UBIQUITOUS HAPTIC FEEDBACK IN HUMAN-COMPUTER INTERACTION THROUGH ELECTRICAL MUSCLE STIMULATION

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Abstract

Humans perceive the environment through their senses. Computer systems stimulate these senses with different output technologies to present and transmit information to users. The visual, auditory and haptic senses are the most important senses for human-computer interaction (HCI). When one of these senses is missing, the interaction with our environment often feels awkward or not real. Computers pervade our environment and are ubiquitous nowadays. The output devices that stimulate our senses have become more and more integrated in our environment. The main reason for this is the so-called trend of miniaturization. Technologies to stimulate the visual and auditory senses have already shrunk to a small size and have reduced power consumption. Displays have been reduced in size from the large CRT display to LCD/LED flat screens, and become mobile in smart phones and wearable in smart watches and were most recently integrated within textiles. Haptic feedback technologies have found it hard to follow this trend in all variations, with regard to mechanics, joints or motors that stimulate the haptic sense. We call haptic feedback that is always available *ubiquitous haptic feedback*. In this work we define criteria that technologies need to satisfy in order to achieve ubiquitous haptic feedback, such as a wide feedback range and the potential to follow the trend of miniaturization. Electrical muscle stimulation (EMS) uses a small current to activate the muscle power of the user. It has long been used in the context of medicine, physiotherapy and fitness. EMS technology has the potential to shrink to a small size and to be integrated in wearable devices and even integration in textiles is possible.

In the context of human-computer interaction, EMS feedback is still in its infancy. Prior research projects contributed a large initial effort to understanding the technology and to developing customized hardware and software to apply EMS feedback. These factors raise the entrance hurdle and make fast prototyping of new ideas difficult. To face these challenges and to achieve ubiquitous haptic feedback through EMS the *Let your Body Move* toolkit for EMS-based prototyping was developed. The toolkit consists of methods, hardware and software components that we made available through open source. It is designed for an easy integration into existing ubiquitous components and is also wearable. The toolkit is used to build several prototypes to investigate different aspects of ubiquitous haptic feedback through EMS, namely: haptic feedback to extend virtual objects with physical properties for (1) *EMS-based free-hand interaction* and (2) *EMS-based target selection*, haptic manipulation of users in everyday scenarios (3) *actuated navigation* and (4) *embodied emotional feedback* to extend the communication of two partners with immersive haptic feedback.

For (1) *free-hand interaction* the users' hands should not be covered with additional feedback devices. If EMS force feedback is applied to a different position, then the effect is perceived. The feedback is applied to the lower arm to actuate the hand. Moreover, EMS technology is lightweight and does not interfere with the user's movements. In (2) *3D hand target selection* users need to control the finger precisely in three degrees of freedom in mid-air. In contrast to 2D target selection, in 3D there are issues with regard to stereo viewing or to occlusion of targets with body parts of the user. Additionally selection feedback can reduce the selection errors, average movement time or can increase the selection throughput. Haptic feedback makes the target perceivable even when it is not visible. (3) *Actuated navigation* is an approach to guide pedestrians to their destinations to reduce visual distraction and cognitive load. In mobile scenarios users are often distracted when they interact with their devices. A voluntary force can guide the user in the right direction to avoid obstacles or to find the right path to the destination. EMS feedback can influence the locomotion system to change the walking direction, supporting the user to solve the navigation task. Finally, (4) *embodied emotional feedback* is an approach to connect remote partners together in an immersive way. It senses the emotional state of the sender implicitly through EEG (electroencephalography), transmits the state to the remote living partner who is actuated to perform representative body language. EMS actuates the body of the receiver to perform different gestures and let the receiver's body become the output device. The main contribution of this dissertation can be divided into two parts. On one hand, there is the developed toolkit with the presented methods and the hardware and software with the sample implementations of the application scenarios. On the other hand, different aspects of the ubiquitous haptic feedback approach through EMS are investigated in the context of HCI as discussed above. Over all, this thesis forms a basis of EMS as haptic feedback method for future research and establishes EMS feedback in the context of HCI.

Key words:

Human-computer interaction

ubiquitous haptic feedback

electrical muscle stimulation

Zusammenfassung

Menschen nehmen ihre Umgebung über ihre Sinne wahr. Computersysteme bedienen sich dieser menschlichen Sinne und stimulieren sie mit unterschiedlichen Feedback- bzw. Ausgabetechnologien, um Informationen darzustellen und dem Benutzer zu übermitteln. In dem Bereich der Mensch-Computer-Interaktion werden primär die visuellen, auditiven und haptischen Sinne des Menschen stimuliert. Wenn einer dieser Sinne nicht angesprochen wird, fühlt sich die Interaktion mit der Umwelt für den Menschen oftmals unpassend oder nicht real an. Unsere Umgebung ist heutzutage durchdrungen von Computern. Ihre Anwesenheit ist allgegenwärtig. Ausgabegeräte, die unsere Sinne stimulieren, werden seitdem mehr und mehr in unsere Umgebung integriert. Möglich gemacht wird dies vor allem durch den Trend der Miniaturisierung. Technologien zur Stimulierung der visuellen und auditiven Sinne sind bereits stark verkleinert worden. Auch der Stromverbrauch konnte erheblich reduziert werden. Aus herkömmlichen Röhrenbildschirmen wurden Flachbildschirme, Displays konnten in Form von Handys mobil und in "smarten" Uhren tragbar gemacht werden. Mittlerweile werden sie sogar in Textilien integriert. Haptische Ausgabetechnologien haben es bisher schwer, diesem Trend zu folgen, da sie Mechanik, Gelenke und Motoren verwenden, um den haptischen Sinn zu stimulieren. Dies verhindert eine allgegenwärtige Verfügbarkeit von haptischen Feedbacktechnologien und beschränkt ihre bisherigen Anwendungsbereiche. Haptisches Feedback, das für den Benutzer immer verfügbar ist, bezeichnen wir als *ubiquitäres haptisches Feedback*. In dieser Arbeit werden Kriterien definiert, die Ausgabetechnologien haben müssen, um dieses ubiquitäre haptische Feedback bereitstellen zu können. Zu diesen Kriterien gehört unter anderem, dass eine solche Technologie eine große Bandbreite an haptischer Ausgabe breitstellen muss und das Potential hat dem Trend der Miniaturisierung folgen zu können. Elektrische Muskelstimulation (EMS) verwendet einen geringen Strom, um die Kraft der Muskeln zu aktivieren. Sie wird schon seit einer längeren Zeit in den Bereichen der Medizin, Physiotherapie und Fitness eingesetzt. Die EMS-Technologie hat das Potential, seine Größe zu dezimieren und in tragbare Geräte integriert zu werden. Auch die Integration in Textilien ist bei dieser Technologie möglich.

Im Kontext der Mensch-Maschine-Interaktion steckt EMS-Feedback immer noch in seinen Kinderschuhen. Der Ansatz der elektrischen Muskelstimulation musste für andere Forschungsprojekte aus den bisherigen Anwendungsgebieten transferiert werden, um passende Hardware und Software für die Anwendung von EMS-Feedback zu entwickeln.

Dadurch wurde die Eingangshürde im Umgang mit EMS-Feedback angehoben und erschwerte ein schnelles Prototyping. Um diesen Herausforderungen gerecht zu werden und um ein ubiquitäres haptisches Feedback durch EMS bereitzustellen, haben wir das *Let your Body Move-* Toolkit für EMS basiertes Prototyping entwickelt. Das Toolkit besteht aus Methoden, Hardware- und Softwarekomponenten, die Open Source verfügbar sind. Es wurde für eine einfache Integration in existierende ubiquitäre Komponenten konzipiert und darüber hinaus tragbar gemacht. Das Toolkit wurde verwendet, um eine Vielzahl von Prototypen zu entwickeln, die zur Erforschung von Aspekten des ubiquitären haptischen Feedbacks eingesetzt werden. Dazu wurden die folgenden Anwendungsbereiche ausgewählt, um das ubiquitäre haptische Feedback von unterschiedlichen Perspektiven zu beleuchten: (1) *EMS-based free-hand interaction*, (2) *EMS-based target selection*, (3) *actuated navigation* und (4) *embodied emotional feedback*.

Bei dem Anwendungsbereich der (1) *free-hand interaction* werden virtuelle Objekte mit physikalischen Eigenschaften durch haptisches Feedback erweitert. In diesem Szenario sollen die Hände des Benutzers in Interaktion mit großformatigen Bildschirmen frei von zusätzlichen Ausgabegeräten interagieren können. Dazu kann EMS-Feedback an einer anderen Stelle appliziert werden, als es wahrgenommen wird. Feedback, das am Unterarm angelegt wird, wirkt sich so zum Beispiel auf die Hand aus. Des Weiteren ist die EMS Technologie sehr leicht und stört den Benutzer bei normalen Bewegungen nicht. Bei (2) *EMS-based target selection* in 3D müssen die Benutzer bei der Auswahl derartiger virtueller Objekte ihre Finger über drei Freiheitsgrade im freien Raum sehr präzise bewegen. Im Gegensatz zu einer Interaktion in 2D ergeben sich hier Problematiken durch das stereoskopische Sehen und durch die Verdeckung von Objekten durch den Benutzer. Zusätzliches Feedback bei der Auswahl von Objekten kann die Auswahlfehler und die durchschnittliche Auswahlzeit reduzieren und den Auswahldurchsatz erhöhen. Das untersuchte haptische Feedback macht die Ziele spürbar, auch wenn sie nicht sichtbar sind. Ein weiterer Anwendungsbereich beschäftigt sich mit der haptischen Manipulation des Benutzers in einer alltäglichen Situation. (3) *Actuated navigation* ist ein Ansatz zum Leiten von Fußgängern. In Navigationsszenarien sind Benutzer oftmals abgelenkt, wenn sie mit ihren mobilen Geräten interagieren. Eine manipulierende Kraft kann den Benutzer in die richtige Richtung leiten, um Hindernisse zu umgehen und den Weg zum Ziel zu finden. Dies reduziert die visuelle Ablenkung und kognitive Last, die durch die Navigation entsteht. EMS Feedback kann in den menschlichen Bewegungsapparat eingreifen, um die Gehrichtung zu ändern und dem Benutzer zu helfen, die Navigationsaufgabe zu lösen. Der Anwendungsbereich (4) *embodied emotional feedback* verfolgt das Ziel, die nonverbale Kommunikation von räumlich getrennten Gesprächspartnern mithilfe immersiven Feedbacks zu erweitern. Hierzu wird mittels EEG der emotionale Zustand des Senders ermittelt und dem entfernt lebenden Partner zugesendet. Dieser nimmt den emotionalen Zustand des Senders wahr, indem er durch EMS-Feedback eine für diese Emotion repräsentative Körperhaltung einnimmt. Dadurch wird der Körper des Empfängers zum Ausgabegerät des Senders.

Der Forschungsbeitrag dieser Dissertation teilt sich in zwei Bereiche. Zum einen liegt der Fokus auf der Entwicklung des Toolkits mit den Methoden und der Hardware und Software mit den zugehörigen Beispielimplementierungen der Anwendungsszenarien. Der zweite Bereich beleuchtet die unterschiedlichen Aspekte des ubiquitären haptischen Feedbacks durch EMS im Kontext der Mensch-Computer-Interaktion. Insgesamt setzt diese Arbeit einen Grundstein für EMS als haptische Feedback Methode für zukünftige Forschung und etabliert EMS-Feedback im Kontext von HCI.

Schlagworte:

Mensch-Computer-Interaktion

ubiquitäres haptisches Feedback

elektrische Muskelstimulation

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Conventions

The Use of 'we'

The presented dissertation contains results of four years of research at the Leibniz University of Hannover. The research results are presented and published on international conferences such as CHI, UbiComp, AugmentedHuman, MobileHCI, 3DUI and in a book chapter. This work is done in a close cooperation with my doctoral advisor, Micheal Rohs, and colleges from international research groups as referred as co-authors on my publications. All concepts were discussed with them and they gave input on these ideas. To give them credit for their inspiration and their work I use in my thesis consistently the scientific 'we'.

The Use of Online Sources in Bibliography and Footnote

This thesis considers products, hardware and software components, and also word definitions that are only available online and not published in an archived library. For example, product descriptions or manuals, specification of used hardware components and online dictionaries such as Merriam-Webster. Some of these sources are generally important for this thesis such as related work and other are very specific aspects such as assembly parts that are used for a prototype. General online resources are referred in the bibliography and specific sources are referred as footnote.

List of Publications

Most of the publications are in the context of human-computer interaction and the results are presented in this thesis.

