4.1 Electrode Placements

Through a preliminary experiment, we found that there were several electrode positions which could stimulate facial muscles to close the eyes (e.g., outer part of orbicularis oculi, inner part of orbicularis oculi). Considering the design consistency of the system, we chose to stimulate the outer part of the orbicularis oculi (Figure 6.6).

The electrodes were implemented inside the HMD (Figure 6.7 (a)). The Oculus CV 1 covers the face breadth but we wanted to place the electrodes to the orbicularis oculi that are located slightly inside from the outer side of the Oculus. Therefore, we integrated an additional layer of sponge inside the Oculus, and attached pairs of electrodes to each side of the Oculus.

We referred to a database information from a national institute [208]. The database indicates that the biectocanthion breadth (the distance between the outer side of both eyes) is 93.6 mm for young men (Mean of N = 56, SD = 3.7) and 90.0 mm for young women (Mean of N = 61, SD = 3.5). The distance between the electrodes in the HMD on both sides were approximately 105 mm, and since the sponge was deformable, the electrodes can be adjusted between ± 10 mm. For the electrodes,"1025 EMG Disposable Surface Electrodes" (The Electrode Store) where used, which are 1.2 mm × 1.2mm each and are made with Ag/AgCl. The distance between the electrodes on one side was 0.9 mm. Considering the values from the database, the design of our system will be well adapted to a majority of users.

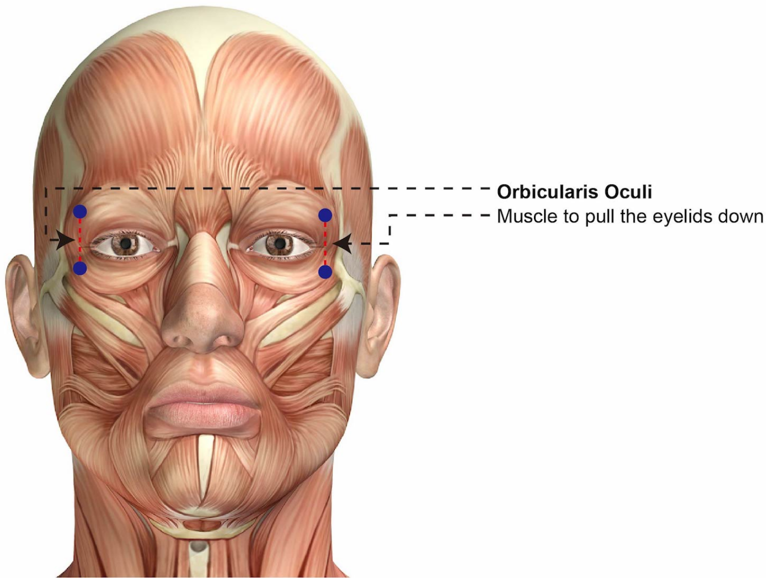

Figure 6.6: The placement of the electrodes to close the user's eye. We stimulate the orbicularis oculi on both sides of the face.

6.4.2 Tactile Feedback Design

We wanted to create a realistic tactile feedback with a force previously measured to be successful. Therefore, we followed the implementation of the solenoid used in *Impacto*. Since the information of the model number is not reported in the paper, we followed the reported measured force. We considered several solenoids by comparing the force, weight, and size (e.g., CB08470090; small but too weak, CB12500045/CB15670130; powerful but too heavy and large). As a result, we used CB10370100 (Takaha Kiko Co. Ltd., 105 g) at 24 V. We measured the force of the solenoid with a digital force gauge. The measured force was 21.73 N (Mean of 20 taps, SD = 0.64), which almost equals to the force of *Impacto* (M = 21.1 N). The solenoid was fixed on top of the HMD. The length of the solenoid was 43.7 mm (excluding the spring) with a 10 mm stroke, where the top of Oculus CV 1 was 70.0 mm. The size of the solenoid was appropriate to be fixed on top of the Oculus, without disturbing the stroke and the center of the gravity (Figure 6.7 (b)).

6.4.3 Circuit Design and EMS

For the EMS implementation, we used an EMS board introduced in Chapter 4 and electrodes from Chapter 5.

The EMS circuit was combined with the solenoid circuit. The solenoid circuit was powered by 24 V, with a motor driver (TB6643KQ, Toshiba). The EMS and the solenoid were both controlled from a single Arduino (Figure 6.8), which communicates with the software (Unity) via serial communication.

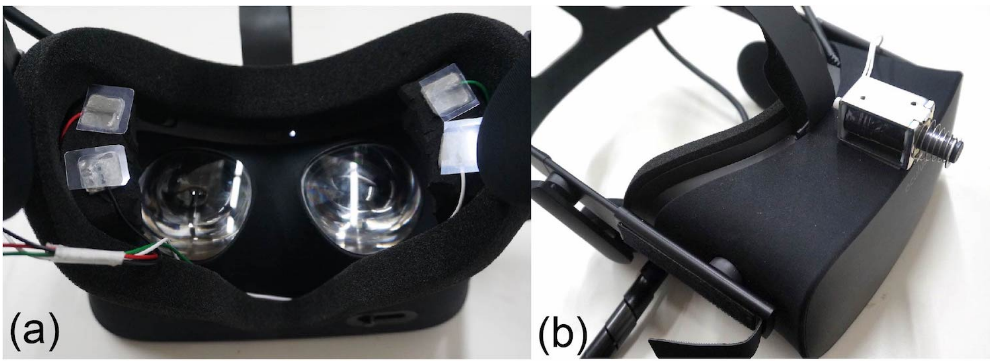

Figure 6.7: The design of the HMD. (a) Electrodes are fixed inside the HMD. (b) A solenoid is fixed on top of the HMD.

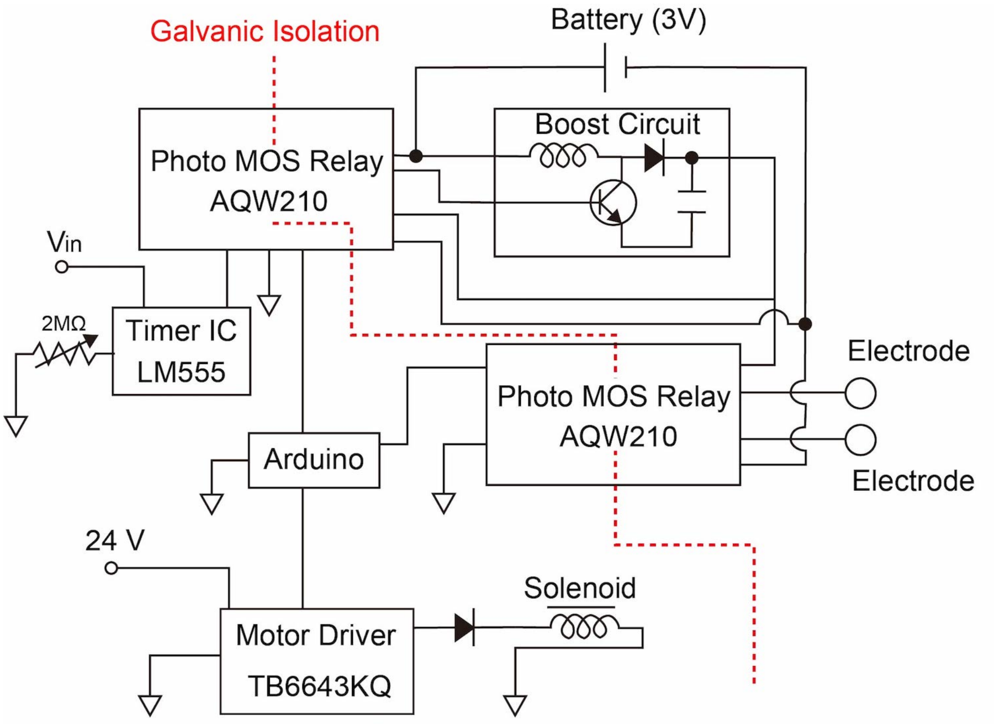

Figure 6.8: The overview of the circuit. The EMS circuit and others are galvanically isolated. They are controlled by an Arduino.

6.5 User Study

A user study was conducted to evaluate how a designed blink reflex and an artificial feedback and facial deformation influence the perceived reality, fear and pain of a virtual experience.

6.5.1 Study Design

An omnidirectional video was recorded by a Theta V (RICOH). The length of the video was 9 seconds and it was an experience being punched for 3 times. The content and the study was designed by following the study of Impacto [167].

The participants wore the In-Pulse system. We conducted a within-subject study to evaluate reality, fear, and (pseudo) pain perceived from five conditions. The participants were asked to rate these statements with a 7-point scale, which was *realism* (1 = artificial, did not feel like being punched, 7 = realistic, like being punched), *fear* (1 = no fear, did not feel fear, 7 = scary, felt fear), and *pain* (1 = no pain, did not feel pain, 7 = painful, felt pain). However, measuring pain can be thought to be a difficult procedure. When measuring pain, it is known that visual analog scale is the most sensitive [101]. According to Guyatt et al. [85] 7-point scale and visual analog scale do not perform significant differences, and 7-point scales can be recommended due to its ease of use. Therefore, to make consistency with our other measurements, we used a 7-point scale for measuring the pain as well.

The five conditions were, video only (VO), video with self blinks (i.e., the participants blinks at the timing of the impact by themselves, SB), video with visual blinks (i.e., the video blackouts at the timing of the impact, VB), video with solenoid tactile feedback (SF), and video with EMS feedback (EF). The order of the study was randomized, where the methods were tested three times each, leading to a total of 15 trials.

We considered that fear and pain can be induced with facial EMS, resulting from many factors. Since we forced the participants to close their eyes by EMS, we assumed that this could be something like a blink reflex. In addition, the vision of the participants will be lost when EMS makes them close the eyes, which may also lead to fear. This is why we prepared the volunteering blinking situation and the visual blinking (video blacks out at impact) situation, and we wanted to discuss what factor effects the result. A volunteering facial deformation task is often used for psychological emotion studies [48], and this was the reason why we used the method for our study. We set the duration of the solenoid and EMS feedback to 200 ms, which we referred to the design of Impacto [167]. For the design of the visual blinking, as the duration of blinking is known to be 100–400 msec [276], we set the duration of the blackout of the impact to 200 msec as well. We hypothesized that SB, VB, SF, and EF all can be more effective to increase realism, fear, and pain. In addition, we hypothesized that physical feedback (SF, EF) can increase more realism, fear, and pain, compared with feedback caused by SB and VB.