2016	M. Pfeiffer, T. Dünte, M. Rohs: Let Your Body Move: A Prototyping Toolkit for Wearable Force Feedback with Electrical Muscle Stimulation. In Proceedings of MobileHCI, 2016.
	M. Pfeiffer, T. Dünte, M. Rohs: A Wearable Force Feedback Toolkit with Electrical Muscle Stimulation. In Proceedings of CHI EA, 2016.
	P. Lopes, M. Pfeiffer, M. Rohs, P. Baudisch: Hands-on introduction to interactive electric muscle stimulation. In Proceedings of CHI EA, 2016.
	O. Kaul, M. Pfeiffer, M. Rohs: Follow the Force: Steering the Index Finger towards Targets using EMS. In Proceedings of CHI EA, 2016.
2015	M. Pfeiffer, L.D.L. Phan, M. Rohs: User - Attached Haptic Feedback on Touch Displays via EMS. IEEE World Haptics - WIP, 2015.
	P. Lopes, M. Pfeiffer, M. Rohs, P. Baudisch: Let your body move: electrical muscle stimuli as haptics. IEEE World Haptics Tutorial, 2015.
	M. Pfeiffer, T. Dünte, S. Schneegass, F. Alt, M. Rohs: Cruise Control for Pedestrians: Controlling Walking Direction using Electrical Muscle Stimulation. (CHI - Honorable Mention Award) In Proceedings of CHI, 2015.
	M. Pfeiffer, W. Stuerzlinger: 3D Virtual Hand Selection with EMS and Vibration Feedback. In Proceedings Extended Abstracts CHI, 2015.
	M. Pfeiffer, W. Stuerzlinger: 3D Virtual Hand Pointing with EMS and Vibration Feedback. In proceedings of the 3DUI, 2015.
2014	M. Pfeiffer, S. Schneegass, F. Alt, M. Rohs: Let me grab this: A comparison of EMS and vibration for haptic feedback in free-hand interaction. In Proceedings of Augmented Human International Conference, 2014.

M. Funk, R. Boldt, B. Pfleging, M. Pfeiffer, N. Henze, A. Schmidt: Representing indoor location of objects on wearable computers with head-mounted displays. In Proceedings of Augmented Human International Conference, 2014.

M. Pfeiffer, S. Schneegass, F. Alt, M. Rohs: A Design Space for Electrical Muscle Stimulation Feedback for Free-Hand Interaction. In Workshop on Assistive Augmentation - CHI, 2014.

2013 M. Pfeiffer, S. Schneegass, F. Alt: Supporting interaction in public space with electrical muscle stimulation. In Proceedings Pervasive and ubiquitous computing adjunct publication, 2013.

2011 U. von Diemar, V. Gruhn, S. Grapenthin, W. Linsmeier, A. May, M. Pfeiffer, C. Tüffers, V. W.-Marting: Cloud Computing in der Versicherungswirtschaft. Internal Study of the paluno, University of Duisburg-Essen and Accenture, 2011.

T. Brückmann, V. Gruhn, M. Pfeiffer: Towards Real-Time Monitoring and Controlling of Enterprise Architectures Using Business Software Control Centers. In Proceedings of ECSA, 2011.

T. Döring, D. Kern, P. Marshall, M. Pfeiffer, J. Schöning, V. Gruhn, A. Schmidt: Gestural Interaction on the Steering Wheel - Reducing the Visual Demand. In Proceedings of CHI, 2011.

2010 M. Pfeiffer, D. Kern, J. Schöning, T. Döring, A. Krüger, A, Schmidt: A Multi-Touch Enabled Steering Wheel - Exploring the Design Space. In Proceedings of CHI, 2010.

2009 A. Sahami Shirazi, F. Alt, P. Holleis, M. Pfeiffer, A. Schmidt: Taxi Media: Interactive Context Awareness Entertainment/Advertising. System Workshop Pervasive Advertising at Informatics, 2009.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

The human senses are the interfaces between the outer world and the human brain. They define how we perceive our environment. Computer systems use abstract models of the real world. One to one representations of real world objects are complex and difficult to achieve, hence, abstract models do not have all properties their real world counterparts have. The representation is reduced to essential properties to be understandable for the user. Apart from abstracting visual information, such as resolution or unimportant details, physical properties are often not represented. In interaction with the physical world the haptic sense helps to feel our surrounding such as sizes or textures of objects.

> *"In interaction with a computer, the human input is the data output by the computer vice versa. Input in humans occurs mainly through the senses and output through the motor controls of the effectors. Vision, hearing and touch are the most important senses in HCI."* - Alan Dix [76, 1 p.]

The word haptic comes from Greek "haptesthai" and means "to touch". The haptic sense consists of the tactile and kinesthetic (chiefly British kinaesthetic) perception [147]. In interaction with computers the haptic sense adds information to the visual and auditory channels. Properties such as weight or stiffness could not be directly communicated using those channels. Visual interfaces are often overloaded. In this case haptic feedback can reduce the complexity and free perceptual and cognitive resources. Humans are genetically preprogrammed and trained to use the haptic sense to interact with their environment. Compared to the other senses the haptic sense is distributed over the body and not located in one place. Furthermore, when the haptic sensation is missing, interaction with objects feels awkward or not real. The physical sensation is mainly simulated by computers through tactile feedback such as in mobile devices or force (kinesthesis) feedback such as in exoskeletons.

Computer systems have pervaded our everyday life due to the continuous trend of miniaturization. The systems get smaller, simultaneously reducing the power consumption and increasing the computing power. Additionally, visual output devices have become much smaller, they are integrated in mobile devices (also known as mobiles) such as phones or tablets and now include wearable devices (also known as wearables) such as smart watches or textiles.

> *"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."* - Mark Weiser [344]

Computers have already become ubiquitous and are always available. The technology is integrated in our environment. Previously, Mark Weiser's idea focused mainly on the visual and the auditory sense and neglected the haptic sense. Since then, haptic feedback technologies have made it hard to follow this trend in all variations. For example, thermal feedback devices can be implemented in a small size, but still have a high power consumption [126]. Due to the small form factor of vibratio-tactile feedback technology, it is commonly used in mobile devices and wearables [180, 284]. The mechanics and the internal mass that is used to generate the vibration limit the construction size or the vibration strength. Haptic feedback technologies with strong haptic feedback or force feedback still need large mechanics and strong motors. Such motors have high power consumption and result in large bulky dimensions. Hence, such feedback devices are not suitable in mobile and everyday contexts regarding the battery operation time and social acceptance. Such technology is still restricted to labs and specific application areas.

Human skeletal muscles have the power to lift objects and move body parts. It is possible to use the muscle power of humans to generate haptic and force feedback. A small current applied to the muscle fibers actuates them, resulting in a movement. This so called electrical muscle stimulation (EMS) is also known as functional electrical stimulation (FES). EMS technology has a long standing acceptance in fitness and physiotherapy. This electrical stimulation can generate a high variance of feedback, from a small tingling on the skin to a strong actuation force. EMS has the potential to shrink down haptic feedback technology to a minimal size, become mobile, wearable, and integrated into textiles. Following Mark Weiser's vision from 1991 haptic feedback can become also ubiquitous [344]. Taking the feedback technology everywhere with us and perceiving a high variance of haptic feedback when we interact with the content in our environment, is the vision of this thesis. For example, while interacting with a display from distance, with virtual objects, and also in everyday scenarios such as walking through a park or communicating with other people.

This thesis investigates the use of haptic feedback through EMS in the context of Human-Computer Interaction (HCI). It introduces the idea of EMS-based ubiquitous haptic feedback. For fast prototyping and running user studies with EMS feedback a toolkit is presented. It is used to show the potential of EMS as haptic feedback technology in several application scenarios. In particular, we show how EMS feedback is shaped to simulate object properties, in 3D target selection, for pedestrian navigation, and for communicating emotions. The findings will be discussed in the context of HCI.

1.1 Research Questions

EMS is a complex technology that is adopted from the fitness and physiotherapy field. Using EMS technologies does not usually come along without an initial effort. The technology needs to be fully understood before focusing on a new interaction paradigm. It has several specific characteristics and safety aspects that need to be taken into account when applying EMS to users. Therefore, EMS is still in its infancy in the context of HCI. Yet, the HCI specific design space is not well understood and there is a lack of processes for prototyping and running user studies. Furthermore, off-the-shelf EMS devices cannot be used instantly to deliver the full variability to explore new interaction techniques. New hardware and software needs to be developed before EMS feedback can applied to the user. An EMS toolkit could reduce the entrance hurdle for researchers to investigate EMS as haptic feedback technology. In addition the toolkit can be adapted easily to new application scenarios and achieves fast prototyping.

RQ1: How to enable fast and easy prototyping with EMS
as a haptic feedback technology?

EMS technology has several application areas such as notification, extension of object properties, guidance, safety and prevention, assistive feedback, supporting rehabilitation or learning movements. For example users could be notified haptically about a personal message or how to move the leg when leaning dancing. The small form factor and the low power consumption make EMS technology potentially suitable for use in mobile setting. In this setting it can generate high viability of feedback that goes from tactile to strong force feedback.

In many scenarios the user must have their hands free to interact with the environment and wearing gloves is not acceptable as they greatly reduce tactile feedback when interacting with physical objects [344]. Common haptic feedback is usually perceived at the same position as it is applied e.g. vibration feedback [180]. An opportunity of EMS force feedback is that the point of applying the feedback different to position where it is perceived or it is visible. For example, when it is applied to a muscle in the lower arm, it results in a movement of the hand or a finger. As discussed, in natural interaction with physical objects the haptic sense gives us additional information to the visual perception such as feeling the surface texture or hardness of materials. Depending on the mental model the applied feedback should be as similar as possible to the real world. When the user interacts in front of a large display or in virtual reality (VR) in mid-air there is no haptic sensation. EMS parameters need to be investigated to simulate such physical parameters.

> RQ2: Is EMS feedback suitable for simulating physical properties
> in free-hand interaction?

Interacting in front of a large display or in VR in mid-air is a common task to select targets. Selecting targets in 3D environments is similar to 1D or 2D. The size and distance of the targets has a significant influence on the error rate, selection speed, and the throughput. At the same time, *hand occlusion* and *stereo viewing* are major challenges in 3D interaction. The interacting hand can occlude a target that the user tries to select. Furthermore, the user can either focus on the selecting finger or on the projection of the target, which is further away. In stereo viewing even if the finger and target is on the same depth level, one or both is out of focus and the user sees it blurred. A selection feedback can reduce these problems. It needs to be considered if EMS is to be a suitable feedback technology for 3D target selection in order to reduce the selection errors.

> RQ3: Is EMS a reasonable alternative to vibration feedback for 3D target selection in stereoscopic environments?

Haptic feedback is also used to reduce the visual distraction and mental load when focusing on a main task in everyday scenarios. For example during navigation, pedestrians need to focus on the navigation device to find the right way. Haptic feedback is already used to reduce the visual distraction. An imposed force could change the walking direction and guide the user to the right destination. EMS can be used to manipulate the walking direction of pedestrians in order to navigate them.

RQ4: Can EMS force feedback be used reliably to guide pedestrians?

Finally it has been shown in previous work that remote living partners feel more connected when they use technology to communicate over distance [77, 167, 240]. The communication has a sender side that inputs emotions or information and a receiver side that displays them. To enhance the communication, emotions can be sensed implicitly, and transmitted to the remote partner. The force feedback technology can then make her express them through body language such as with an emotional gesture. In this case the receiver becomes the output device to express the emotional state of the sender. An area of investigation is, therefore, the way in which EMS can be used to generate voluntary gestures that represent emotions.

RQ5: Can EMS actuated gestures communicate emotions over distance?

EMS has a broad application field in HCI to support users while interacting. This thesis considers a subset of possible application fields and focuses from different perspectives on the discussed research challenges. In particular the five main challenges can be extracted from the discussed research challenges; (RQ1) enabling EMS as a haptic feedback technology, (RQ2) simulating physical object properties, (RQ3) supporting 3D target selection, (RQ4) actuated guidance and (RQ5) communicating emotions.

1.2 Research Methods

Electrical muscle stimulation (EMS) was investigated in medical research in the middle of the last century [165, 182] and adopted to the field of human computer interaction (HCI) recently. Yet, EMS is still rarely used in HCI, but got more attention in the research community. There is still a lack of design and evaluation methods. This thesis provides a common ground of knowledge about EMS and prototyping methods that are adopted to EMS as haptic feedback in HCI (Chapter 2 and 4). In HCI prototyping and evaluating with user studies are typical research methods [177].

Several prototypes are developed to investigate the aspects of EMS as haptic feedback technology. These prototypes are used to evaluate such aspects in quantitative and qualitative user studies with a large number of participants. In this work guidelines are developed for user studies. EMS is an immersive technology that has medical issues and some user groups are excluded to use it. Before using EMS each user should be informed about the potential risks. For safety reasons, off-the-shelf EMS devices are used in evaluations and user studies to generate the current that is applied to the user.

1.2.1 Prototyping

Several hardware and software prototypes are built to explore and evaluate aspects of EMS feedback, in close collaboration with colleges from our and other internal research groups and in student projects. The “Let Your Body Move” toolkit (Chapter 4) is a central component in all prototypes. It was adapted to the project’s specific requirements and different hardware and software versions were developed. The so called *control modules* are used to apply EMS feedback. A main focus of the toolkit is a safe use and easy integration in other prototype setups. Regarding safety the EMS control module used off-the-shelf EMS/TENS devices to generate the EMS signal (Chapter 4). In addition to the toolkit the prototype setups contain other systems such as tracking systems, mobiles and wearables. Therefore, specific control and study software was developed. An overview of the prototypes is presented in Section 1.3.