Through the study, we used an oscilloscope to measure the voltage applied to the participants. As a result, the applied voltage ranged between 16.4–33.2 V (M = 26.7 V, SD = 4.03). We videotaped the study, and had all the participants to agree to a liberty waiver and confidentiality.

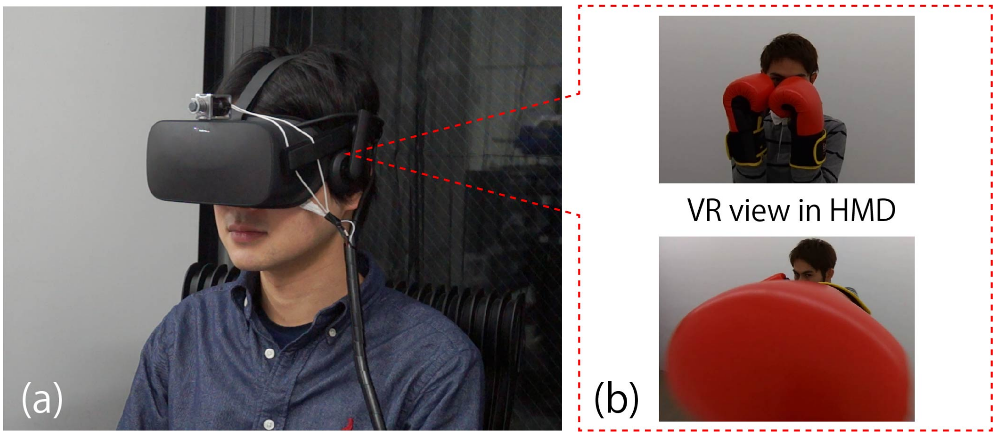

Figure 6.9: The study setup. (a) The participant wears the HMD with a solenoid, and electrodes on their orbicularis oculi. (b) The participant sees a first-person view experience of being punched in their face.

Participants

We were aware that some people may have potential fear of having electricity applied to the body. However, since we wanted the participants to evaluate the perceived fear from the deformation and the feedback elements, we made effort to recruit participants that are not afraid of the EMS itself. Therefore, we chose participants who have previously experienced EMS in some way. As a result, we recruited nine participants for our study (Age: M = 24.0, SD = 2.1, 1 female). However, one male participant was removed from the study because the participant failed to find a appropriate setup for the EMS to be applied without causing pain. Furthermore, one participant measured the reality too high for the first trial and caused a ceiling effect. Therefore, the results of this element were removed from our analysis.

Calibration

The calibration process of EMS was an important element for our study. Since we wanted to measure the *pain* generated by the EMS with combinations with the visual content, we had to ensure an appropriate ground truth level. We calibrated the EMS to a level where a deformation of the face was noticed, and the user did not feel *real* pain from it.

Through tests with the authors, we experimentally found that the positions of the electrodes influenced more significantly to the muscular movements, rather than the intensity or pulse conditions of the stimulation. Therefore, instead of trying to adjust the signals, we fixed the frequency to 100 Hz and the pulse width at 100 μs, and rather focused on adjusting the position of the electrodes.

We asked the participants to note how the stimulation feels for every trial. Two elements were mainly considered; muscular movement and tingling feeling. When the position of the electrode is correctly placed, a muscular movement can be noticed without having any (or almost any) tingling feeling. Following comments from the participant, we advised moving the electrodes to a new position. For example, when the participant feels tingling feelings in the bottom area of the eyes, we asked them to move the electrodes up. When they say they do not feel anything, we asked them to push the electrodes harder to the face. Since we could not observe or attach the electrodes directly to the face, this calibration procedure took multiple times, lasting 4–10 minutes. Once an appropriate position was found, we then adjusted the intensity of the stimulation. We gradually increased the intensity until the participant finds a comfortable and sufficient movement on their eyelids. Finally, when the stimulation is comfortable, we asked them to use the feelings of the stimulation as a baseline to evaluate the pain for the EMS feedback, i.e., the EMS feedback without the video should be rated as 1 (no pain, did not feel pain).

6.5.2 Results

Quantitative Results

Figure 6.10 shows the quantitative results. We conducted our statistical analysis by using Wilcoxon signed rank test with Bonferroni correction. No main effects were found among the repetition, therefore, we used all three repetitions as data (all pairwise comparisons among each factor).

- Realism No significant difference was found between VO-SB, VO-VB, and SB-VB ($p > .05$, the three conditions that had no physical feedback). However, significant difference was found between the VO and SF, as well as EF ($p < .001$). In addition, significant difference was found between SF and EF ($p < .001$).

- Fear As like the measurement of realism, no significant differences were found between VO-SB, VO-VB, and SB-VB ($p > .05$, the three conditions that had no physical feedback). However, significant differences were found between the VO and SF, as well as EF ($p < .001$). We found no significant difference between SF and EF ($p > .05$).

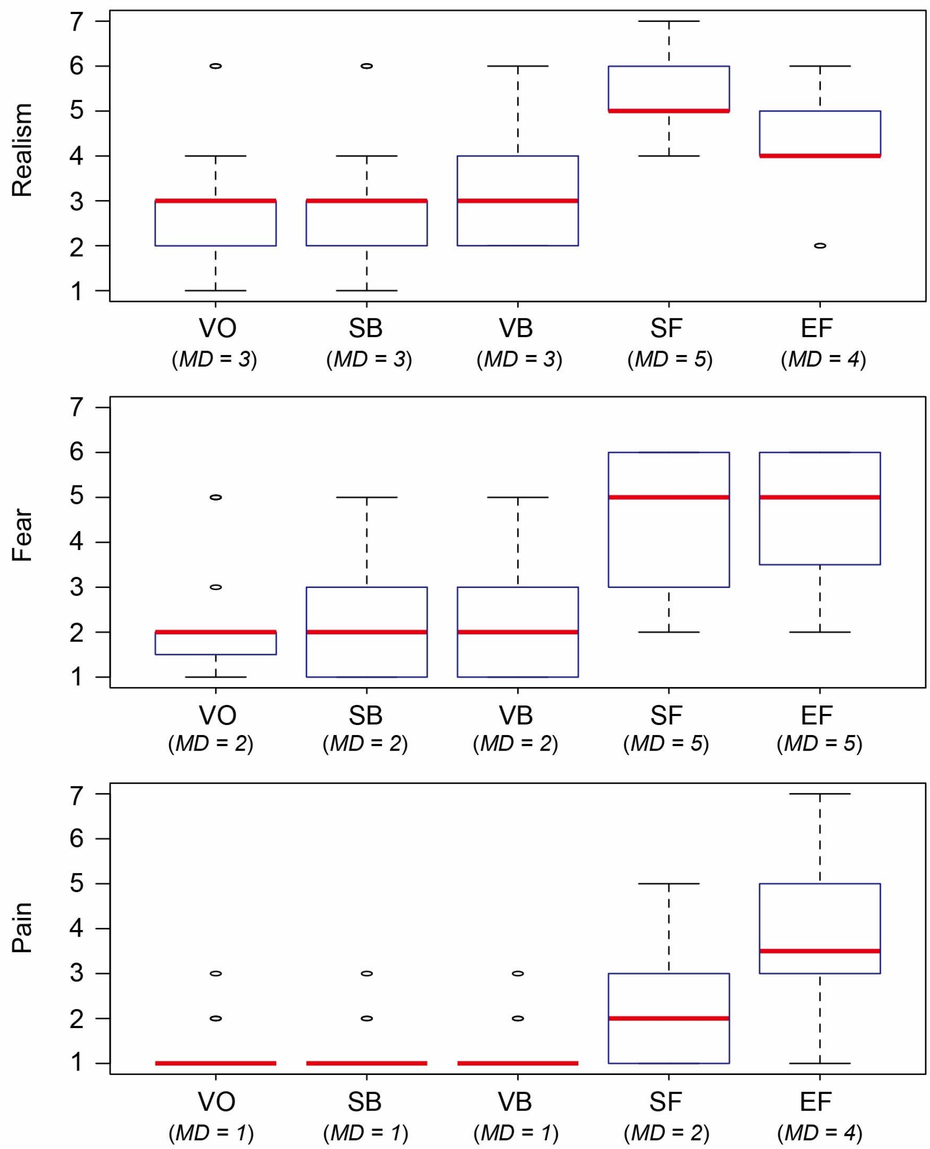

Figure 6.10: Counts of the perceived realism, fear, and pain rated with a 7-point scale.

- Pain No significant difference was found between VO-SB, VO-VB, and SB-VB ($p > .05$, the three conditions that had no physical feedback). However, significant differences were found between the VO and SF, as well as EF ($p < .001$). In addition, a significant difference was found between SF and EF ($p < .001$).

Qualitative Results

As we were interested in what influenced their rating and how the experience was, we conducted an interview of the participants after all trials.

None of the participants indicated positive effects for the volunteering blink (SB). P3 said *"When I performed a volunteering blinked, the experience felt more fake, because I felt I was acting on it by myself."* Volunteering facial deformation tasks that are often used in psychological studies [48], seem not to work for blinking tasks in our case.

Furthermore, a visual blackout of a short duration was not notable to the participants. Since the duration of the blackout was same as the duration of a blink, participants could have blinked at the same time (the timing of the impact), however, the participants did not realize or reported that they blinked by themselves. As a result, the visual blink failed to induce additional effects.

Overall, the solenoid feedback had high satisfaction. P7 said *"I felt afraid and my body got shook."* and P8 said *"The feedback of the solenoid was interesting. I felt that I had to avoid the punch."* Although the solenoid had the impact only to the HMD/head, some of the participants reacted larger than the original impact of them. This experience could have led to increase of realism and fear, as well as some pain. P3 said *"I felt like I was being punched over the HMD. And I also closed my eyes in a reflex."* This was another effect caused by the solenoid feedback, which satisfied the participant's experience.

For the EMS feedback, P7 said *"I preferred the EMS feedback better than just seeing videos without anything."* However, P5 and P8 noted that they did not think the EMS on the face was real. Other successful cases were observed, for example, P6 said *"When I knew that I get stimulated at the impact of the punch, I close my eyes prior to the electrical stimulation to guard myself."* P4 said *"When I know that there is only visual information, I notice that I will not get punched in real. But I got nervous when there is an electrical stimulation to me."* and P2 said *"I feel fear because I can estimate the feedback."* From these comments, we may consider that the EMS feedback helped the participants to feel fear from the experience. It was important for the participant to understand whether the punch has a physical feedback or not to feel fear from the experience.

For the EMS feedback, P5 said *"I feel the impact through my whole body when I have my eyes moved without my intention."* and so did P7 and P8. Both the solenoid and EMS feedback influenced body movements. Since the EMS only moved the eyelids downwards, it was interesting to see that this actuation led to other body movements.