1.2.2 Evaluation

User feedback is important to understand user behavior, to measure interaction effects and to explore the user acceptance for immersive feedback technologies such as EMS [177]. The evaluation of new concepts and approaches was carried out with users in lab and outdoor studies. On one hand, the user studies focused on quantitative measurement for an objective evaluation. In Fitts’s Law experiments, effects such as error rate, selection time and throughput were analyzed. Also walking trajectories were recorded to calculate deflection from the walking path. The subjective feeling of the EMS current makes qualitative feedback important, as well as an individual view on how interactions are perceived by the user. On the other hand, the user studies also focused on qualitative feedback. This feedback was collected by questionnaires and interviews. The questionnaires mainly consist of Likert items, selection lists and open questions. Additionally workshops with users were conducted. For further analyses the interviews, parts of the studies and workshops were audio and/or video recorded. The calibration of EMS feedback is extensive and takes in many cases at least half of the study time. Also safety aspects needed to be taken into consideration when applying EMS current to users. Hence, user studies that involve EMS feedback are challenging and time-consuming.

1.2.3 Study Guidelines

Study guidelines and templates to ensure the study quality and reproducibility were developed. Before each user study the documents needed to be adapted to the specific context. The guidelines consist of a general description and template documents for the participant and for the experimenter. The template documents for the participant are a textual overview of the study, a general consent form, a consent form for photo, an audio and video recording of the study, a pre-study demographical questionnaire, a textual study introduction and a post-study questionnaire as shown in Table 1.1. Samples of adopted documents will be found in Appendix I Study Forms. The template documents for the experimenter are a pre-study documentation, the experiment structure, a detailed study overview and an observation form.

Document	Description
Study overview	Gives the user a general overview of study context and procedure.
General consent form	Describes EMS safety aspects and data recording conditions. The user confirms that she/he understands it.
Consent form photo, audio and video records	The records and publication conditions of photos, audios and videos will be confirmed in an extra from.
Pre-study demographical questionnaire	Selects general demographical information about the user such as age, gender and background.
Textual study introduction	Introduces the user task and ensures that all users start with the same introduction.
Post-study questionnaire	Considers questions about the user task, interaction and understanding of the user.

Table 1.1: Overview of study guidelines templates for the participants.

1.2.4 Ethics Boards

For user studies we used the pd-net ethic process [175] or requested an ethic approval from the local ethics board of the Leibniz University of Hannover. All participants got a detailed introduction on the background of EMS and on possible medical issues. The EMS specific ethical questions such as self-determination and manipulation of movements are discussed in Chapter 9.

1.3 Contributions

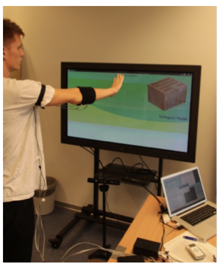
This thesis builds the foundation of electrical muscle stimulation as haptic feedback in Human-Computer Interaction. The main contribution can be divided into three aspects. (1) Reducing the entrance hurdle for researching and enabling fast prototyping, (2) building prototypes to evaluate new interaction concepts and (3) investigating set of interaction concepts that are based on EMS haptic feedback.

1.3.1 Enabling EMS Haptic Feedback

The developed *Let Your Body Move toolkit* is an open source project that reduces the entrance hurdle of using EMS for haptic feedback. The toolkit itself consists of hardware and software that enables the flexible use of EMS in various research projects. To do so, the toolkit uses a simple text based protocol to manipulate and activate EMS parameters. This achieves a fast prototyping and makes it easy to use EMS in user studies. Around the toolkit, knowledge that is previously used in the context of physiotherapy and fitness was consolidated and parameters were tested in the context of HCI. In addition, a prototyping and evaluation process was defined. Furthermore it has been investigated how the system can be calibrated on the user to achieve an actuation of the user's limbs, how to run studies in which EMS is used, and the EMS parameters that should be reported.

1.3.2 Research Prototypes

A set of research prototypes was developed with the goal to explore application scenarios that benefits from lightweight haptic feedback technology with large variability of feedback. The toolkit was used to apply the EMS current to generate the haptic feedback. The toolkit's set of *control modules* was developed by evolution and adapted to characteristics that are needed in the prototypes. The toolkit was integrated in the prototype settings and connected to tracking systems, mobiles and wearables.

Prototype	**Description**	**Control Module**	**Chapter**
	*Let you body move:* A set of sample apps that connect to one or many EMS control boards. Mobiles or wearables can be used to control or manipulate the users movements.	EMS module with BLE - scaling EMS intensity - EMS protocol	Chapter 4
	*Let me grab this:* Calibration part to adjust corresponding vibration strength to an EMS level and a Kinect part that plays vibration or EMS feedback when the user performs a gesture toward a large display.	EMS module WiFi - on/off	Chapter 5

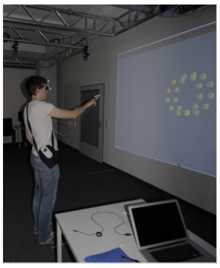
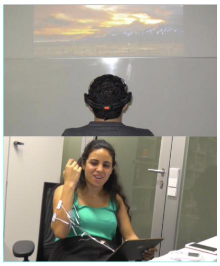
	*3D target selector:* A head tracked 3D stereo display prototype that presents 3D targets in front of the user. When the user enters targets visual, vibration or EMS feedback is played. The selection can be confirmed with a hand-held button.	EMS module WiFi - on/off - EMS protocol	Chapter 6
	*Course control - lab study:* A prototype for EMS strength calibration to rotate the leg and for tracking walking trajectories to measure the resulted deflation of users. *Course control - outdoor study:* A Wizard-of-Oz prototype that lets the legs rotate with a button on a mobile to guide a user through a direction.	EMS module with WiFi and a EMS module with BT - scaling EMS intensity	Chapter 7
	*Emotion actuator:* A EMG sensing and EMS actuation prototype that senses implicit emotions, transmits them to a receiver and plays a representative actuated gesture with the receiver's body.	EMS module BLE - scaling EMS intensity - EMS protocol	Chapter 8

Table 1.2: Overview of the developed prototypes

1.3.3 Interaction with EMS Feedback

This thesis makes contributions in different areas of HCI that show the potentials of EMS as haptic feedback technology. The main findings are the extension of visual objects with haptic properties, manipulating users in real world scenarios, and haptic notifications.

Haptic Extensions of Virtual Objects: EMS has been successfully used to support free-hand interaction. It is suitable to interact with displays, which are not reachable for the user and apply a large variance of feedback. EMS is a lightweight, wearable technology that consumes a minimal power. The user's muscles are successfully actuated to generate a force feedback that is adapted to different gestures and materials. The feedback reflects the interaction with hard material and provides more realistic interaction with virtual objects. People are willing to wear this kind of technology for specific scenarios and got quickly used to the tactile feeling.

3D target hand selection was extended by EMS-based haptic feedback. A Fitts's Law experiment has shown a significant effect for the *error rate* of EMS compared to no additional feedback. However, the other feedback conditions had the same effect. Only the visual feedback condition had a significantly better *throughput* and *movement time* than the non-feedback condition. The qualitative results indicate that EMS feedback is a valuable addition to visual feedback.

Real world manipulation: In a real world scenario the locomotor system of users was manipulated to guide people. The concept of *actuated navigation* was introduced to reduce the visual distraction, the mapping and the mental load for pedestrian. The results of a user study show that the walking direction can be manipulated by EMS feedback into both directions. Finally an outdoor study approved that pedestrians can be guided through a public park with this approach.

Haptic notifications: An approach to communicate by nonverbal abstract states such as emotion from a sender to a receiver in an immersive way has been investigated. The so-called *embodied emotional feedback* system senses the implicit emotional state of a user, sends it to a remote person, who expresses the emotion with an actuated gesture. The receiver becomes the output device. An end-to-end prototype is evaluated in three user studies. EMS feedback can let people perform actuated gestures to represent different effective states and is perceived in an immersive way.

All these scenarios benefit from ubiquitous haptic feedback and become possible with EMS.

1.3.4 Publications

The described projects are carried out with international research institutes such as the Institute for Visualization and Interactive Systems (Albrecht Schmidt), the Media Informatics Group (Florian Alt), School of Interactive Arts + Technology (Wolfgang Stuerzlinger) or Human Computer Interaction Group (Patrick Baudisch). Aspects of this works such as concepts, figures and text passages are published in a book, on international conferences and workshops [158, 194, 195, 253, 254, 255, 256, 257, 258, 259].

1.4 Thesis Outline

This thesis consists of nine chapters, shown in Figure 1.1. After introducing the context of this work in this chapter, we discuss the problem domain and the elicited five research questions.

Then, the research methods used are discussed, followed by a summary of the main findings of this work. In Chapter 2 the background knowledge that covers all chapters is presented. We explain how humans perceive their environment with the focus on the haptic sense and the different views of haptics in literature. Then, tactile and force feedback technologies are considered. This is followed by presenting work that considers EMS in fields of medicine, fitness and the arts. After that we present related work that considers EMS in the context of HCI and finally focuse on textile output electrodes for EMS.

Based on this background, in Chapter 3, we introduce the concept of ubiquitous haptic feedback. To achieve this approach, haptic feedback technologies need to follow the current trend of miniaturization. Problems that current haptic feedback technologies have in following this trend are considered. Further discussion considers whether EMS technology has the capability to achieve ubiquitous haptic feedback. With this concept new possible application scenarios are envisioned. To realize these scenarios, on one hand general EMS challenges need to be faced and on the other application specific challenges need to be solved. First the specific challenges are discussed and then the application of three fields are selected to address these specific challenges.

In Chapter 4 the "Let Your Body Move toolkit" is presented in order to investigate four aspects of the application fields. General EMS parameters, adapted from medical and fitness fields, are presented as foundation for the toolkit, followed by a description on how EMS feedback can be applied to users. This includes sample electrode placements, calibration routines, EMS parameters that should be reported for reproducibility of user studies and important safety aspects. As a next step, an EMS prototyping process to use the toolkit is introduced. Then hardware and software parts and a communication protocol of the toolkit are presented. The toolkit is used in four simple applications for mobile and wearable prototyping. Instances of the toolkit are evaluated in a workshop. Different versions of the toolkit are used to investigate the four aspects (Chapter 5 to 8) as discussed in Chapter 3.

Chapters 5 and 6 consider how virtual objects can be extended with haptic properties. In Chapter 5 EMS is used to support free-hand interaction. In a first study the corresponding level of vibration and EMS is found. That is used in a second study to compare modalities with object properties (hard and soft) and gestures (touch, grasp, and punch). In Chapter 6, both feedback modalities are applied on 3D target selection with head tracking stereo shutter glasses. In a Fitts's Law experiment both feedback modalities are compared with no extra feedback and visual feedback.

The manipulation of users in a real world scenario is considered in Chapter 7. The approach of actuated navigation is introduced and compared with previous work. In a lab study EMS-based

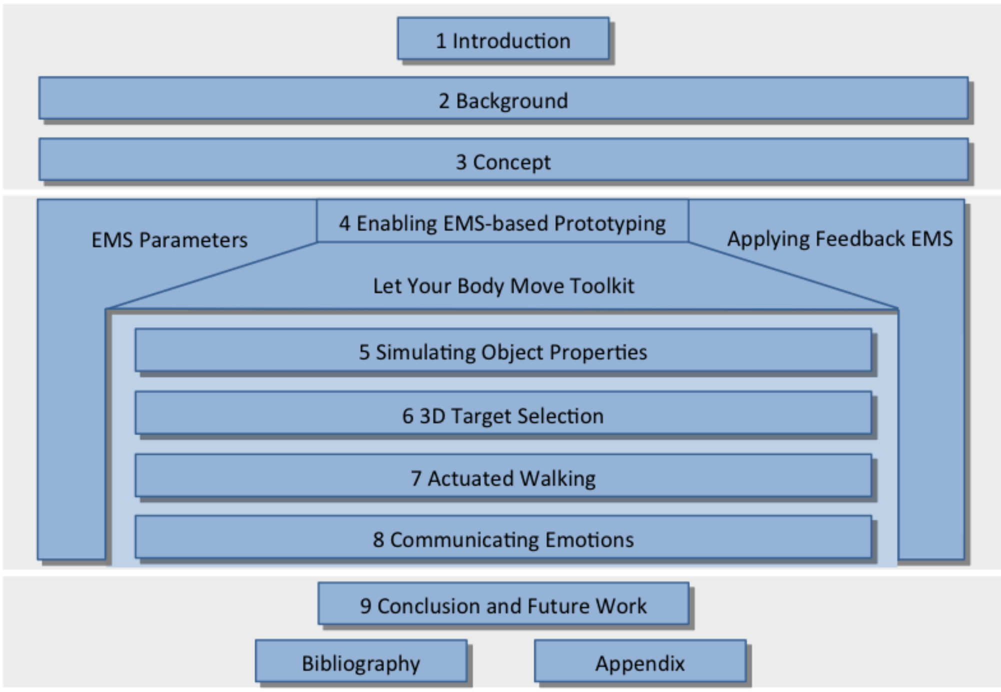


Figure 1.1: Outline of the thesis

actuated walking is investigated and tested to determine how large the manipulation of the walking direction by the participants is. In an outdoor study this approach is used to guide pedestrians through a park.

The last aspect in Chapter 8 considers how immersive notifications could be implemented with EMS-based gestures. In an explorative prototype the concept of *embodied emotional feedback* is implemented. The approach is investigated in three user studies. In the first study, it is investigated how emotions can be implicitly sensed on the sender side. In the second study the ability of the receiver side to express the emotions with actuated body language is tested and in the third study the end-to-end system is explored.

Chapter 9 concludes this work with a discussion of the potential of EMS in HCI, considering the five research questions, and takes the concept of ubiquitous haptic feedback into account. Then ethical questions that come along with these new ideas and approaches are discussed. Limitations of EMS as haptic feedback regarding calibration, muscle exhausting, exact controlling, and user acceptance are considered. Presenting further open issues, the scope for future work, and a summary of the thesis contributions concludes this chapter.

Chapter 2

Background

This background chapter frames the thesis within the context of current research and delimits it from other works. First of all we present how humans perceive haptic feedback through the skin and other receptors in the limbs, to show complexity of haptic sensation. Next we discuss the difference between tactile and haptic feedback. After that, the common ground of this work is discussed. We focus first on tactile feedback and on force feedback technologies. Then the history and background of EMS in the medical field is introduced. Afterwards we discuss how electrical feedback is used to stimulate tactile sense and give force feedback in computer human interaction (HCI). Finally, we focus on textile output for EMS.

2.1 Haptic Perception

The description of the human senses goes back to the Greeks. The senses let us perceive our environment and give us the ability to react to external stimuli. For human computer interaction three senses are manly involved; vision, hearing and touch [76]. Not all senses are equally involved when users interact with traditional interfaces. The visual sense is used much more than the others senses and is often overloaded. The visual sense is used when we are reading or looking at figures. Less often audio feedback is used such as notifications or text to speech output. When a user is typing on a common keyboard the sense of touch lets the user feel the resistance of the keys. Each sense has a different capability of perceiving information.

There are different views and ways of classifying the human senses. The “early view”, classifies the senses based on their abilities that go back to Aristotle. The five basic senses are known as; visual, auditory, smell, taste and touch [26, 83, 135, 343]. First we will briefly consider these five basic senses and then focus on the classification of the haptic sense (Section 2.1.1). In the next step we consider the physiological view and classification that describes the senses based on receptor nerves and sensor systems. This view describes how stimuli are perceived by the receptors and which physiological system they belong to. We consider how haptic feedback is distinguished between tactile and proprioception sensation (Section 2.1.3).

2.1.1 Human Senses

From the historic point of view the human sensory nervous system is divided into the five basic senses; sight (vision), hearing (audition), smell (olfaction), taste (gustation) and touch (taction) [83]. The "early view" is more a descriptive approach. It describes how the senses perceive the environment or objects and what kind of information we get from them [86, 135, 147, 332, 343].

Visual sense: The visual sense gives us optical information about our environment. Our mental models and symbolic thinking is defined from the visual perception. It gives an impression of depth and lets us perceive colors, contrast and movements. It helps to interact with the environment and a feedback is perceived when objects change their visual properties. During communication with other individuals it helps to identify the other person. The body postures and facial expressions give the communication partners important information about emotional state or if other individuals act aggressive. It enables us to see visual symbols such as letters on paper and lets us map them to words while reading a text. Our visual organ (our eyes) can move around very fast. During the moments the eyes scan (saccade) or focus (fixation) on objects or symbols in our environment [16].

Auditory sense: The auditory sense lets us perceive sound waves, which give us additional information about our environment. When something happens out of our view and it makes noises such as an animal at our back, we still can recognize it and calculate the direction where the noise comes from. We differentiate between frequencies and can distinguish between sounds that enable verbal communication such as speech.

Smell sense: The sense of smell can detect different chemical materials that can be mapped to previous experiences such as positive or negative. It helps us to detect if there is an animal or a rival nearby, as well as if something is edible or has became tainted.

Taste sense: The sense of taste is the last instance before something reaches our stomach. There we decide if it really fits to our prey spectrum and tells us what kind of food it is.

Touch sense: The sense of touch delivers information by bringing a body part into contact with objects or with the environment that we wish to explore or understand it [216]. The sense of touch can be perceived all across the skin. It is the most widely spread sense and it covers the whole body. It can be divided into several sub perceptions such as thermal, mechanical, chemical or electrical perception. It could be perceived passively or actively. In contrast to the other four basic senses the haptic sense is the only one that is actively used to explore and manipulate objects in the physical world. In contrast to the visual sense it can measure weight, hardness or temperature [338].

The "historical" classification shows the importance of the human senses, each sense covers parts of our outer perception. In this classification the senses of proprioception or of balance are missing [83]. For whole body interaction the normal five senses plus these two senses are used to perceive feedback of how the near environment changes [86]. Furthermore, Gibson et al. [113] described outer or inner oriented sensation, that involves the perception of the environment and the perception of the body such as the ordination of limbs and the state of our organs. They place this sensation to the sense of haptic.

2.1.2 Haptic Sense

In the 19th century, the word haptic (from Greek *haptesthai* for *to touch*) entered the English language and was used in the medical context as a synonym for tactile [216]. Haptics is defined by ISO 9241 as *"sensory and/or motor activity based in the skin, muscles, joints and tendons"* [147]. In contrast to dictionaries such as Merriam-Webster [216], where haptic is given as a synonym for tactile sensation, the ISO uses haptic as generic term for touch and kinesthesis (kinesthesias). The tactile sense is used in a specific manner for mechanical stimulation, rather than for force or torque sensation. The kinesthesis (kinesthesia) is defined as the kinesthetic sense of movements and tensions, which is perceived by receptors that are located in muscles, tendons, and joints [217].

There are several different viewpoints and a diversity of terms and meaning of terms [147]. In the following we will discuss different definitions of the terms haptic, force, tactile, and self vs. external applied stimuli. After that we define how haptic and force feedback is used in this work.

Exploration of our environment could be either passive without moving limbs or active by using the limbs to explore the body of an object as discussed in [343]. Bracewell distinguished between passive and active touch. The passive touch is the perceived sensation when another person is touching a user and the active touch when a user actively touches an object for

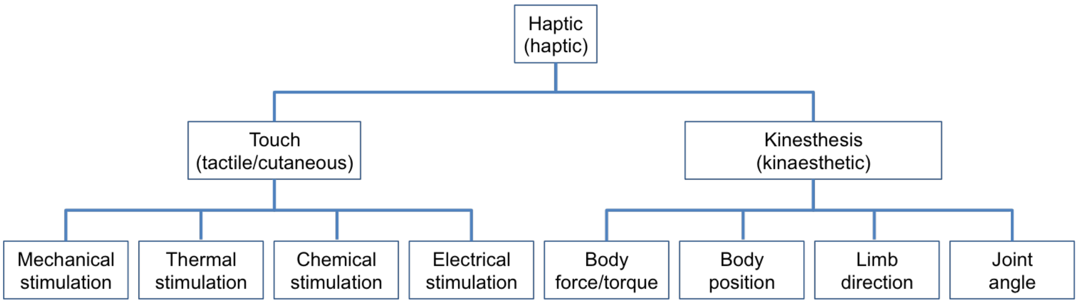


Figure 2.1: Haptic can be divided into touch and into kinesthesis based on [147].

exploration (texture and shape). The movement collides with an object and a sensation to the user is triggered [35]. In [147] it is stated that passive touch does not involve kinesthesis. Moreover, it has found the an active touch has a higher perception resolution than a passive touch on places with the same receptor density [135].

El Saddik et al. [83] describe the sense of touch as active interaction with devices and that we are receiving tactile and kinesthetic cues from our environment. Furthermore, Bicchi et al. state that the elementary tactile information comprises force, texture, temperature and frequency of an exploration [26].

The ISO 9241-910 definition of tactile and haptic, divides the haptic sensation (haptics) into touch (tactile and cutaneous) and kinesthesis (chiefly British kinaesthesia) as shown in Figure 2.1. The ISO view is more technical and describes the stimulus and senses based on physical parameters.

A touch is a sensation based on the stimulation of receptors in the human skin [147]. The stimuli could be mechanical, thermal, chemical or electrical. Force or kinesthesis includes the input and output channel. This perception describes the sense of the "body image" of a person. The kinesthesis is the passive sensing of the environment and the active manipulation of it to exchange information and action in bi-directional way [147].

It includes the perception about the position of the body or body parts and how they are orientated (angle/direction) or how much torque or force they apply [147, 332]. This perception involves the muscles, tendons, and joints. This view is extended with the senses of balance and proprioception [83, 86].

Wang et al. [338] divide the sense of touch relating to the neural input into cutaneous, kinesthetic (force) and haptic systems. They follow the physiological view of the touch sense based on the sensors in the skin from the cutaneous system and in joints, tendons and muscles from the kinesthetic system. Wang et al. define the haptic system as combination of both sensor systems with the difference being to the physiological view that the sensation is caused by an active control due to human motions.

This work follows basically the definition of the ISO standard, but focuses more on the tactile and force parameters in the classification. Based on Brewster and Brown [40] the human sense is divided into the kinesthesis (force) and cutaneous (tactile). On one hand the kinesthesis stimulus is perceived by the muscles and joints and on the other the tactile side the stimulus such as sensation of vibration, temperature, pain and indentation is perceived by the cutaneous (skin, hair, tissue etc.) receptors. In this work kinesthesis and the sense of force are used as synonymously. The tactile and force sensation can be generated from an external haptic feedback device that applies the sensation to the user's body (passive) or through an active exploration of the user's body. According to that, applying electrical muscle stimulation (EMS), the electrical stimuli on the skin is a tactile effect. The actuation of the muscle produces a force (kinesthesis). In the case of EMS the user could stay passive, but still perceive properties of kinesthesis in contrast to the OSI definition [147].

In this work it is defined that *tactile* stimulus could be actively or passively presented to the user's skin and is perceived by the user. For example, an active tactile feedback is perceived when exploring the structure of a surface and a passive tactile feedback is perceived when the vibration alarm of a mobile is ringing in the pocket. A *force* stimulus is defined as a force that is applied from an external device when the user is active or passive and is perceived by the user. This force could influence active movements of the user. It could support a movement or counteract against it to slow the movement down or stop it. Furthermore, when the user is passive the device could move the user with voluntary force into a posture with a direction, a torque and applying a specific strength. The user perceives the kinesthesis while staying passive. The force to achieve these movements could be provided externally through mechanics or internally through muscle actuation.

The tactile and force stimuli are perceived through the receptors in the body and are generated by haptic technologies. The way in which the body's receptors perceive the stimuli is described in the next section. The technologies that generate these stimuli to provide a haptic feedback will also be described later.

2.1.3 Physiological Perception

The human senses as discussed in the previous section are the connection to perceive the environment. The human senses are based on specialized receptor cells to perceive the external and internal stimuli. For example to perceive light within the eyes there are different receptors such as rods and three types of cone receptors to see colors [16]. The nerves transmit this information to the central nervous system. The type of sensation a person feels depends on where these nerves in the central nervous system are ending and how the information is processed [125].

The haptic sense, from a physiological view, is placed in the somatosensory system and is described as “somatic sense” [147]. In contrast to other human senses this sense dose not have a single sensory organ and is spread over the whole body. To perceive haptic stimuli sensory receptors and free nerves are placed in the skin, muscles, tendons, joints and internal organs. From a physiological view the somatic sense is divided into exteroreceptive sensations that involve the surface of the body and the skin and mucosa, the proprioceptive sensations that involves the locomotor system and the physical state of the body, visceral sensations for the inner organs and the pain sensation [135].

Tactile Perception

The sensation of the skin is divided into the sense of touch and the temperature sense [135]. The skin or cutaneous tissue (related to the skin such as nerves or hairs) perceives the external influences of our environment. It has an average size of 1.79 m^2 [283]. The receptors and free nerve endings in the skin react to tactile stimuli such as mechanical stimulation, temperature change or electrical current [35, 147].

Based on Hick [135] the skin receptors are divided into pressure (force), touch, vibration and thermal sensors. Receptors in the skin (haptic nerves / sensors) [16] are Merkel cells (expanded tip receptors), Ruffini endings (or Ruffini corpuscles), Meissner’s corpuscle, Pacinian corpuscle, warm and cold receptors.

Merkel cells and Ruffini endings react to deformation of the skin. The receptor’s reaction is proportional to the strength of stimulus and depends on the magnitude of the stimulus. They react as long as the receptors are stimulated and the adoption behavior, as compared to the other receptors, is very slow [135].

Merkel cells: Merkel cells are placed vertically under the outermost layers of skin (Epidermis). They react under continuous pressure [135].

Ruffini endings: The Ruffini endings react when the tissue is twisted. They are placed below the outer layer of the skin in the Corium and also in the joints [135].