6.6 Discussion

6.6.1 Emotional Effects

The main objective of our study is to induce fear and pain for virtual experiences. These may be understood as negative emotions, however, we believe that stimulation of these negative emotions can contribute to increase the immersivity. This is because a human can sometimes enjoy having negative feelings [5]. Horror movies and roller coasters are good examples. The human body movements are strongly related with emotions [247], and there are some reflexes against fear [87].

As well as inducement of fear, another important challenge of this work was to induce pseudo pain. Prior knowledge indicates phenomenon based on mirror neurons [224]. For example, people may feel pain from seeing others being injured or when shown painful events [221]. However, these are cases when seeing a painful event on a third-person. It is unclear if there is a methodology that can induce pain for the first-person experience. In our study, both solenoid and EMS found significant effects for pain, compared with visual stimuli (see section Quantitative Results - Pain). This indicates that combinations of tactile or EMS feedback with first-person view videos can induce pseudo pain to users. We consider this effect results from cross-modal effects [280], where multiple elements react with each other leading to additional perception. In our case, the solenoid/EMS feedback with the video of being punched could have recalled an experience of having a strong impact on their face, which led to the perception of pain.

Our study shows that combining some feedback methods with visual stimuli in virtual experiments can increase not just realism, but emotional aspects such as fear and pain. Both mechanical actuators and EMS can be effective for these emotion simulations.

6.6.2 Mechanical or EMS

One significant advantage of EMS is its mobility. EMS is considered to be an effective technique that can produce strong power with a tiny package [165]. EMS has introduced many applications to substitute mechanical actuators. This aspect will also be an important element to think about when one considers the use of mechanical actuators and EMS for fear and pain inducement. In the situation of our study, both mechanical actuator and EMS was found effective for realism and fear stimuli, but EMS had the advantage to induce pain. Usage of mechanical actuators may design good reality and fear, but EMS can do so with a smaller package.

6.6.3 Limitation

A limitation of our work is the low number of participants for the user study. This could have led to performing potential biases for our result. As we have mentioned in the study design section, all of our participants had some experience of EMS, and knew the basic idea of EMS usages. This was necessary to omit potential fear much as possible, from electricity being applied to the body. However, the tactile and EMS feedback both performed notable effects for all measured factors. Therefore, a possible tendency exists, which may indicate our approach to be effective for the concept of negative emotion simulation. In addition, as we can tell from the comments from the participants, the approach may be said to be more favorable for a better VR experience (see qualitative results). Our future directions include studying with novice participants for EMS, with a larger participant pool to increase the generalization.

6.7 Conclusion

This chapter proposes a concept of negative emotion simulation, and introduced a proof-of-concept prototype named In-Pulse, which is a design and study for inducing fear and pseudo pain for virtual experiences. We hypothesized that a volunteering or artificial blink reflex can increase the fear and pain perceived by the user. Five conditions were compared and studied through a VR boxing experience. The conditions were designed to compare between a baseline video and volunteering blink, visual blink, solenoid feedback and EMS feedback. Our study found that an external feedback from solenoid or EMS can help users perceive more fear and pain as well as reality in a VR experience, while visual and volunteering feedback found no significant effects. Our findings show that solenoid and EMS feedback can both benefit to enrich VR contents, and EMS can be more effective to induce pseudo pain for first-person experiences.

Chapter 7

Power Distribution through a Potentialized Human Body

This chapter introduces a practice for power transmission. The area has been accomplished both in wearable and cyborg approaches, and this chapter is to clarify the overlaps of applications among the approaches.

7.1 Introduction

A power supply has always been an inevitable element of electric and electronic devices [76, 77]. Many low-power electric devices at home are powered by batteries, e.g., remote controllers, electric toys, and various types of tools. However, using batteries is not always beneficial to the user, since batteries come in a variety of sizes and standards, which makes it difficult for users to find the right type when replacing one.

Although power supplies still have significant issues, an increasing number of electronic devices are becoming popular because of the development and spread of the Internet of Things (IoT) and ubiquitous computing. This also results in an increase of battery power supplies or corded connections to commercial power supplies. Rechargeable batteries are now common for these types of electronic devices; however, they still need to be recharged frequently. Furthermore, lines connected to external power sources may disturb a user's activity or even conflict with other devices because of a limited number of power outlets.

As electric devices have multiplied, their power consumption has decreased. Low-power electronic components, including semiconductors, sensors, and microcontrollers, only consume a few microwatts. As the demands of electronic devices increase, their power requirements will continue to decrease. This will enable the supply of power through various methods, not simply with batteries or commercial power. Moreover, it may also enable devices to become smaller, as the power source is placed outside the device, enabling them to exist passively.

In this chapter, we introduce the concept of human-centered interaction based on power distribution through the human body (Figure 7.1). We present a method for distributing power to low-power electric devices using a common power source. The system enables a user to carry a common power source on his/her body that distributes power by interacting with electronic devices that have no power sources of their own. It is obvious that many low-power electric devices will require interaction from the user in order to activate.

Some researchers have explored battery-free user interfaces that source their power from the physical effort involved or required when interacting with them [131, 321, 11]. These are methods for harvesting energy; however, in this work, instead of harvesting the power, we use power sources existing and held on the body. We always carry some kind of power source, and it is now common, and possibly indispensable, to have smart devices or other wearables (smartphones, smartwatches, or even mobile batteries) with us. We focus on obtaining a radical power source from these devices and supply the power to the target devices via a human-body interaction. Zhang et al. introduced TouchPower [362], which can be positioned as a wearable version of our method. They called the concept, Interaction-based Power Transfer (IPT), which shares a common interest with ours. Therefore, our method can be considered to be positioned in the middle of wearable and cyborg technology, where security and power distributing interaction through signal transmissions with interfaces occur.

To allow the power to safely travel through the user, a high-voltage power source oscillates at a high frequency. The target devices have simple rectifying and regulating circuits, need no internal power source, and therefore remain passive.

Our contributions are summarized as follows.

- We have developed a wearable power source for powering low-power electric devices. The power is supplied through the human body and its interactions; therefore, the electric devices need no internal power sources and remain passive.
- We clarify the safety concerns for using our system and designed the device based on observing electricity passing safely through a human body.
- We present several example applications and scenarios to prove our concept and its feasibility. We show examples of powering electronic devices and paper

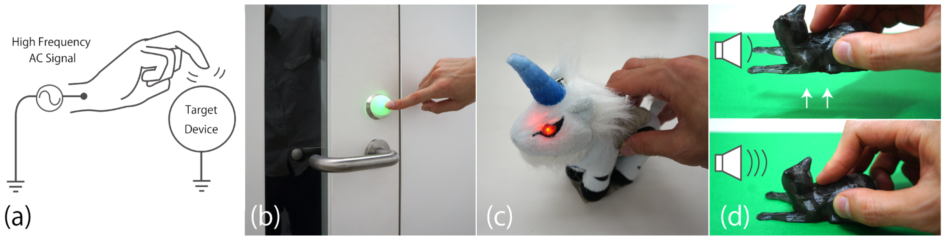

Figure 7.1: Intentiō and its applications: (a) Intentiō enables users to distribute power to electronic devices from power passing through their body. (b) Electronic and IoT devices are activated and powered by power distributed from the user. (c) Electronic stuffed toy activated by the user. The LED eyes emit light when the user touches the toy. (d) The user can adjust the amount of power distributed to the target device. Here, the volume of an electric music box is being adjusted.

crafts/cards, as well as interactions between multiple users, and discuss further possibilities for Intentiō.

7.2 Related Work

We describe related work from two aspects. One is the power-source side. Several researchers have investigated power distribution to passive objects or the collection and harvesting of energy to activate low-powered devices. In contrast, many attempts have been made to apply electricity to the human body. Moving electricity through the human body has been applied for HCI.

7.2.1 Power Distribution and Harvest

When we consider dealing with electric devices, it is important to consider their power sources. Although circuits and wires are now thinner, lighter, and more functional, power sources, e.g., batteries, are still required. Some researchers have proposed solutions by distributing power from external elements [217].

The use of a magnetic field is a major method of transferring power without wiring connections. Magnetic MIMO [114] and PowerShake [344] are devices that charge phone batteries without a direct connection. They use multiple coils and coupling for the power transfer.

Radio-frequency identification (RFID) is also a common solution, and many RFID products have been deployed [215]. RFID technologies enable power to be transferred over a distance. WISP [271], PaperID [158], and RapID [289] are examples of transferring power to an object and enabling input sensing. They use ultra-high frequencies and activate the sensors using the power generated from transceivers, allowing the target device or object to be passive, without any batteries or other direct power sources.

Gathering energy from the environment is also a method of creating power [199]. The usage of microwave oven leakage [137] is an energy-harvesting example of activating low-power kitchen devices with power generated from the environment. Instead of passively gathering the power from the environment, studies that attempt to harvest energy from users' active interaction have been conducted [131, 321, 11, 291, 153]. These studies consider harvesting power from handling and interacting with user interfaces. We also build on these studies' ideas and focus on supplying power when the user interacts with an electric device. However, our work does not harvest power; rather, it uses power sources that exist around the user; e.g., smart devices and mobile batteries.

7.2.2 Human Body and Electricity

There are some notable studies that attempt to use body tissues as conductive leads. Red Tacton [6] and PAN [369] are studies that transmit signals through the body for the use of a communication network. CASPER [325] uses the body as a path to charge wearable devices from charging stations in the environment. Varga et al. [320] studied groundless body channel communication methods and proposed guidelines for future wearable devices.

Although we are aware of many studies that use electricity and apply it to the human body, Corona and the work proposed by Post et al. [243, 242] are the only prior work that is applied for power distribution. We share a common interest with these works; however, we contribute to the research field by proposing further variations of applications and circuit models with our original method, including safety considerations and discussion. We believe that there is plenty of room for further studies, discussions, and applications for power distribution through the human body.

7.3 Power Distribution Through a Human Body

In this section, we present an overview of Intentiō and its operating principles (Figure 7.2). The words *high-voltage* and *high-frequency* are generally used for voltage over 600 V and signals around RF (radio frequency), however, in this chapter, note that we use the words *high-voltage* and *high-frequency* for voltage above 100 V and frequency of around 10–100 kHz to address the difference from requirements of small electronic devices, commercial power supplies (100–250 V, 50–60 Hz), and other research based on signals up to 1 kHz [14, 15]. Power distribution to passive electronic devices through a human body is accomplished through the following steps.

(1) High-voltage and high-frequency AC power is applied to the body through a wearable device that potentializes the user.