Meissner’s corpuscles: The Meissner’s corpuscles are nerve structures that are also placed directly below the outer skin layer. They are reacting to shear forces that are applied to the skin, such as when an object is moving over the skin. They react to stimulus changes, in this case on changing of the speed, so they are called differential receptors. They quickly habituate to the stimulus (50-500 *ms*) [135].

Free nerve endings: Free nerve endings transfer the sensation of pain. They are placed in the skin, in the extremities and organs. In the skin they have the highest resolution of all receptors. There is very little habituation to the stimulation of pain. They stop sending the pain sensation only when the stimulus stops [135].

Hair follicle sensors: Hair follicle sensors are also differential receptors and react due to the speed of the hair deflection. The nerve fibers are placed around the hair ending in the deeper skin layers (Corium and Subcutaneous) [135].

Warm and cold receptors: Warm and cold sensors are also differential receptors and are similar to free nerve endings. They have a smaller diameter of 1-3 μm compared to mechanical sensors (10-15 μm) [135]. Cold sensors are placed in the outer layer of the skin (Epidermis) and warm are sensors deeper in the skin (Subcutaneous). Temperatures below 5 degrees and above 45 degrees result in pain.

Pacinian corpuscles: The Pacinian corpuscles are sensitive to acceleration of skin deformation and react on vibration. The largest reaction of the receptors occurs at a frequency between 150-300 Hz [135]. The reaction threshold is, compared to the other receptors, very low and the adoption to the stimulus is fast. They are placed in the adipose tissue (Subcutaneous), in joints and in internal organs such as the stomach.

Resolution and sensitivity depend on the number of receptors. The tongue, lips and fingertips are very sensitive compared to the back, upper leg or upper arm. The resolution is, based on Hick [135], the minimal different distinguishable distance of two stimuli. The average resolution at the tongue tip is 1-2 *mm* and at the back 55-75 *mm* for an adult.

Proprioception

The proprioception, also known as kinesthesis sensation, describes the sensation of orientation, angular position or movement and force on the body part. Proprioception together with the sense of balance informs about the posture of the body and spatial orientation. The receptors of muscles, tendons and joints provide information about the angle, rotation, stretch or compression and the force that is generated by muscles. The proprioception sensation is divided by Hick [135] into the sense of posture, motion and force.

Sense of posture: The sense of posture gives information about the angle and rotation of the joints. Even without active movements the human is aware of his body and location of the body parts [135].

Sense of motion: The sense of motion enables awareness about the speed, distance and orientation when a body part is moved. The motion could be done actively through the muscles or passively by an external stimulus [135].

Sense of force: The sense of force enables a person to turn a joint or to lift a body part up with the appropriate amount of muscle force. With this sense the human is able to lift an object and hold it in the same position without looking at it.

The sensation of the skin also influences the proprioception, it gives feedback about the stretch of the skin and the kinesthetic that is applied to the body. The main sensation is located in the locomotor-system [135]. To measure this sensation there are specific receptors in muscles, tendons and joints.

Muscle sensors: The muscle sensors also known as Golgi tendon organs have different kinds of nerve fibers that are around the muscle spindle and at the muscle ends. The nerve fibers change the impulse frequency depending upon the state of the muscle. They measure the length of the muscles. When the muscle is stretched the impulse frequency increases and when the muscle is compressed the frequency decreases. The impulse frequency changes in a different pattern depending upon the stretching. For example, the impulse frequency differs for active isometric contraction and passive stretching. Also the stretching speed can be detected [135].

Tendons sensors: There are also nerve fibers for stretching and compression in the tendons. In contrast to the muscle sensors these nerves do not fire in the rest position, but only when the tendons are stretched or compressed [135].

Joint sensors: The joint sensors measure the orientation of the joint and the speed at which it is moved. The adoption time of the sensors is low. The joints differ in density of receptors for each functionality such as inner or outer rotation [135].

The described senses and receptors are simulated by computer systems to present the state of the system to the user. Depending on the output, different receptors are stimulated with different types of technologies. In the following section haptic feedback technologies is presented that are used in human computer interaction to stimulate these senses.

2.2 Haptic Technologies

In interaction between humans and computers, the computer's output is the human's input [76]. This input is perceived through the human sensory system. Feedback is a response from a manipulation of a system, haptic feedback is the haptic response that is perceived by the user. The system transmits a piece of information or adds further information to another feedback channel such as to the visual. Haptic feedback technologies generate haptic stimuli to the user to code such information. Additional haptic feedback can result in an increase of recognition, precision, efficiency, perception, and user experience [135, 180, 224, 228, 237, 239, 306].

The haptic feedback extends the interaction to increase the information density. In case the other feedback channels are overloaded the haptic channel can be used to transmit more information such as navigation information [325]. Due to disabilities one or more of the other channels may be imitated. In Germany around 353.000 people are blind and around 293.000 are hard of hearing [299]. In this case other feedback channels can help to overcome these limitations. The information could be converted and presented through the haptic channel [215].

The haptic sense reacts fast to tactile stimuli. In case the other channels are involved with other tasks or slower the information can convert to a haptic stimuli, which can increase the performance of the user. For example, in driving scenarios users react faster when getting a tactile feedback compare to visual or audio feedback [291].

However, when humans interact with the real world almost all senses are involved as discussed in Section 2.1.1. In simulations of the real world usually not all senses are involved. For example in virtual or mixed-realties the user often perceives only a visual representation and no haptic or tactile sensation. In the real world the haptic sense is involved when exploring our near environment and interaction with objects. When these sensations are missing the interaction does not feel natural. A haptic stimulus to simulate physical properties of objects in the virtual environment - such as weight, hardness or texture - can increase the realism of the interaction [147].

As discussed in Section 2.1.1 the haptic sense is not located in a single organ, but is spread all over the body. It has different abilities depending on the stimulus and on the position or how the stimulus is applied. Perception feedback can be divided into tactile or force feedback.

Tactile feedback is described as cues for textures, vibration and bumps [83], but also for fast response [291] and as additional channel [325]. Force feedback is a force that is applied and detected by the user. Force feedback is often involved in addition to the tactile feedback, the proprioception [147]. Force feedback is described as “mechanical production of information” that is perceived as feeling of motions. The information is sensed by the muscles, tendons, and joints[83].

Force feedback and tactile feedback are not clearly distinguishable as discussed before (Section 2.1.1). For example, an external force that is applied to the user, activates the tactile receptors first and when increasing the force it moves the body, which activates the kinesthesis receptors. In this work tactile and force feedback is distinguished through the perception. A pin that stimulates the mechanic receptors uses a force, but stimulates the tactile sense and will be called tactile feedback. A slider or a dial that stops or changes the physical resistance while the user is interacting applies a force on the user's movement and will be called force feedback. Tactile and force feedback have a broad application domain such as for accessibility, robotic, medical (training, surgery robots, rehabilitation), games, arts, interaction on desktop and mobile usage. An overview of haptic feedback technologies is presented in [21, 83, 147, 303]. In the following, selected samples of tactile and force feedback technologies are presented that simulate the haptic sensation in different ways.

2.2.1 Tactile Feedback

Prior work consider to provide tactile feedback through vibration [180], skin stretch [132], temperature [340], air [297], ultrasound [235], laser [221] and water [276]. Electric currents has also been used to generate tactile feedback which is considered in Section 2.3.2. The following selected samples show the variability of tactile feedback and technologies that stimulate the cutaneous receptors [21].

Vibration feedback is the most common haptic feedback technology. It is integrated in nearly every mobile phone and several wearable devices. A vibration-based stimulus on the skin is also known as vibrotactile feedback [147]. Vibration feedback is usually based on simple technology, in its simplest form a small motor with a rotating eccentric mass is used. The imbalance of the mass generates an alternating force that is perceived as vibration by the skin receptors. The motor and mass can be minimized in size. Coin vibration motors are even more compact and flat. Vibration motors are available in various sizes and feedback strengths. Regarding the mass and the motor performance the strength of the feedback correlates with size and the power consumption. Vibration feedback is used in the mobile context for notification [285], enhanced communication [52], for guidance [180] and navigation [325], learning movements [143] and simulation of surface textures [237].

In mobiles vibration feedback is used for notification when auditory feedback is not suitable. Vibration patterns are used for messages, alarms or incoming phone calls [166, 284, 285]. In the touch panels of a mobile device vibration motors simulate the feedback of virtual buttons on a flat screen [102]. Brewster et al. [41] study the efficiency of tactile feedback (sound based vibration) for mobile text entry on public trains. They found that the tactile feedback reduces significantly the number of corrected errors. Likewise, multiple vibration patterns can be presented at the back of the devices such as patterns moving from right to left or from top to bottom [359]. Furthermore, ComTouch [52] transmits additionally to the voice tactile feedback to enhance the communication. This tactile feedback device detects the pressure patterns and intensity of the sender squeezing the device, translates it to vibration feedback, and stimulates the hand of the receiver.

One of the largest application fields of vibration feedback is navigation. Belts are used to code navigation information such as directions and distances [61, 88, 325]. Additionally, Bial et al. [25] investigate vibration patterns with four vibration motors in motorcycle gloves for navigation while diving. Moreover, PocketNavigator [261, 262] used a single vibration motor to navigate pedestrians when the mobile is in the pocket. The navigation was mapped on vibration patterns that the user needed to decode during walking. Further work about haptic feedback for pedestrian navigation will be considered in Chapter 7. Beside navigation Lehtinen et al. [180] uses vibration feedback to support pointing on a large screen. They use vibration motors in a glove to guide the user via a vibration pattern towards a search target on a large screen.

Vibration is also used to teach motion of the lower and upper arm. With the vibration feedback the user performed significantly better in leaning movements after four days of training in contrast to only visual feedback [14]. Another learning scenario uses tactile feedback to increase the piano playing skills after 30 min practicing. Gloves with five coin vibration motors were used while training. Each motor was mapped on one note while playing [143]. Finally, Okamura et al. [237] investigated vibration patterns to simulate behaviors of the surface with different materials such as wood or steel for virtual environments. They applied the feedback while users were interacting with virtual objects. The simplicity and the small size of vibration motors lead to the success of vibration feedback.

Tactile feedback has also been presented though other mechanisms. For example, tactons is a non-visual display that uses an array of vertical pins to present “tactile icons” to the finger tips of the user [40]. The icons follow patterns of positions, frequencies, amplitudes, durations and rhythmics of tactile stimuli. Moreover, force is used as an approach to stretch the skin at the finger tip for tactile feedback [132]. Likewise, Luk et al. [197] stretch the finger tip with feedback patterns for list selection and scrolling, direction signaling and background notification when interacting with a mobile device.

In addition to the mechanic tactile feedback, temperature changes were used for thermal feedback. Wettach et al. [347] discuss potentials and challenges of thermal feedback for mobile applications. It has been tested all over the body such as fingertips, palm, forearm, wrist and upper leg. For mobile use the position on the hand palm, the wrist and the upper leg were compared [126]. The hand palm was identified as the optimal position for thermal feedback in a mobile context. Thermal feedback is compared to the other tactile feedback technologies [350] and is used for thermal icons [349]. Thermal feedback was integrated in clothing and it has been shown that higher thermal changes are necessary to feel the stimulus. The material between the thermal source and the skin changes the response time for example with no material the stimuli took 3.06 s, for nylon 3.3 s and for cotton 4.71 s [126]. These tactile feedback technologies are designed for mobile usage and the feedback is applied directly to the user's body.

Tactile feedback technologies have also been integrated into the environment of the user. Therefore, different methods and technologies have beed investigated such as air pressure, ultrasound, laser and water, to simulate the user's tactile receptors. For example, air-vortex (closed air loop) can be perceived by users at a remote location. AIREAL [297] uses this air pulses that are precisely shot towards the user's point of interaction. Their approach is limited to a distance of up to 1 m and has a low tactile intensity. AirWave [119] provides tactile air feedback with larger distances up to 3 m. Air is also used to produce pressure on extremities such as the wrist to present tactile feedback [263]. Ultrasound waves that are collimated on the surface of the skin can also be perceived as being tactile. Ultrasound feedback is provided by Obrist et al. [235] with 64 ultrasound transducers in an 8x8 array connected to the user. The transducers provide different frequencies and rhythms as feedback. Hoshi et al. [140] used an ultrasound array of 18x18 transducers to simulate tactile feedback of virtual objects. Lately, lasers are being used to generate a tactile sensation on the skin [179, 221]. They used laser-induced thermoelastic effects to stimulate the mechanical receptors on the skin. Finally water has also been used to generate a tactile sensation under the shower [141], as design element for tangible interfaces [208] and touch interfaces [276].

The presented feedback technologies stimulate all tactile receptors through various stimuli, patterns and materials. Looking at the history of research the first prototypes were usually complex, large and were limited in resolution. These are suitable to understand the basic concepts and investigate first interaction concepts. Over time the prototypes are getting smaller and obtaining higher resolutions to investigate more complex interaction techniques and combine them with other input and output technologies. Finally some of the technologies have shrunk and have become mobile and wearable. However, these tactile feedback technologies are limited in strength and only stimulate the surface of our body - the skin. Movements of the body and the physical response of objects due to force can be only simulated implicitly with tactile feedback. In order to simulate these behaviors explicitly a strong force is needed. Such a force needs the capability to simulate physical properties such as the stiffness of virtual objects or the ability to move body parts in a certain direction.