(2) The potentialized user touches the target electronic device, and power is supplied to the device by electricity passing through the user's body.

(3) The AC signal received from the user is rectified. The rectified signal is regulated to an appropriate value to activate the device or is otherwise left as a fluctuating signal controllable by the user.

The wearable device that supplies power to the body is powered by a smart device or an external power source. It consists of a transformer that boosts the voltage to a few hundred volts and oscillates the signal at a few thousand hertz. Since the human body is not completely safe when conducting electricity, it was necessary to consider the system's values carefully. We provide a detailed discussion of the safety concerns in the next section, including the reason such high-frequency signals were used. The body acts as a power cable and can supply power to devices by touching or holding them. It is necessary for a user to touch the devices with his/her hands. The activated target device requires no power sources, e.g., batteries or corded connections from power supplies. Instead, it requires a simple electric circuit that will rectify and regulate the power supplied by the potentialized user. The idea is to use a common power source and have each device adjust the power for its own required values. This will help users to more easily manage such devices because they exist passively and can be activated through a single common power source.

Figure 7.3: Intentiō system: (a) The design and size of the wearable device. (b) The wearable device is worn on the wrist, belt, ankle, or inside a shoe. (c) An example design of the receiving circuit. The size is not fixed, and can be designed to be the same shape as a coin cell.

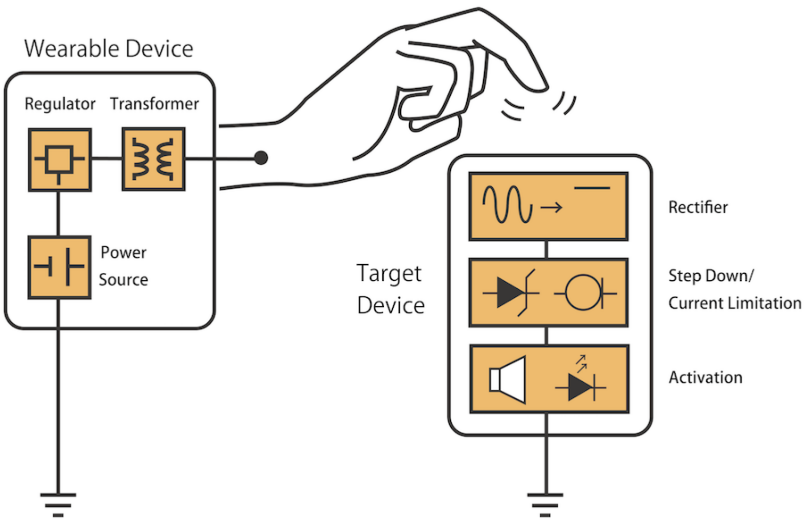

Figure 7.2: Principle of operation. The wearable device converts the original input, which is supplied to the user, to an appropriate power. The user distributes the power by touching the target device, which rectifies and regulates the signal for its activation.

7.4 Safety

The work is conducted by following the knowledge presented in Chapter 2.2 and Chapter 3.

However, as our system is for continuous use, we must carefully discuss safety in such conditions. The main risk of continuous usage of high-frequency power is heating. For example, high-power and high-frequency current is used for electrosurgery [283]. However, this phenomenon is usually considered to occur for frequencies over 100 kHz, and studies report that no established effects are found at lower frequencies [274, 283, 107]. Nevertheless, it is also mentioned that further studies are required and the effects of long-term usage are unknown. Therefore, we must still be careful when using our system continuously, and further research is necessary.

7.5 Implementation of Intentiō

Intentiō's implementation consists of three main features: a wearable power source, a circuit to receive the power from the user, and carefully designed grounding conditions to create a closed-circuit model.

7.5.1 Wearable Power Supply

The wearable power supply (Figure 7.3 (a)) is powered by smart devices or other external power sources. The device can be connected via USB or more direct methods, and direct connection to the battery inside the external power source is required. Since they have different voltage outputs (usually DC 3.7–5.0 V), we first regulate them to 3.3 V. Then, the source is applied to a transformer (LM05100), which boosts the voltage to approximately AC 250 V at 30 kHz. The maximum current at this point is less than 6 mA, and is considered safe to pass through a human body at 30 kHz.

The AC signal is then supplied to the body through an electrode pad. We used an electrode that was originally designed for electric therapy equipment (Omron HV-LLPAD, 98 mm $\times$ 64 mm or cut to half the size, the electrode is washable and reusable). The device must be in contact with the user; however, its location is not fixed and there is a lot of freedom as to where the user can carry it, e.g., on the wrist, in pockets, in shoes, or anywhere else on the body (Figure 7.3 (b)). An electrode can be attached on the back of the device, or it can be extended from the device with an additional wire to enable contact with the body when the device is covered by the user's clothing.

7.5.2 Device Receiver

The target electric device does not need an internal power source; however, it will require a different circuit for activation. High-voltage AC power is first supplied to the device; therefore, we must rectify the signal and step-down the power voltage. It is important to take care not to consume too much current at this stage so that the power will not influence the performance of the device significantly. We used an LM385 (National Semiconductor) for our prototype, which consumes 10 μA at minimum. However, appropriate components must be selected depending on the input voltage of the activated device. An alternative approach is to use a current limiting diode and protect the device from overcurrent. We may also leave the signal to fluctuate and make it controllable by the user for interaction. The circuit can be implemented in various forms. Figure 7.3 (c) is an example of the receiving circuit in a form of a coin cell.

7.5.3 Designing the Grounding Conditions

To activate the target device, the device and user must share a common ground. The user can share a common ground with the device without direct grounding connections because the device can be connected to the ground via an insulating layer (e.g., air, table with an insulated coat). However, the conditions of the user and device, in particular, the impedance of the capacitive links connecting the device to a common ground, crucially influence performance. For example, the performance may change depending on the distance or the insulating material between the device and the ground.

In the following sections, we present example circuit models followed by impedance considerations and performance details of our current prototype.

Circuit Models

Figure 7.4 (a) displays an example circuit model of Intentiō. The user has the Intentiō system in his shoe, where one side of the output is connected to the user via an electrode and the other is connected to the ground. The device side couples its ground to the table, and the table is linked to the ground. Figure 7.4 (b) shows an alternative model in which the grounding is accomplished through the Intentiō device on the user's wrist. A variety of circuit models are available, depending on where the Intentiō device is worn by the user.

Providing a direct connection between grounds ensures more stability and a larger amount of power. We designed our work for safe use under these conditions so we can leave application space for devices that require a larger amount of power. However, creating direct connections via wires may disturb the users; therefore, we focus on the method that does not require directly connected grounds for now.

Capacitive Coupling and Body Impedance

Capacitive coupling with the load and the ground are applied, and the capacitance can be expressed as $C = \epsilon_0 \epsilon_r S/d$, where ϵ_0 is the permittivity of free space, ϵ_r is the permittivity of the relative material (e.g., air or a table), S is the area of the electrode, and d is the distance between the electrodes. The reactance X is $X = 1/2\pi f C$, where f is frequency. Thus, the relation of the reactance to the distance and area of the electrodes can be expressed as $X = d/2\pi f \epsilon_0 \epsilon_s S$.

Although an equivalent model of the body impedance can be expressed as $X_b = -1/2\pi f C_b$ (X_b is the reactance of the body and C_b is the capacitance of the body) [70], considering and estimating the impedance of body precisely is difficult because there are so many elements that influence its value (e.g., voltage, frequency, current duration, contact area, contact pressure, skin condition, moisture level, and current route) [80]. The skin impedance is the most difficult to characterize since it is nonlinear, time-variable, and depends on environmental and physiological factors [259]. However, studies show that skin impedance under high-frequency conditions decreases in value and the total body impedance approaches the internal body impedance [265, 260]. Nevertheless, the impedance is still difficult to estimate.

The total impedance Z_t of the Intentiō circuit model can be expressed as $Z_t = Z_g + Z_i + Z_b + Z_l + Z_{g'}$, where Z_g is the impedance of the device to the ground, Z_i is the internal impedance of the device, Z_b is the impedance of the load, and $Z_{g'}$ is the impedance of the load with respect to the ground. In most scenarios, Z_g and Z_i are constant, therefore, techniques mentioned in REVEL [14] (current sensing the output from the generator) for constant current output may be applied to stabilize the output of Intentiō. However, in our present prototype, we stabilize the power on the receiving device module.

Performance

In the meantime, our system model enables a maximum distribution of approximately 2.0 mA and 5.0 mW. The voltage is not really an issue because the system can supply over 100 V, which is far higher than the requirements of low-power electronics, i.e., the system can activate components requiring up to 100 V as long as the total power requirement remains under 5.0 mW. Nevertheless, note that to allow Intentiō to supply this value, a robust connection is required (e.g., large electrodes or another human body must be used for grounding). Therefore, lower power is supplied in major capacitive coupling grounding conditions.

We will display results of some measurements. In the situation of Figure 7.4 (a), we used an LED (OptoSupply,OSG58A5111A) as a load, which was powered by approximately 2.0 V–2.2 V. The voltage was not fixed, since we attempted to measure the performance of the current value. The LED was loaded on a breadboard with our receiving circuits. No additional electrode was implemented. The table used for the capacitance coupling was 1600 mm x 800 mm, which was made of wood with metallic legs, covered by dielectric material. When the LED board was on the table, the current value passing through the LED was 84.5 μA. However, when the board was lifted up and the distance between the board and the table was 100 mm, the value decreased to 46 μA. The measurement of Figure 7.4 (b) was established with the same board with the LED. When the board was 50 mm away from the device, the current value was 52 μA. The value was 43 μA when the distance between the board and the device was 200 mm. Note that the results may change depending on the body conditions (i.e., the body impedance) as mentioned in the previous section.

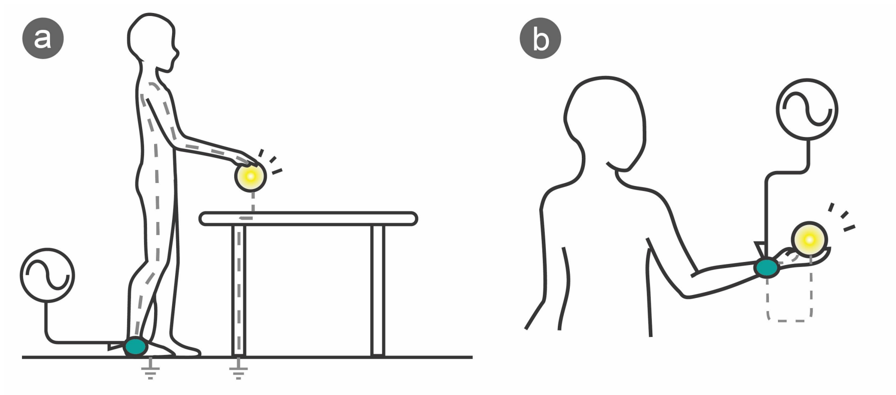

Figure 7.4: Example grounding connections: (a) A user has a wearable device in his shoe and is potentialized. He touches the electronic device and distributes power. The powered device is connected to the ground via the table. (b) A user has a wearable device on his wrist. The power is distributed to the electronic device through the user. The ground of the wearable device and the electronic device is coupled via the air between them.