2.2.2 Force Feedback

A force that is applied to the human's body is perceived as tactile and a kinesthesis sensation. ISO 9241-901 [147] defines force feedback as a force that is presented to and perceived by a user. The feedback devices generates the force stimuli that the user's kinesthetic system perceives with receptors in the body as discussed in Section 2.1.2. The perceived feedback should be mapped to the interaction for example hitting a ball generates resistance.

Force feedback is used in robotic, medical (training, surgery robots, rehabilitation), games, arts, and interaction on desktop and mobile usage. It makes the interaction with a system more realistic [78, 300] or simulates behaviors that are hard to test in the real world such as inserting a needle through tissue, cutting with a scalpel through human skin or driving a car [75, 210]. In many cases force feedback technologies are used in stationary systems and for specific applications [75, 105, 108, 227, 345]. Force feedback can be generated through vacuum, pneumatic and hydraulicsystems [122, 323], magnetostrictions systems [22] and electromagnetic motors [130, 131]. There are several books that discuss typical feedback procedures and technologies such as [26, 83, 105, 117, 166]. In the following examples are presented of how these technologies apply force feedback in human computer interaction.

For example, air pulses or vortices do not produce enough force to move limbs [263]. But, vacuum can be felt sucking the flesh of a finger through a hole on a surface. VacuumTouch [122] uses this effect on interactive surfaces to provide feedback depending of the presented context. Magnets can also be used to produce force feedback. FingerFlux [345] is a magnetic based near-surface force feedback approach. An array of electro magnets under the screen manipulates the interacting finger that has a magnet applied on top of the fingertip. Depending on the content targets gets an attractive or repulsive force. Furthermore, similar to motor driven force feedback devices, Berkelman et al. [22] present a magnet driven device for 3D interaction with six degrees-of-freedom. In addition to magnet force feedback, the moment of mass inertia or gyro moment are used to produce a counter force to movements or let move an extremity to a certain direction [316, 357]. Furthermore, GyroTab [11] uses this force on the back of an mobile device to extend the interaction. The rotation speed of the motor and the mass give the maximal force that can be generated by a device and limit minimum size.

Motor-based force feedback can be applied directly through mechanics, to the user's body and indirectly through joints or spiders. These are the most common force feedback devices One degree-of-freedom (DOF) force feedback devices simulate physical behavior of interfaces such as buttons, doorknobs, dials or sliders. For example, knobs for doors are expanded with additional force feedback [204] or dials that simulate physical properties [121]. Similar, Swindells et al. [310] rendered friction, inertia, and detent and developed from the findings guidelines for physical consoles. Moreover, different properties for linear sliders where evaluated with force feedback [171, 279]. Also physical behaviors of handles were being simulated such as TorqueBAR [311], which simulates the torque of a tilting physical mass.

More complex stationary systems provide force feedback for six or more DOF. Systems such as RUPERT [13, 127] (a pneumatics based system), ARMin-arm [227] and Freedom-6S [72] are used for rehabilitation, simulate properties of objects in virtual environments, and for remote control [212]. They simulate properties such as hardness and softness, size/volume, shape (spheres, cones, cylinders) and weight [83, 298]. Moreover, in medicine stationary force feedback systems are used for training and to control surgical robots [59, 317]. For training, force feedback simulates properties of the skin, cartilage or bones and other tissue such as the resistance, friction and depth [71] with devices like PHANTOM Omni [108], HapticMASTER [331], or VISHARD10 [327]. These medical force feedback systems are also used to control surgical robots [209] such as DLR MIRO [123]. They are used for high precision tasks and give very precise feedback [236]. Furthermore, medical force feedback systems are used as actuation devices for rehabilitation, Maciejasz et al. present an overview [201]. However, depending on the application scenario the devices control movements of the whole arm joints or single fingers like CyberGrasp [64]. The precision of the actuation depends also on the application filed. Devices like the CyberGrasp and PHANTOM Omni are also used to simulate object properties in virtual environments. Furthermore, for increasing the interaction space SPIDAR-8 [105] uses, similar to CyberGrasp, strings to actuate the arm or the fingers. Such devices focus on force feedback to different parts of the body such as fingers, hands, arms and shoulders.

Exoskeletons actuate whole body parts such as arms or legs moving them to a specific position and oientation. Lo and Xie [187] focus on the upper extremities in their literature review. Dollar and Herr [78] present a state-of-the-art overview of exoskeletons for lower extremities that support walking. Pons gives a general overview of wearable exoskeletons [267]. For example, arms can be moved for training [13], but also for simulating the resistance of robot arms [227]. Furthermore, Tsagarakis et al. [323] present a 7 dimension-of-freedom (DOF) system for VR based on pneumatics. On the other hand for lower limbs the Hardiman [92] or BLEEX exoskeleton [161] increases the carrying power of the user in mobile scenarios. In addition, body exoskeletons suits such as HAL-5 exoskeleton [159, 286], nurse assisting exoskeleton [355] or muscle suit [169] are used for rehabilitation and to support users in lifting heavy objects. Such exoskeletons can be used in virtual environments to simulate object properties [101]. For mobile use the power consumption and the duration of usage are the major challenges.

Finally, high fidelity force feedback simulators work with hydraulics and lift the whole human body up, down and rotate it, to simulate acceleration, rotations and g-forces. Such simulations are limited to scenarios such as spacecraft, aircraft and driving. The simulators are used for training and testing in cases where it is too expensive and too dangerous to do in real environments [54, 99].

The application areas of force feedback systems are broad, simulating the behavior of physical objects or augmenting the abilities of the user. Different technologies are used to generate and apply the force feedback. The variability of feedback goes from a small nudge to a strong force that moves body parts or the whole body. The parts of the body that are actuated depend on the usage and goes from a single finger joint up to the legs and full body. Therefore, the device size and the power consumption vary. Furthermore the precision and accuracy varies between the different application areas. Overall force feedback systems are used mainly in stationary or in specialized environments. Mobile systems have a correlation between maximal force, period of use, size, and weight of the system.

2.3 Electrical Muscle Stimulation

Electrical stimulation has a long history in the medical field. It has been adopted for fitness training and started to enter the mass market. Recently it has been used to support human computer interaction and is integrated in wearable devices. In the following the focus we first on the history and discuss the application fields of medicine, rehabilitation, fitness and arts. Next it is presented how electrical tactile and force feedback is used to support human computer interaction and finally it is discussed how stimulation electrodes for EMS can be integrated in textiles and wearables.

2.3.1 EMS Background

Electrical stimulation has been investigated since the 18th century. Galvani explored the mechanical responses of muscles in 1791 [106]. In the 19th century Duchenne, Erb, Remarck and Du Bois Reymond founded a base for today's use of electrical stimulation in medical applications [165].

Electrical stimulation is known and discussed under many different names such as transcutaneous electrical nerve stimulation (TNS or TENS) [74, 295], functional neuromuscular stimulation (FNS) [163] also as electro-motor stimulation [186], electromyostimulation [223], electrical muscle stimulation [91, 186] (EMS) or functional electrical stimulation (FES) [165, 361] as well as neuromuscular electrical stimulation (NMES) [164] or Russia electrical stimulation [339]. These are often used in literature as synonyms or they overlap one another. Electrical stimulation uses small currents to stimulate muscles, receptors and nerves. There are two main medical fields using electrical stimulation for therapies. The pain therapy that stimulates receptors to reduce the pain sensation of receptors and nerves, such as in joints and muscles, [74, 295] and functional stimulation to actuate the muscles for medical application [165], rehabilitation [211, 246] or training [93, 206]. The application differs in parameters such as intensity of current, frequencies, patterns, application periods and applying position. In this thesis the term electrical muscle stimulation (EMS) is used as an acronym for electrical stimulation. The different parameters and settings are discussed in Section 4.1.

In the 1950s the first broad use of EMS in a medical application was for the pacemaker. Both external and implanted pacemakers were investigated [165]. In its current form, EMS goes back to the 1960s, where Liberson et al. [182] tested the actuation of simple limbs such as feet and hands. Lloyd [186] gives a general overview of the beginning of the use of electrical stimulation in rehabilitation. Moreover, Strojnik et al. used it for rehabilitation therapies [305] in the 1970th. They investigated how complex muscle movements can be supported through muscle stimulation and supported stroke patients while walking. The rebuilding of movements such as for cycling is considered by Gföhler [112]. Kern [165] reports about the effect of EMS training with paraplegia patients and shows that the size of muscle fibers and blood flow both increase. The function of upper limbs are supported with electrical stimulation to relearn reaching and grasping of objects [168]. Keith et al. [163] considered a fully implanted system that enables full grasping gestures.

Gillert [114] describes early application areas for electrotherapy. Porcari et al. investigated how EMS impacts on different human body parts [269]. Similar Popovic [269] reviews technologies for grasping and walking. Masani and Popovic [211] present applications and work about the foot drop problem, walking, standing, reaching and grasping. Further research review will be found in [20, 24, 361]. However, in this work it is focused only surface application of EMS and neglect implants and injections as discussed in [163, 165].

EMS is also used to train the muscles of athletes in sports. Ward and Nataliya [339] discuss a training method that is supposed to increase the force of athletes about 40%. They give details about the so called Russian electrical stimulation such as signal forms and application intervals. Effective training and development of the user's physical performance are discussed in [63, 94]. Morrissey [223] presents a review the first work on EMS in sports medicine. Kern [164] gives an detailed literature overview about current uses of EMS in sports and physical medicine and rehabilitation.

Beside research projects EMS output is already used commercially in products and art performance as shown in Table 2.1. In rehabilitation, wearable systems support stroke or spinal cord injury patients in grasping such as the NESS H200 [28] or the Bionic Glove [271]. UnlimitedHand [120] is a haptic game device. That haptic feedback bracelet generates hand movements with EMS electrodes on the lower arm. The feedback depends on the game situation. Furthermore patients with the so called foot drop problem are supported while walking (L300 [27]). Such stroke patients are not be able to lift the foot tip during the swing phase of walking. With an EMS contraction the foot tip is lifted up when the patient raises the foot. Mainly for fitness training portable EMS devices were developed by Brewing [39] and Miha Bodytec [218]. This full body suits contact the main skeletal muscles while performing simple exercises. Finally, artists have used EMS as an output technology to manipulate facial expressions [84, 85] or the whole body [302] and to let a group of people perform music (DUTY [69]) or even let people fight (GAME ON [70]).

Project	Description	Actuated Muscles
NESS H200 [28]	Rehabilitation device that helps stroke patients to grasp objects	In the lower arm to enhance the grasping strength
L300 [27]	Rehabilitation device to support patients with the foot drop problem while walking	In the lower leg to lift the foot tip in the swinging phase
Unlimited-Hand [120]	Force feedback gaming bracelet	In the lower arm for force feedback in the hand
ARTIFA-CIAL [84]	Art project to actuate facial expressions	In the face to change facial expressions
Ping Body [302]	Art performance in which the body of the artist is controlled by ping commands	In the upper and lower body
DUTY [69]	Art performance that lets people play bells	In the arms to lift up and shake the bell
GAME ON [70]	Art performance in which the audience controls two boxers	In the arm and shoulder to perform punches

Table 2.1: Projects using EMS as output.

2.3.2 EMS in Human Computer Interaction

The tactile and force feedback effect of EMS is also investigated, in human computer interaction.

Electrical Tactile Feedback

Small electrical currents can be used to activate tactile receptors and generate a tactile sensation [147]. There are no specific receptors found that explicitly react to an applied current. Moreover the mechanical receptors such as Meissner Corpuscle, Merkel Cell and Ruffini ending are stimulated [153, 154]. The upper threshold ends in actuating the pain receptors. The parameters depend on many factors and will be discussed in Section 4.1.

This tactile sensation is investigated to create haptic display on different places on the body like on the finger tip [109, 353], hand palm [103], forehead [152], and tongue [274].

Kajimoto et al. [151] investigated a grid of 4x4 electrodes for tactile sensation and presented different patterns. Likewise, SmartTouch [155] is device to detect visual textures such as black and white stripe and translate them into an electrical tactile output. Also different colors were translated to a pattern and presented through a electrical tactile grid [154]. Scanned material textures of a paperboard, wood, textile fabric and rubber were simulated on a grid of 32x8 of electrodes (diameter 1 mm, distance 2.5 mm) [109]. Further textures were projected onto a conductive surface. The user's finger was connected to an larger electrode and while exploring the surface a current is flowing, which leads to tactile sensation at the finger tip [353].

Furthermore electrical tactile feedback has been used to support blind people. For example, a grid of golden electrodes (12x12) on the tongue were used to detect the ordination of targets [274]. Furthermore, electrodes were placed on the forehead to feel the texture of images [152].