7.6 Application

In this section, we present several proof-of-concept Intentiō applications. We present examples in which we use the system as a power supply as well as interaction methods that can be applied through our system. The system has the potential to promote communication between multiple users.

7.6.1 Activating Electronic Devices

One of our main purposes is to activate the electronic devices that are increasing in number nowadays, including IoT devices. Many of these devices require low power, and button cells are often used; e.g., the standard discharge current of an LR44 button cell is 0.12 mA (in the case of the Toshiba LR44EC). This is sufficiently low and matches our system's specifications.

Figure 7.5 shows an example of activating a calculator that was originally powered by button cells. We modified the device, removed the cells, and implanted our own power-receiving circuit. Furthermore, two electrodes were added to the back of the device; one the user must touch to supply the power, and the other creates grounding conditions from the floor or table.

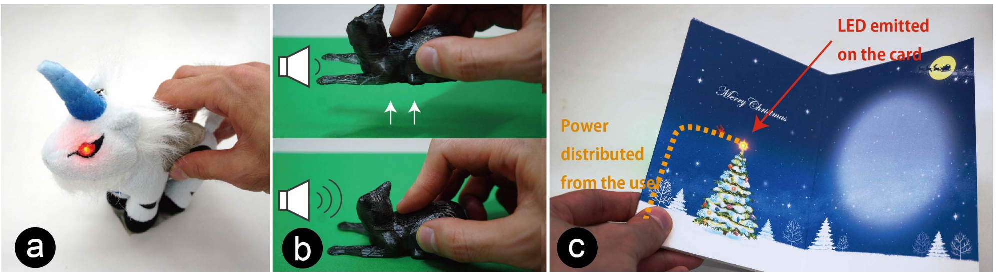

Figure 7.6: Example applications of Intentiō: (a) An electric stuffed toy powered by the user. (b) A music box powered and adjusted by the user. (c) A Christmas card with electric components activated by the user.

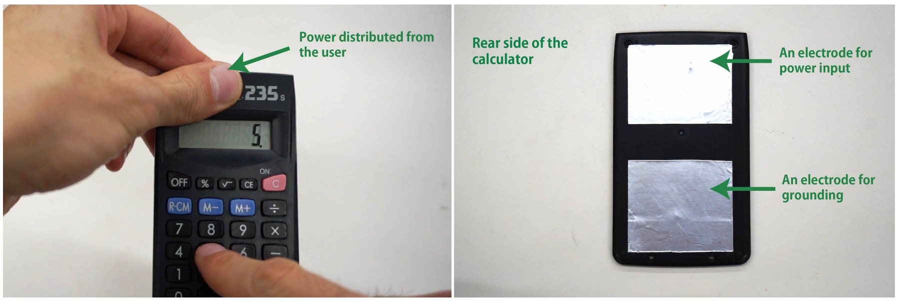

Figure 7.5: Calculator powered by Intentiō.

7.6.2 Interaction for Entertainment

Our system can be used to interact with electronic toys or other entertainment products that have low-power electronic components. Figure 7.6 (a) shows a stuffed toy powered by our system. The toy's eyes (LEDs) light up when the user touches and holds the toy. Instead of stabilizing the power supply, we may leave the signal to vary depending on the grounding conditions. The user can then move the toy up and down to control the brightness of the eyes, since creating a larger gap between the toy and the table will change the power supplied to the toy. This implementation can be also be applied to an electronic music box (Figure 7.6 (b)). The user can switch on the music box and play the music by holding the music box on the table. When the user wants to adjust the volume, he/she can hold up the music box. The volume is related to the height of the music box.

Implanting our receiving circuit into electronic paper crafts [249] or event cards (e.g., birthday and Christmas cards) may be worth considering (Figure 7.6 (c)). Instead of using buttons, sensors, and button cells to activate these types of paper, the user will simply touch the card to simultaneously activate it and act as a power supply. Intentiō can eliminate button cells from these types of low-powered electric elements.

7.6.3 Multiple-User Interaction

We previously mentioned the issue of ground coupling. A human without our system can also act as a good ground connection. One user with our system and another user without it can share a common ground and supply electricity through elements that exist between the two users. Figure 7.7 shows an LED activated by two people. The left user is potentialized by wearing the Intentiō device, and the right user is not potentialized. A potential difference occurs between the users, causing the LED to emit. We assume that these types of interaction methods can be applied to encourage and develop communication, e.g., when users touch or shake hands. Compared with prior research that allows communication and signal transmission via handshaking [6, 369], our system focuses on visible or perceptual application domains.

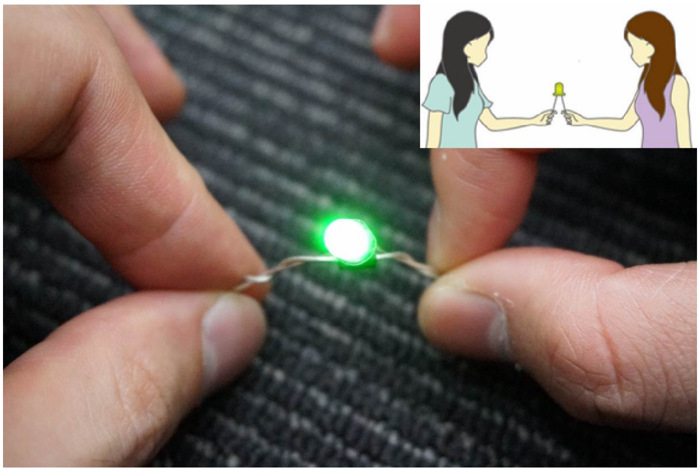

Figure 7.7: Example applications based on multiple-user interaction: An LED emitted by two people. The left user is potentialized by wearing the Intentiō device, and the right user is not potentialized.

7.7 Discussion

Intentiō has several limitations. We will discuss the limitations due to interaction and power. We also introduce our vision for future applications that can be considered by applying our concept.

7.7.1 Interaction Limitation

As the Intentiō system requires the user to directly touch the target device, our approach will not be appropriate for devices that require continuous power supplies. We assume Intentiō will be applied to devices that require human interaction and that do not require continuous power when they are not in use. In addition, the target device's range of operation is limited because of the grounding limitations mentioned in the previous section, i.e., the device cannot be freely held in mid-air. The limitations differ depending on the size of the devices' ground areas. However, we are exploring possibilities by investigating conductive clothing and considering where to place the wearable device.

7.7.2 Current Limitation

Our present implementation enables the activation of certain electronic devices and components; however, some devices will require a larger amount of current. The largest issue occurs from the grounding condition; thus, our circuit model may not be appropriate for such usage. We believe that there is still room to improve our system to increase the available current. To overcome this limitation, we consider connecting the ground of the device and the user via an additional wearable. Figure 7.8 presents a wearable designed for this purpose, where one electrode is extended to the index finger. The power is supplied through the index finger and creates a closed circuit with the user's thumb.

7.7.3 Vision of Future Application

Activating Wearables

As well as activating IoT, UbiComp, and everyday devices, we envision applying our concept to activating wearables. We are aware of an increasing number of wearable devices being developed, including very thin components, circuits, and sheets attached to the skin [335, 129, 357, 342]. Although these types of wearables are naturally worn and attached to the user, they require wires or batteries for the power source, which disturbs the design. Using our system, we can eliminate the wiring or batteries and activate them from the power applied from the skin in specific situations. This will still require some process to the clothing or require limitation of the system position on the user at the current stage.

Signal Modulation

Many applications have been powered using electric signals passing through the body (e.g., Touche [272], Red Tacton [6], PAN [369] etc.). In these cases, high-frequency signals are used to recognize the user's gestures or to communicate with signal transmission. Intentiō does not need to oscillate at a specific frequency; therefore, we can merge techniques from these types of previous research to acquire additional information. This can be applied for security purposes; e.g., a device that only activates when touched by a user with a specific frequency pattern. However, note that additional safety discussions are required before using such higher frequency signals with large current.

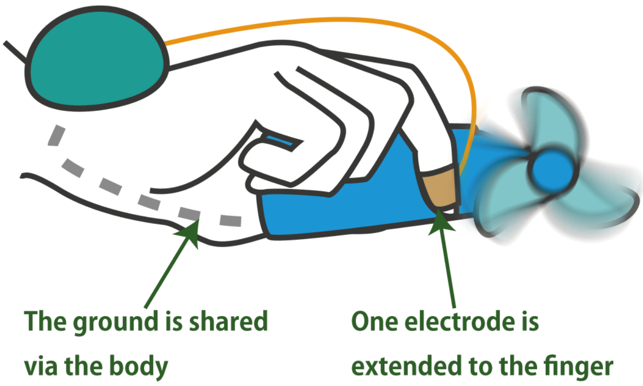

Figure 7.8: Connecting the ground of the wearable device and the electronic device will allow a larger amount of power to be supplied.

7.8 Conclusion

In this chapter, we introduced a concept where a potentialized human body supplied power through their body by interacting with low-powered electric devices. A wearable device that supplies high-frequency AC power to the body was presented, followed by a circuit model to enable the activation of electronic devices without their own power sources.

We addressed the safety concerns that arise when supplying electricity to a human body and presented carefully considered solutions to safely develop and manage our system. Several proof-of-concept applications were demonstrated, including the activation of electronic devices, interaction techniques, and application by multiple users. We discussed the limitations of our system and introduced possible future applications. We believe that a potentialized human body has the potential to augment and diffuse human-centered interaction.

Chapter 8

Discussion

In this chapter, I will give a discussion of how my contributions can increase the acceptance of body hacking. Finally, the limitations of my work are noted.

8.1 Acceptability

Existing techniques that are already deployed include implants such as pacemakers and hearing aids. Approaches that insert artificial things temporary inside the body such as endoscopy [96], are known examples as well. Common topics of such existing techniques are health and life. If the technique is obvious to be necessary for maintaining one's health or life, the technique tends to be more acceptable in society. However, my main interest is to expand the domain of such cyborg approaches, not limited to the medical area. Therefore, I will consider the acceptance from models considered in HCI and related discussions from body hacking.

There have always been discussions about acceptance of technology in many fields, including HCI [145]. When considering acceptance of new technologies, a technology acceptance model (TAM) or an extended version of it, is often used for the validation. TAM was first proposed by Davis in 1985 [41]. Since then, the model has been explored and expanded through various aspects [142]. For example, there is research for TAM focusing on wearables [81] or aesthetics of fashion [316]. Figure 8.1 shows the categories of how the TAM has been modified in the past years.

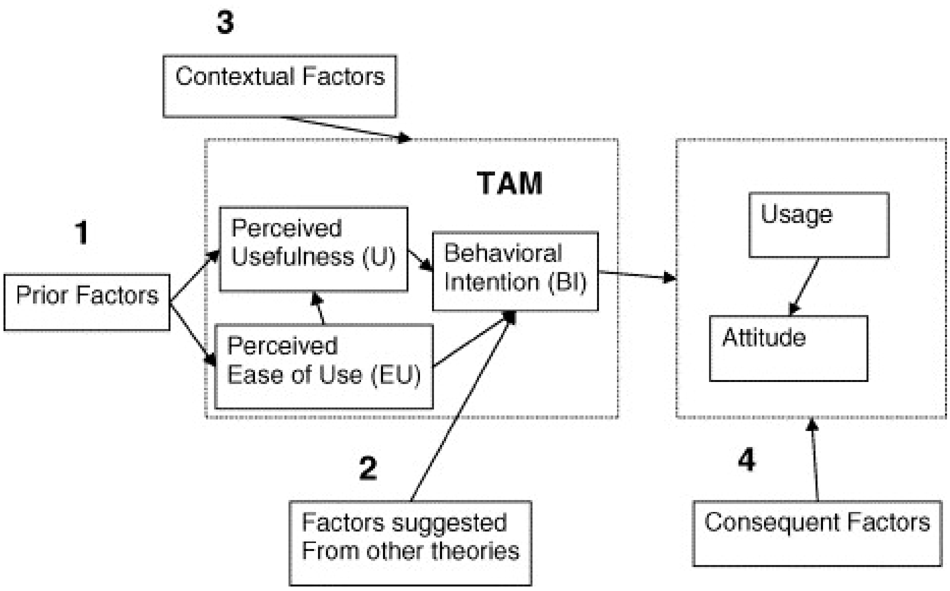

Figure 8.1: Technology acceptance model (TAM) and four categories of modifications. This figure is adapted from King et al., 2006. Figure 1 [142]. (1) The inclusion of external precursors (prior factors) such as situational involvement, prior usage or experience, and personal computer self-efficacy. (2) The incorporation of factors suggested by other theories that are intended to increase TAMs predictive power; these include subjective norm, expectation, task-technology fit, risk, and trust. (3) The inclusion of contextual factors such as gender, culture, and technology characteristics that may have moderator effects. (4) The inclusion of consequence measures such as attitude, perceptual usage, and actual usage.

From the TAM, we can see that behavioral intention (BI, Acceptance) is influenced by the perceived usefulness (U), as well as the perceived ease of use (EU). For other factors, there may be parameters such as safety, risk, emotions and so on. Reinares-Lara et al. [261] studied the effect of ethics on neural implant acceptance (a cyborg approach). In the study, the results revealed that the attitude towards ethics influences the intention of using the technology. However, while the results show that positive and negative emotions affect the intention of use, anxiety was found to be not effective. In this case and other cases that studies the effect of risks, they usually do not mean the safety against health but mean the anxiety and risks against security aspects. Therefore, I still believe that contextual factors regarding medical safety are significant topics since it may result in danger [225]. In contrast, Park [225] says that most people react to the approach of merging technology to humans by “fear” because the body integrity could be impaired. However, Park further indicates that this is not a serious problem since there has been a culture of non-medical body modifications (e.g., tattoos) in society. Taking this prior analysis, I conclude that in order to increase acceptance of body hacking technology, it is important to clarify the safety against potential danger, and to clarify the benefits, which are usefulness and presentation of applications. "Why" does it have to be an implant. Clarifying the necessity of implants is important. At the same time, this means that a majority of the attempts may be achieved by hybrid or wearable methods, including electrical body hacks.

In case of electrical body hack, even though the human body is naturally potentialized by some electric signals (e.g., from commercial power supplies), some users still have concerns about applying electricity on their bodies. Therefore, addressing the safety discussions and presenting safety guidelines for usage will be important and will help users increase the acceptability. This is why we started to discuss and clarify the safety aspects of electrical stimuli in HCI and related fields. Helping people to understand the threats and the safety of such approaches will possibly reduce the potential fear and hate for applying electricity to the body. In addition, discussing application domains will also help our system's acceptance. Clarification of the results and applications that would benefit from the system is required.

One significant benefit of cyborg approaches is its "mobility." A successful technology that is integrated into the body will result in high mobility. As we can imagine that a small and comfort device can be more acceptable, in contrast, a system lacking mobility may become unacceptable. In the future, if we successfully overcome the issues and increase the acceptance of cyborg technology, I envision that the acceptance of body hacking technologies will change, where cyborg technology will become more acceptable than wearables. This is because a wearable or mobile device may be just bothering to carry, or to wear [96]. The ultimate goal of cyborgs, will be where the technology becomes invisible and not notable, which will fit well into the context of ubiquitous, calm and ambient computing [337, 338]. On the other hand, there are still advantages for approaches using surface electrodes. For example, Kevin Warwick states that FES approaches are a lot safer, and are more robust against noise, while implants directly connected to nervous-systems require micro-volt signals that are more easily affected by noise [331].

There is an interesting hybrid approach, which is known as "The North Sense [37]." The North Sense is a device that notifies the user when they face the "north," i.e., is a human integrated compass. The interesting point about the device is where it has a base implanted inside the body, and the actual digital device is attached on to the base over the skin (Figure 8.2). The approach overcomes several issues, including safety and power sources. In the meantime, this method may be an alternate way to bridge the gap between wearables and cyborgs.

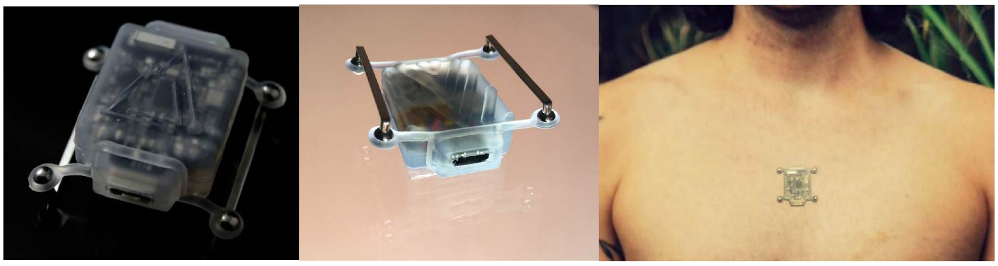

Figure 8.2: The North Sense Product [37]. The sensor vibrates when the user faces the north, and indicates the direction he/she is facing. The main device is attached to the body over the skin to the implanted attachments.

Body modification, originally considered by Fakir Musafar and called as "modern primitive [341]," was a counter-culture movement that includes body piercing and body suspension rooted in ethnic activities [179]. However, body modification is not always a counter-culture movement anymore, and can become popularized in the society for future human-computer interaction. There are still notable obstacles that we must tackle, which includes not only safety but for law maintenance or historical culture and religion.

8.2 Aesthetics

Aesthetics is an important interest for body hacking research and deployment. This is because it is obvious that there are many people are actually modifying their bodies for aesthetic purposes [225]. Examples are *piercing* - where a hole is opened on the body to pierce and attach an accessory, *tattoo* - where inks are implanted into the skin, and *cosmetic surgery* - where various methods are applied in order to deform a certain part of the body. In this sense, modification of the human body can be thought acceptable for people who have motivation for aesthetics. In fact, there are many approaches that build computational elements on the skin that contributes to aesthetic aspects [129, 335, 357].

In the case of electrical body hacks, improving the design and visual product of the electrodes can be thought to be significant. Despite the functional developments on the topic, aesthetic efforts seem to be left behind. Therefore, this is a significant point that should be considered for future work.

8.3 Limitations

There is a limitation in the aspect of the time axis for my work. Through the review of electric safety, we found many elements that are still unclear. In cases for continuous and longtime usages, the safety and threats were not clarified, and discussions are still undergoing, where there are researchers arguing safety and danger from both sides. It seems a difficult and challenging topic to clarify this point, since it may be difficult to provide reasonable evidence, regarding long time exposure. In addition, our individual work did not explore continuous usage, which also requires additional consideration to be generalized for a longer time span.

As I indicated in Chapter 1, this thesis do not cover biohacking. However, I believe that this domain is important when considering human augmentation. This domain will hopefully require additional and different discussions, regarding the ethics resulting from the approach (e.g., how can clones be acceptable?).

Human augmentation/enhancement are reached by dealing with various abilities [332], which includes not only bodily interaction but for intelligence. We do not cover artificial intelligence (AI) or brain stimuli but for a limited condition.

I have discussed the acceptability of the work by referring to other related discussions and models such as TAM. However, I have not evaluated whether my work has quantitatively affected the acceptance, which will require a long time observation to measure the effect.

8.4 Findings

Through the studies in this thesis, I noticed several findings that can be important for designing and demonstrating electrical body hacking systems.

As like I noted in the previous section, aesthetics of the system may be important. The aesthetics, or the design of the systems can affect the acceptance of users. For example, users may find naked circuits unacceptable. Although prototypes can be used in this way for convenience, the appearance of the system will influence the confidence. In addition, naked circuits can be unsafe. When users accidentally make contact with the circuit, they can get shocked or electricity may pass through unintended paths. Therefore, it is recommended to consider the appearance and design of the system you develop.

Another point that I would like to note, is the methodology of demonstrating electrical body hacking systems. It is great to first demonstrate with your own (the person who is demonstrating) body, and on a popular body part for the user (the person who is experiencing the system). Demonstration using your own body can lead to an increase of acceptance, where people observing that can understand the system to be safe and harmful. Another technique is to use the system with high amplitude or density with your own body. I think this can increase the acceptance of users to experience the system with a lower amplitude or density for their initial trial. Starting with a lower level compared to the demonstration with your own body, will reduce the hurdle for using the system. However, note that when conducting a study for research purposes, due to the effect for biases, this cannot be done.

Through my experience of EMS, and from some comments I received during my work, I noticed a technique to improve the experience and to decrease the uncomfortableness. This is, when the stimulation is activated, you voluntarily move the relative body part by yourself and support the muscle activation and movement. I think of this as a kind of *Ukemi*, which is originally a judo falling technique to fall safely. This kind of interaction between human and electrical body hacks, is an interesting future domain, which I think is a kind of human-computer integration.