Electrical tactile displays were also used mobile, they were adopted to the back of mobile devices [103]. Button and icons, which were presented on the screen, give a tactile response on the backside of the device. The user feels the feedback of the interaction in the hand palm when holding the device in the hand. Furthermore, HamsaTouch is an add on for mobile devices that translate the camera input to an electrical tactile image [156]. The hand palm can be placed on the electrode grid (32 x 16) of this device and the user can perceive the shapes of the video stream. The video stream is filtered with a Canny filter and dilation operation to detect edges, which are tactile presented on the display.

Electrical tactile feedback is applied through grids of electrodes with different sizes. The area, where the tactile feedback is felt, can be easily extended and the resolution can be made higher compared to vibration feedback. The electrodes can be designed much smaller than vibration motors since there is no need for mechanics. Furthermore electrode grids can be designed to be flexible and adapted to the surface structure [176, 278].

Electrical Force Feedback

EMS has received considerable attention for providing force feedback in the field of Human-Computer Interaction (HCI). It is still in his infancy and not fully explored. The effect of muscle contraction has been used to present voluntary force as feedback to users. For example, PossessedHand [314, 315] is a device for controlling each finger joint individually by EMS. Two strips with 28 EMS electrodes are used to apply the current to contract the muscle of each joint. The authors show that electrical feedback is suitable for mixed reality, navigation, and learning to play instruments.

In the context of virtual reality, EMS was tested as a feedback method for a 3D computer game [172]. Farbiz et al. [89] investigate mixed reality EMS feedback for visualizing a ball that can be hit by a real racket. Interaction with large displays in public space has been supported by EMS [256]. In a Kinect-based game EMS provides force feedback to users with interaction without a physical connection to the display. Free-hand interaction with large displays will be investigated in Chapter 5. EMS is compared to vibration when performing gestures towards displayed objects. We show the effect of EMS feedback in 3D virtual hand selection in Chapter 6). The results indicate that EMS is a suitable alternative to vibration feedback and visual highlighting. Kurita et al. [173] simulate in virtual environment different strength stiffness with EMS as force feedback. When the user touches a virtual object the hand is pushed back with varying strength. They found a relation between the target stiffness and perceived stiffness. Impacto [191] combines a tactile actuator with EMS feedback for virtual reality. It simulates the impact of virtual objects that are hit by the user.

The real world or objects in it are augmented with EMS feedback to add new behaviors or to communicate with the user on how to use objects or to guide her to a place. Lopes and Baudisch [189, 190] use EMS in a mobile game as force feedback. The EMS generates a voluntary force with the user's lower arms to move the mobile depending on the game situation to a direction. The user mapped this movement of the hand to the device and to the game situation. They investigate strength of EMS signals and test the amount of force a user can provide. In addition haptic feedback for flat surfaces, such as touch displays or tracked paper maps, was investigated [254]. The feedback device is attached to the user and can connect to systems that the user interacts with to provide force feedback. The feedback depends on the presented content such as texture or images. This makes the force feedback always available.

Furthermore, hidden affordances of physical objects or tools were communicated with EMS gestures to the user [193]. Before the user reached, or while interacting with an object, a voluntary force shows the user how the object is to be held or used. For example, a spray needs to be shaken before usage, therefore the device performs a shaking gesture when the user grasps the can or the user's hand is pushed away from a hot cap. In Chapter 7 Cruise Control for Pedestrians is presented. In this approach the walking direction of pedestrians is manipulated so that the user automatically walks to a place in the real world. The user does not need to focus on the navigation task so reducing the amount of visual and mental distraction.

In "follow the force" the user's hand is guided toward a target and disambiguates the target with a midair gesture. The user's finger is actuated with EMS to point into four directions. The user needs to follow the direction of the finger to find the target or draw a midair gesture [158]. The gesture could describe how the targets look like. Lopes et al. [192] presented eyes-free interaction based on proprioception of the actuated limbs. Stages of the software are transmitted through a motion for example on the hand of the user. The hand could present the stage of slider or a progress bar of a video. The user recognizes the position of the limb and maps it to the progress of the video. Nishida et al. [233] present a device for shearing kinetics feedback between two users. As follow up they present bioSync [232] to transfer motion from one person to another. It is an I/O system to measure the muscle activity of the muscles in the lower arm and stimulate it with the same electrodes as output. In Chapter 8 we present an end-to-end system that detects emotion of one user, transmits it to a remote partner and lets her express this emotion as representative gesture using EMS.

2.3.3 Textile and Wearable Output

Since this work focuses on surface electrodes, the EMS signal is usually applied with self-sticky electrodes. These electrodes can be only used a limited number of times and they are not washable. Textile sensor electrodes are already well investigated to measure body feedback such as skin resistance, EMG, ECG, or EEG. They are used in sports, fitness, medical care and physiotherapy [304]. To measure the electrocardiogram (ECG) [266], electromyography (EMG) [308], or electroencephalography (EEG) [188] sensor electrodes are mounted on the skin surface and made of conductive materials. Again, it is focused in this work only on surface electrodes and excluded implanted electrodes. The textile electrodes can be made of metal, conductive plastic, or silicone. In contrast to self-sticky electrodes they can be washable and integrated in the textiles. Such textile electrodes can have different forms so as to cover specific muscles [280]. These electrodes are designed to be comfortable to wear in long-term monitoring. Hoffman and Ruff present flexible dry-surface electrodes for long-term ECGs [137]. Other textile sensor electrodes need salt solution, sweat, or conductive gel for an optimal conductibility between electrode and skin.

In contrast to other haptic feedback methods EMS is lightweight and has relatively low power consumption. The EMS signal can be applied to the user's body through flexible conductive materials similar to textile sensor electrodes. Rotsch et. al. [280] discuss how to use textile sensor electrodes for EMS output. They tested these electrodes with common textile test methods such as washing, against abrasion and sanitizing ability. The authors used typical EMS parameters and concluded that the perceived EMS stimulus does not change after running these test methods compared to new textile electrodes. EMS technology is well suited to textiles since the current is applied to the muscles over the skin, usually at the places that are covered by clothes, such as arms or legs. Similar to textile sensor electrodes EMS electrodes always need a conductive path to the user's skin [266]. This can be achieved with tight clothing such as functional underwear, vests, or bandages.

Project	Description	Electrodes
Miha Bodytec [218]	Gym suit for EMS-based training	Wet electrodes to actuate large body parts
XBody [354]	Gym suit for EMS-based training	Wet electrodes to actuate large body parts
Antelope [342]	Sports suit to intensify exercise with EMS	Silicone electrodes on sweat basis
ARAIG [144]	Sound, vibration, and EMS gaming suit	6 speakers, 40 vibration motors, 4 electrodes
Teslasuit [322]	Force feedback gaming suite	Up to 56 electrodes, type of electrodes are not clear specified

Table 2.2: Projects using textiles for EMS output.

Commercial projects use textile electrodes in the context of sports or gaming (an overview is shown in Table 2.2). EMS gyms like Miha Bodytec [218] or XBody [354] use wet textile electrode bands and electrodes that are integrated into vests to apply EMS current during fitness exercises (Figure 2.2).

Antelope [342] is a full suit with integrated textile electrodes to enhance sports like running and cycling and to make the exercises more exhausting. This suit is connected wirelessly and controlled via a mobile application. ARAIG [144] and Teslasuit [322] are startups that build force-feedback gaming suits. These suits apply feedback depending on the gaming situation, such as when an explosion happens or the player gets shot. Teslasuit has up to 56 electrodes

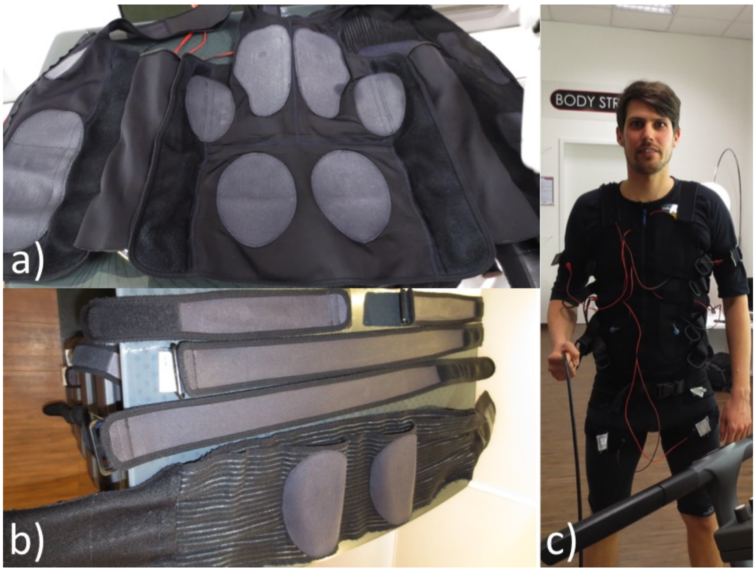


Figure 2.2: EMS training suit with textile electrodes: (a) EMS vest for breast, abdomen, shoulder, and back muscle; (b) EMS bands for arm, leg, and gluteal muscle; (c) a user wearing the suit.

that are supposed to be integrated in the suit. These projects show a general trend, namely that EMS feedback is likely entering the mass market and will be integrated in textile for comfortable wearing.

In this chapter we gave an overview of how tactile and force feedback is perceived by humans. This is followed by an in depth overview of existing tactile and force feedback output technologies.

This shows the variability of the use of haptic feedback and the effort that is required to stimulate physical contact in HCI. Then we discussed the origin of EMS and the main application fields. After that it has been shown how EMS is used in the background of HCI for tactile and force feedback. Finally we discussed how EMS output could be integrated in textiles and clothes to make it comfortable to wear and always available. In the following chapter we envision, based on this background, how EMS could be used in the future and the challenges that need to be solved to achieve it.

Chapter 3

Concept

Everywhere available haptic feedback can help to extend the interaction with our environment. Through this additional feedback channel non-existing object properties maybe stimulated. New ways of manipulating the behavior of users in the real world, such as moving a body part towards a direction, become possible. Copying gestures or movements from other persons can be achieved with force feedback.

In this chapter we first introduce the concept of *ubiquitous haptic feedback*. Then we discuss the limitation of common haptic feedback methods regarding the trend of miniaturization. As a next step we consider how EMS feedback technology fits into this trend to achieve this concept. Following the idea of EMS-based ubiquitous haptic feedback, we envision new applications in the context of notification and coded information, extending object properties, guidance, safety and prevention, assistive feedback and learning movements. As a next step we focus on challenges that need to be solved in order to use EMS feedback technology to achieve ubiquitous haptic feedback in the long term. To show the potential of EMS as feedback technology and looking from a different HCI perspective at the technology, we select three application areas. The focus is on extending virtual objects with physical properties in virtual realities, real world manipulation of users and haptic notification representation with gestures. While doing so, we point out scenario specific challenges that are considered in Chapter 5, 6, 7 and 8. Finally we discuss how EMS feedback could be controlled through open and closed feedback loops.

3.1 Ubiquitous Haptic Feedback

The real world starts to fuse with the virtual world. Passive objects become interactive and new ways of representing information appear such as textile displays [238, 247]. The world is augmented with new additional features such as virtual objects, that users can interact with. The borders between reality and virtuality become indistinct, it is a reality-virtuality continuum [333]. These technologies are leaving labs and specialized environments and becoming integrated in our environment. Cars see their environment to detect pedestrians [87, 110] and smart watches understand what we ask them [37]. Additionally, wireless communication is nearly everywhere available. One main reason why technology penetrates our everyday life is the trend of miniaturization, reduction of power consumption and a wireless communication of such devices. Nowadays computers are in our environment anytime and everywhere.

This is known as pervasive and ubiquitous computing. Ubiquitous technologies support us in our everyday life and are integrated in our environment [290]. The vision of Mark Weiser comes almost true, infrastructure technology is shifted to the background and devices with different size (tabs, pads and boards by Weiser) are always connected [344]. For example, mobile devices let us communicate with people remotely. Also personal data such as documents or emails are always available. Furthermore, these devices instantly teach us new tasks or how to use a tool such as to tie a tie or to use a chainsaw safely. Mobile devices provide such information mainly through the auditory and visual channels. However, the haptic channel is often neglected, regarding the fact that for haptic feedback technology it is hard to realize this trend of miniaturization. As discussed in Section 2.2 the haptic sense is very important in HCI and a lot of effort has been done to stimulate this sense. The absence of one basic feedback channel (vision, audio or haptic) can make the interaction unnatural [76]. For example, when the user interacts with virtual 3D objects the haptic properties of the physical object such as force or rigidity are missing. Haptic feedback could add such features to a virtual object and voluntary movements can simulate these missing haptic properties. Furthermore, the auditory or the visual channel is often overloaded. The presented information could be swapped to the haptic channel to reduce the load of the other channels. For example, instead of presenting navigation information on the device, a voluntary force can manipulate the walking direction and navigate a pedestrian towards a destination. The user does not need to focus on the navigation task any more.