Chapter 9

Conclusion

This thesis challenges to bridge the gap between wearable and cyborg technologies. There is a significant interest on "hacking" the body, and to implant computer technology inside the body since it has several benefits including mobility. However, this approach tends to face acceptance issues, due to safety and social acceptance issues. In order to contribute to the acceptance of such methods, I worked on "electrical body hacks" where surface electrodes are used to input artificial electric signals into the body for human augmentation purposes. I presented some practice of electrical body hacks, to reveal the potential and availability of the approach and to provide an experimental platform for developers and users.

In general, there are several concerns for electrical body hacks, which includes safety and fear of application on unacceptable body areas and signals. Therefore, we started by clarifying safety knowledge of electricity applied to the human body, and presented a guideline to serve as a literature for future development.

To explore the potential and acceptability of electrical body hacks, and to increase the availability of the method, we designed a toolkit for electrical muscle stimulation with multiple channel output. As a result, the toolkit found a significant demand for human augmentation purposes. We consider that this contributed to further deployment and acceptance for electrical body hacks.

We further presented a practice on the face where potentials were revealed for electrical body hack on socially unacceptable body parts. In the practice, electrodes were attached to the users face to manipulate facial parts computationally, in order to simulate emotional experiences.

A common application domain for mobile, wearable and cyborg technology is for communication with electrical components. Therefore, we have attempted to work on an approach for power distribution and communication via electricity applied to the human body. This practice was to show that electrical body hacks may share common interest among wearable and cyborg attempts.

Finally, I discussed how my work can contribute to the increase of acceptance of electrical body hacks and for future cyborg research. I discuss limitations of my approach and presented potential future work in the field. I also shared some findings that I realized through my work, which I think can contribute as guides for demonstrating electrical body hacks and to present future directions.

This thesis provides an experimental platform constructed with my practices and discussions, which includes a design guideline, a prototyping tookit, and example applications. Through this experimental platform, I envision future development and research of body modification to be more safe and acceptable for human augmentation.

Appendix A

Design Guideline for Designing Safe Systems that Apply Electricity to the Human Body

A.1 Design Guideline

This appendix presents a guideline for developing safe systems that apply electricity to the human body. Future researchers may refer to this guideline to discuss the safety of their system.

The following points are significant elements that a researcher must consider when applying electricity to the human body.

A.1.1 Elements

The following list is an overview of elements that are required to be considered.

- Current (A): The main risks arise from the amount of current.
- Frequency (Hz): Low AC frequencies are especially dangerous.
- Path: The threshold of safety becomes serious when the signal passes across the heart.
- Time: Long period usage may lead to low-temperature burns or health risks.
- Health conditions: Signals may disturb or exacerbate health conditions or electronics.

Consideration of the current is the most important factor. The heart of the human body may be affected by strong currents passing through the body. There are several risks, and there are several threshold levels provided [104]. A muscular contraction can occur, as well as a difficulty in breathing. Serious risks include breathing arrest, burns and even ventricular fibrillation. These risks are observed mainly for signals below 100 kHz. For signals over 100 kHz, there are generally no stimulation effects, however, it becomes necessary to consider thermal effects [107].

A.1.2 Testing on the Human Body

Health Concerns

When conducting user studies or examinations, you must pay careful attention to the user's health conditions. The followings are example conditions to take care.

- Heart concerns (do NOT use)
- Pregnancy
- Epilepsy
- Cancer
- Recent surgery
- Sensitive skin
- Skin disease

It is a good idea to obtain permissions from doctors and to have an external oversight for the study.

Agreements and Responsibility

Collection of agreements for the study and a liberty waiver is recommended. This ensures that the state of the users' health is clear and that concerns about system safety are understood. These are important to control the risks for both the researcher / developer and the users.

A.1.3 Values

Sensing / Transmission

The literature on *sensing* does not generally provide discussion on safety. Such studies typically involve the use of high-frequency signals ranging from 1 kHz to 60

GHz, which have a low risk for electric shock. In the use of electric signals for *sensing*, low current magnitudes are needed (typically, a few micro-amperes). As long as the signal does not exceed 0.1 mA, the current is considered to be safe [58]. However, most currents up to 0.5 mA can also be considered safe in many conditions (as long as the electrodes are NOT attached anywhere near the heart) [104, 107].

Actuation

When EMS electrodes are treated appropriately, they do not pose a serious hazard risk. However, incorrect or high-power signals can cause pain or fatigue, as well as burns when used for a long duration. Typical electrode parameters include pulse widths of 30–800 μs [231], frequencies of 1–150 Hz [231], and currents of 10–30 mA (currents above 40 mA can stimulate pain receptors) [231], and the maximum recommended current output is 100 mA [305, 169].

Perception

Stimulating Organs To stimulate organs, currents of up to 3 mA are typically used [8, 93, 318, 126]. These values are applicable to stimulation around the face and for haptic applications. Note that, in such applications, the signal does not pass through the heart but applied to a limited body area in a short distance.

Tongue (Gustatory) The tongue is a damped area of the body and therefore has lower impedance and requires more careful treatment. Stimulation of taste sensation appears at 4–400 μA [204]. For example, currents of 20–200 μA [252] and 250 μA [203] have been used in prior work. Different currents and frequencies are used for different taste types.

Other Applications

In applying electricity to the human body for the purpose of new and/or challenging research, the electrical signal must be treated carefully. The current value and frequency are essential elements for consideration. In general, currents of up to 0.5 mA are thought to be safe independent of the frequency. When a larger magnitude of the current is required, the frequency must be increased. When the frequency is between 2.5–100 kHz, the maximum current should be limited to $0.2f$ mA and 20 mA when above 100 kHz (f is the frequency in kHz) [107]. However, the values must be decreased when the electrodes form a current path which directly passes and significantly affect the heart (we generally do not recommend using systems this way). Note that when using strong signals at high frequencies, it may be necessary to consider the effects of electric and magnetic fields.

A.1.4 Notes

- The current limitation of signals that pass through the heart may slightly change.
- There are still unknown risks in applying electricity to the body. Therefore, it is recommended that no signal be applied continuously without a reason for doing so.
- The body's electrical characteristics differ from person to person.
- The referred literature for the proposed guideline may be updated.
- Refer to main article for more detailed description.

Table A.1: Overview of signal values for various applications.

	Maximum Current	Frequency, Pulse Width	Paths
Sensing / Transmission / Other Application	0.5 mA	up to 2.5 kHz	Variable
	$0.2f$ mA	2.5–100 kHz	Variable
	20 mA	over 100 kHz	Variable
Actuation Muscular Stimulation	100 mA (30 mA will generally be enough)	1–150 Hz, 30–800 μs	Short path of the same body part
Stimulating Organs	3 mA	Variable	Short path of the same body part
Gustatory	400 μA	Variable	Tongue

Note: f is the frequency in kHz.

Appendix B

Circuit Design for EMS

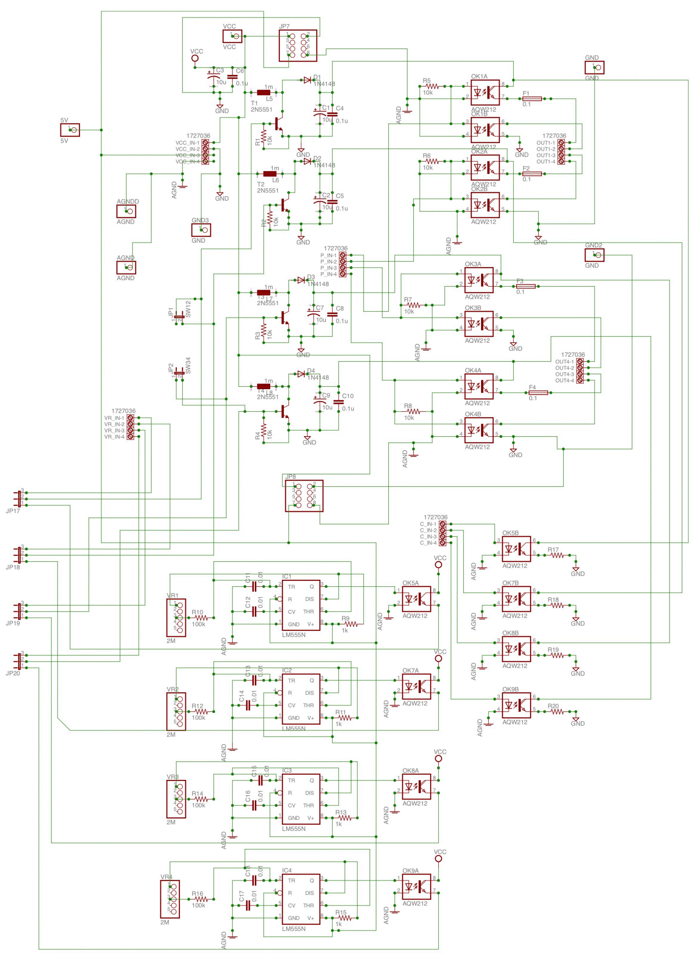

Figure B.1: The circuit design of the toolkit used in the thesis.

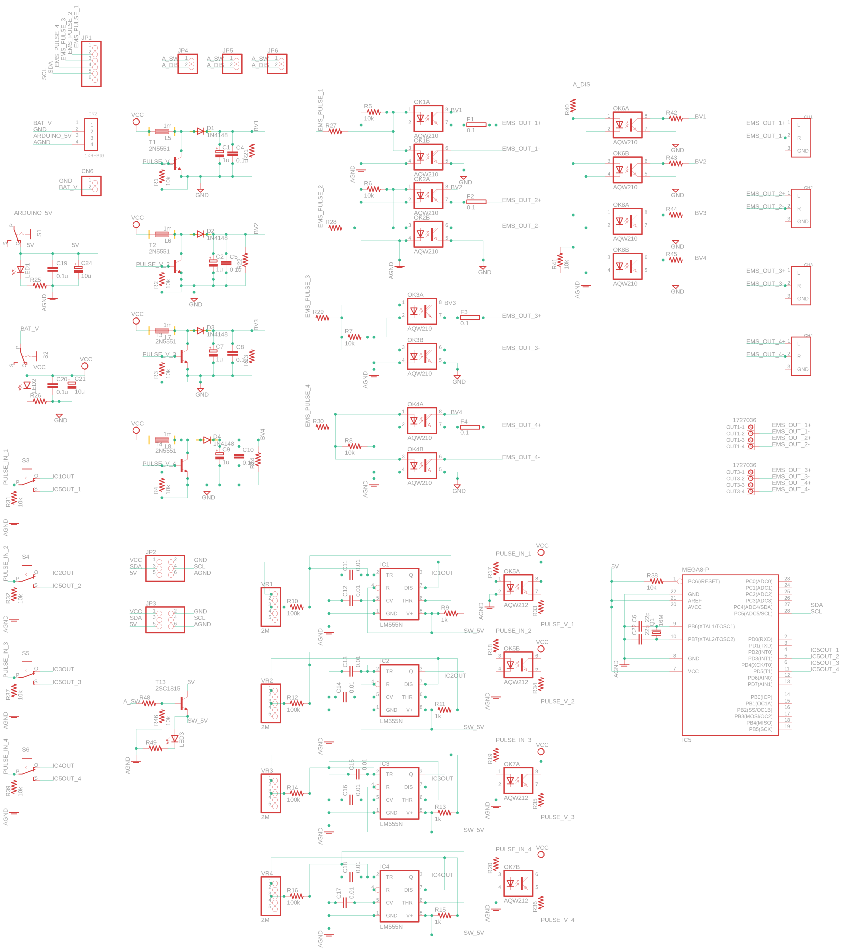

Figure B.2: The improved circuit design of the EMS toolkit.

Appendix C

Effect of Electrical Muscle Stimulation and Electrode Placements on the Face

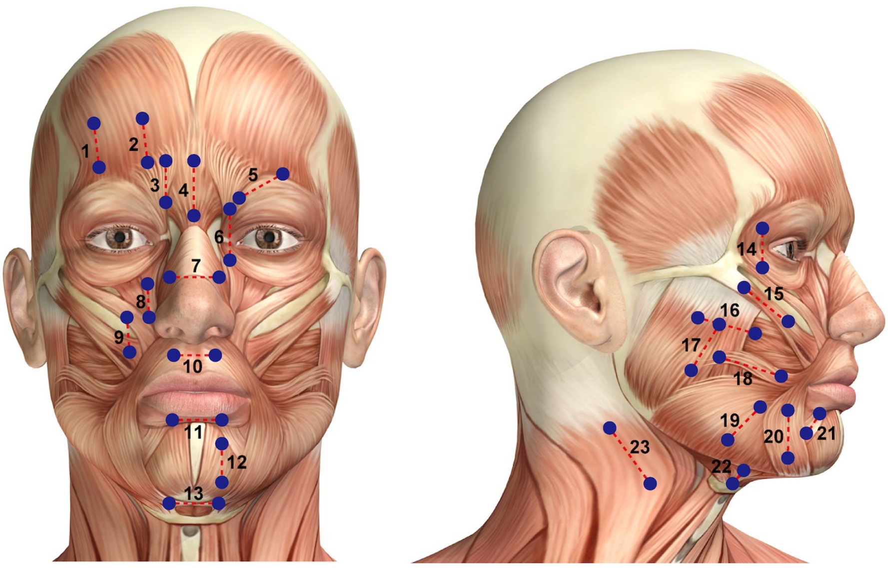

Figure C.1: The positions of the muscles and the appropriate position of the electrodes are displayed. The blue dots are the electrodes, and the red lines indicate the route of the current path of the electrode pairs. (We do not display the electrodes on both sides of the face for muscles that are located symmetrically on the face.)

Corresponding Number in Figure C.1	Muscle Name	Muscle Location	Effect of Stimulation
1	Frontalis	Both Sides	Raising the outer side of the eyebrows
2	Frontalis	Both Sides	Raising the inner side of the eyebrows
3	Depressor Supercilii	Both Sides	Lowering the eyebrows
4	Procerus	Center	Lowering the eyebrows
5	Corrugator Supercilii	Both Sides	Raising the eyebrows
6	Orbicularis Oculi	Both Sides	Closing the eyes
7	Nasalis	Center	Moving the eyebrows towards the nose
8	Levator Labii Superioris	Both Sides	Lowering the eyebrows
9	Zygomaticus Major and Zygomaticus Minor	Both Sides	Raising the mouth
10	Orbicularis Oris	Center	Shrinking the upper lip towards the center
11	Orbicularis Oris	Center	Shrinking the lower lip towards the center
12	Mentalis	Both Sides	Moving the mouth angle downwards
13	Mylohyoid	Center	Opening the mouth
14	Orbicularis Oculi	Both Sides	Closing the eyes
15	Zygomaticus Major	Both Sides	Closing the eyes
16	Buccinator	Both Sides	Raising the mouth angle
17	Masseter	Both Sides	Mastication
18	Risorius	Both Sides	Pulling the face sidewards
19	Platysma	Both Sides	Lowering the mouth angle
20	Depressor Anguli Oris	Both Sides	Lowering the mouth angle
21	Depressor Labii Inferioris	Both Sides	Lowering the mouth angle
22	Digastric Anterior Belly	Both Sides	Lowering the mouth angle
23	Sternocleidomastoid	Both Sides	Rotating the neck

Table C.1: Overview of facial muscles and their reactions against EMS. We present 20 variations of muscles than can be stimulated by EMS. Some muscles are located on both sides of the face, which can be stimulated simultaneously to provide a symmetrical output. Here we present the name of the muscle as well as the effect that can be observed when they are stimulated. Priorly, Elsenaar [63] presented a table based on Ekman's facial action codes [62]. However, this table is based on knowledge from experiments conducted by ourselves.

Appendix D

History and Parameters of Electrical Muscle Stimulation

The history of EMS is rooted from 1791, when Luigi Galvani used electric current to cause a muscle of a frog to constract [20]. At this time the mechanism was still unknown, however, attracted a great scientific interest, and was studied through the 1800's to reveal the principles [19]. In 1903, Prof. Leduc introduced a form of electric current to minimize the energy for muscle contraction [190]. This was where the pulsed inputs that are still used nowadays, were investigated and applied for muscle stimulation. For the experiments, an anaesthetized cat was used to observe the effect of stimulation [190]. The terms "Chronaxie" and "Rheobase" was first stated in Lapicque's paper in 1909 [110]. These terms are used to discuss the relationship between the strength and duration of a rectangular pulse and it's threshold (Figure D.1). Later in 1977, "Russian currents" have been reported by Yakov Kots [327]. Russian currents consist of 2.5 kHz AC signals that are burst modulated at 50 Hz with a 50 % duty cycle. Although this seemed to be an effective method for electrical stimulation, it is now been studied to be inferior to other types of signals [19]. Since then, various research with various signals has been conducted and may devices have been created for rehabilitation and training purposes [162, 301].

When using EMS, considering the type of signal is an important element. There are studies that have compared various types of waveforms (Figure D.2). Araújo et al. noted that square waveforms can be more uncomfortable compared with triangular and quadratic waveforms [9]. Laufer et al. said that monophasic and biphasic signals have an advantage over polyphasic waveforms (2.5 kHz) regarding the generated fatigue [155]. Petrofsky et al. compared sine, square and the Russian waveform, and

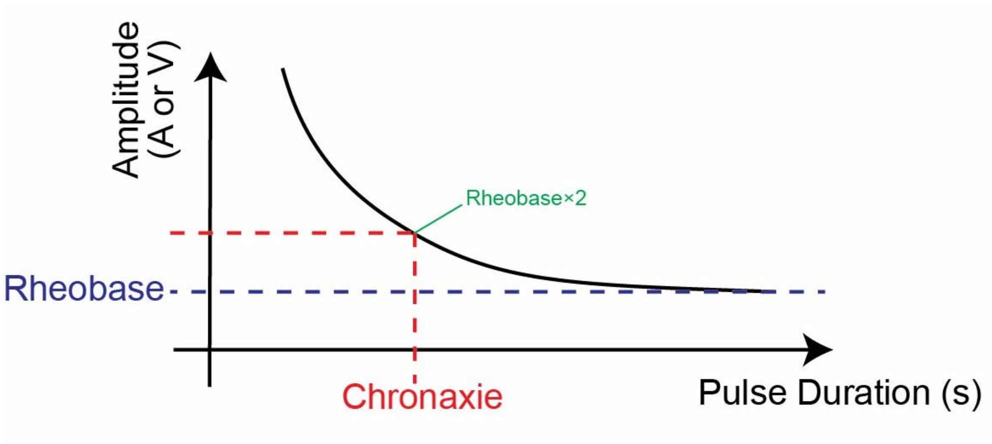

Figure D.1: Chronaxie and rheobase are points on the amplitude-duration curve for stimuling tissues/nerves.

found that sine waves were found to be the less painful, still having a greater muscle strength [230]. Prausnitz presented a review for the effect of the current applied to the skin [246]. For interactive usecases, Knibbe et al. concluded that various parameters can be explained differently when experienced [143]. Other considerations include the electrode size that also may influence the stimulation of EMS [178]. Researchers should carefully consider the parameters for their purposes.

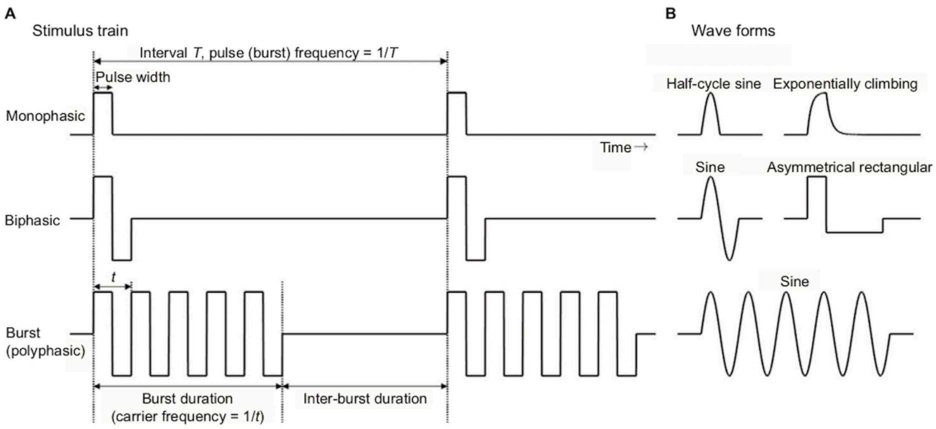

Figure D.2: Figure adapted from Takeda et al.'s article (Figure 2) [301].Parameters of NMES. (A) Monophasic, biphasic, and polyphasic stimulus train. (B) Examples of wave forms. A specific stimulus, burst sine wave of carrier frequency of 2,500 Hz and burst and inter-burst duration of 10 ms is called a Russian current. Author notes: there are also other waveforms considerable, such as triangular waves [9].

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