Mark Weiser neglects this haptic feedback channel in his vision [344]. Everywhere available haptic feedback technologies with a large variance of feedback could support the user in many scenarios. We will call this approach *ubiquitous haptic feedback*. Yet, the potential of the haptic feedback channel is not fully used. In contrast to the visual and auditory sense, the haptic sense is not clearly located. As discussed in Section 2.1 the haptic sense is divided into sub-sensations such as tactile and force sense. Further, the whole skin (1.79 m^2) is tactile sensible and the body has about 700 named muscles. This is a large area where the user can perceive feedback from the environment. This work enables this potential to present *ubiquitous haptic feedback* to users.

The requirements for ubiquitous technologies are a high level of embeddedness and mobility [199]. Hence, the technology to provide ubiquitous haptic feedback can be either integrated in the environment or placed on the users. In the latter case, the user is augmented by the feedback technology, which follows her, and the feedback can be applied when it is needed. The feedback technology needs to communicate with the environment. It is very important that the technologies is light weighted and do not disturb the user in everyday life. Such a feedback needs the strength to lift whole body parts to let the user perform voluntary movements and produce a counterforce against the movements.

3.2 Miniaturization of Haptic Feedback

To follow Mark Weiser's idea and to achieve *ubiquitous haptic feedback*, tactile and force feedback should be everywhere available and have the requirements as discussed above.

Haptic feedback technologies can either be loacted in the environment [105, 297] or on the user herself [159]. The ubiquitous haptic feedback could be passive or active when it is integrated in the environment. Passive ubiquitous haptic feedback in a virtual environment could be objects that are already there and are integrated with the into a virtual scene [301]. Such an object should have similar haptic properties to and needs to be at the same place as the virtual object. The user perceives these haptic properties when she is interacting with this object. Active ubiquitous haptic feedback manipulates the user and influences the physical behavior. An example of an active ubiquitous haptic feedback system is a lane keeping assistant that turns the steering wheel to bring the car back onto the lane when the user is inattentive. The user perceives this when the hands turn with the steering wheel. Augmenting the environment takes a large effort and is hard to achieve in mobile scenarios. For example, when the user leaves the car the feedback technology does not follow her. In cases of augmenting the user, the technology is worn by the user and follows her [293].

On one hand, tactile feedback technology already follows the trend of miniaturization and shrinks down step by step. Tactile feedback devices are mobile, wearable and some are already integrated in textiles. However, tactile feedback technologies are very limited in feedback strength and some still have a high power consumption (Section 2.2.1).

On the other hand, force feedback devices have made it hard to follow this trend of miniaturization. Motors and mechanics that generate force feedback are hard to shrink down. There is always a relation between the generated force and the size of the device. For example, a force feedback device to lift up a leg or an arm needs strong motors. In a mobile context the user additionally need to wear the weight of the device including the batteries. Some devices become mobile, such as mobile exoskeletons suits [159], but they still have high power consumption that leads to a limited usage period. The extremities that are manipulated need to be fixed onto the device, which can make long wearing periods cumbersome. As well, they usually obstruct hands, forearms, legs, and other body parts and restrict both the tactile sense and the mobility of the user. Finally force feedback devices are often bulky [64, 169] that could lead to social acceptance problems when wearing such a device in everyday life. These issues restrict many force feedback technologies to labs or very specific applications such as surgery robots (Section 2.2.2).

Regarding these problems we believe that there is still an open gap between miniaturized tactile feedback and strong force feedback to achieve *ubiquitous haptic feedback*.

EMS has a large variance of feedback, from tactile sensation to strong force that can move limbs such as fingers, arms or legs. Research from medical and rehabilitation fields have shown that complex movements can become possible (Section 2.3.1). Compared to most of the common feedback technologies as discussed above, EMS does not need mechanical parts to generate haptic feedback. EMS activates the force of the user's muscles, which reduce the power consumption. As discussed in Section 2.3.3, wearable and textile electrodes are available for measuring EMG input and can be used for EMS output. EMS technology that is integrated into textiles and with this saving of power consumption can run the whole day. The feedback becomes accessible any time and everywhere. We believe that EMS haptic feedback can achieve *ubiquitous haptic feedback*.

3.3 Vision

Given the idea of an EMS-based *ubiquitous haptic feedback*, new applications and interaction techniques become possible. The application fields are very broad, ranging from virtual and mixed reality over real world interaction to communication of abstract information.

Notification and coded information: EMS can be used for new forms of notification in everyday life scenarios. Silent but immersive alarms can inform users about upcoming events or messages. The user feels the feedback or performs a movement or gesture and becomes the output device. A smartwatch that is connected to the muscles of the user's lower arm could make the user lift the hand up and then push it down, to let the hand wave. Such a waving gesture could be mapped to event or message types. If it is a standard gesture, the user, but also the people around, can interpret the gesture. A new sign language for actuated output could be created. This abstract information could be a message or notification that represents the mental stage of the sender. The receiver could be used as an output device and could present it in an immersive way, such as through a complex actuated gesture. Moreover, a private silence message could be communicated to the user through tactile feedback or coded in secret gestures that only the user knows. The output device and the user could have a shared secret like a pin code. In addition the system detects a combined authorization gesture in which one part is performed by the device and an additional part by the user.

Extending object properties: In interaction with non-physical or virtual objects in virtual or mixed realities direct haptic feedback is often missing. The user interacts in mid-air and does not feel the object size, weight, or surface structures. Furthermore, the user often does not want to have the hands covered with an additional device. In case of a ubiquitous haptic feedback such object properties can be simulated by EMS feedback. For example in remote interaction with public displays, the user may not be able to touch the surface of the display, so the user interacts in mid-air [256]. Varying strengths of EMS feedback may simulate the different properties. Moreover, touch displays usually have flat surfaces. A ubiquitous haptic feedback could simulate surface texture or resistance of a button [254]. In another real world scenario, EMS gestures can present missing physical object properties to the user. A number of physical objects have hidden or not directly visible affordances, such as a door knob that needs to be turned in an unusual way. In this cases EMS gestures could communicate this missing affordance to the user [193].

Guidance: Haptic feedback can guide people to objects or points of interest in our near environment or further away. In our near environment a hand on a paper map can be guided by EMS feedback to a point the user is searching for. In addition, the spatiality of a map can be explored by simulating the surface structure such as streets and buildings [254]. A complete tracking of the environment and an automated search would be necessary. Guiding people to lost objects is still challenging [104]. It could be possible to show the direction towards the lost object with the hand [315]. The user only needs to follow the finger or hand. In this case no audio or visual output is necessary to find the lost object. Similar to this situation, the user could be guided to a sight with the hand and distinguish it from other sights with a representative gesture [158]. When ubiquitous haptic feedback becomes available, it enables people to be navigated in everyday scenarios.

Safety and prevention: In working environments people are often exposed to dangerous areas or are located close to dangerous machines. Force feedback can reduce the likelihood that a worker moves towards dangerous areas. The force feedback can push the hand of the worker away from hot objects or dangerous machines when the worker is inattentive or distracted from the main working task [193]. Moreover, an accident avoidance system can prevent a person from running in front of a car. Inattentive pedestrians can automatically change the walking direction or stop before they enter a critical situation. Finally a vestibular correction system could prevent a person from falling by automatically triggering a side step.

Assistive feedback: Assistive feedback with EMS is already considered in research and in commercial products that support stroke patients while performing grasping or walking movements (Section 2.3.1). In the future with electrode grids and closed control loops, it could be possible to let the user perform more precise and more complex movements or gestures. This can support stroke or paraplegia patients but also a normal user in their everyday life. Moreover, blind people could be assisted while walking to let them feel obstacles in front of them. A virtual white stick could provide a haptic response and make the obstacles in the environment perceptible or automatically guide the user around them. It is possible to simulate textures of visual representations such as photos or figures, but also of 3D models with EMS feedback [254]. This could assist a blind person to explore haptically such presentations that are only visually perceivable.

Learning movement: Learning movements, movement sequences, gestures or postures with high precision involve many training repetitions and corrections. Nowadays teachers or trainers support people while learning. Today most practices are done in groups, since one-to-one mentoring is costly. Yet one-to-one mentoring is often more effective. The teachers or trainers are not always around. One of the most common health problems related to modern office jobs are spinal and back disorders that mainly result from wrong sitting postures. In back therapy physiotherapists teach correct sitting postures and special exercises for the back muscles. When no trainer is around, sitting postures may be monitored and haptic feedback given automatically through EMS. EMS could actuate the back muscles to help the patient move into the correct sitting posture while training the neglected muscles. Furthermore, haptic tutorials can teach new movement sequences such as dancing steps. It is hard to control the whole locomotion system but pushing or moving body parts into the right direction is often feasible. In addition, learning rhythms could be supported by EMS feedback to find the right moment. As well playing music could be assisted by a system to learn a sense of timing [315].

There are many more examples and application scenarios that could benefit from ubiquitous haptic feedback that is always, or in specific situations, available.

These are everyday scenarios transmitting abstract information though the haptic feedback to the user. The information is represented through haptic pattern, voluntary movement, gestures or counter force and it could be a notification, a message, an instruction, a guidance, or a warning. The feedback could be position dependent and be applied on different body parts. Depending on the position or pattern the user can decode the information. Furthermore, the transmitted information can be context or location specific. The information can also be a simulated property of objects that does not exist or add new properties to existing objects. Furthermore new properties can be added to the environment. Such as a path that only exists virtually. Or voluntary movements can let a user perform abstract gestures or postures to communicate such abstract information. *Ubiquitous haptic feedback* can actuate the user in this situation and communicate this abstract information. Again, the feedback must be suitable for everyday scenarios and needs large variability.

This information could be transmitted either tactilely on the skin or with force on the body by moving a body part rhythmically. Tactile feedback is perceivable on the skin and simulates objects that hit the skin or a sequence of tactile feedback could simulate objects moving over the skin. Finally abstract patterns could code silent, not visible notification or messages. With regard to the large area of the tactile sense, the position could also be used to represent information. Force feedback can apply volunteer force, counter force and apply movements when the user stays relaxed. This kind of force can simulate object properties, resistance or code other information. It can also support the user while grasping or walking. When applying movements that the user needs to interpret, the user becomes the output device.

Some of the examples could easily be explored and some pose enormous research challenges. Some of these ideas are already partly explored with EMS feedback in research, as discussed in Section 2.3.1.

To achieve and explore such envisioned examples using EMS technology as ubiquitous haptic feedback, several challenges need to be solved. Some of these challenges come along with the characteristics of EMS technology and others appear in specific application scenarios. In the following Section 3.4 we first look at such more general challenges and discuss in Chapter 4 how to face these challenges. Then we select aspects as envisioned from three HCI areas to investigate different perspectives of this approach. We focus more into the detail of how virtual and mixed reality interaction can be supported, how the user can be manipulated in a real world scenario and how abstract information can be represented with EMS as haptic feedback technology (Section 3.5). After shortly introducing the application area and considering the aspect, we discuss which specific challenges need to be solved to use EMS in these scenarios and what we can learn from a HCI perspective. In Chapter 5 to 8 we will explore and implement the application scenarios using EMS as haptic feedback technology.

3.4 Challenges

EMS-based haptic feedback in HCI is still in it infancy. The reasons are therefore, the large entrance hurdle and understanding of this immersive technology, the lack of processes to use it in HCI and user acceptance. For example, to achieve a single voluntary movement, at least two electrodes need to be placed exactly over a muscle and in general the movements look awkward and imprecise.

The information that should be transmitted needs to be composed into haptic feedback that is suitable for EMS. To copy a behavior from the real world, this behavior needs to be split into its separate parts and translated into EMS movements or tactile patterns. It needs to be considered where the EMS current should to be applied and how strong the feedback needs to be to get the expected feedback. For example, when the system should let wave the user's arm. The elementary movements are lifting the hand up and pushing the hand down. This requires knowledge of how this movement is generated naturally, which muscles are involved, where and how many electrodes need to be placed, what kind of parameters for an actuation current is needed (strength, pulse form, pulse width, frequency or action length), what are the user's individualities and how the current is applied in a safe manner.

However, adopting EMS from the medical field as haptic feedback creates specific challenges. The most obviously challenge is, to control the current, which is actuating the user's tactile sense or muscles. Applying current to users concern always safety. Before using EMS with users, a basic understanding of the technology is necessary. In Section 4.1 typical EMS parameters are presented that are adopted from the medical field. The presented parameters are successfully tested in user studies and workshops. The second challenge is applying EMS feedback to users. The placement of electrodes to achieve movements, gestures and counter force is complex. This work focuses on surface electrodes regarding user acceptance and safety aspects. In many cases, it makes it hard to reach deep and overlaid muscles. However there are several muscles that can be easily reached with surface electrodes (examples are presented in Section 4.2). It is also described what need to be taken into account when placing electrodes. Furthermore, in the context of HCI there are no guidelines that describe user individualities and a user dependent EMS calibration for tactile sensation or movements. There are no standards for which parameters need to be reported when running EMS experiments. However, there are medical issues with EMS that are even more important when using EMS in a non-medical background. With regard to these issues some user groups could not use EMS such people with implanted pacemaker. These aspects need to be taken into account when EMS is applied to users as haptic feedback for prototyping.

After adopting the EMS basics to the HCI context and understanding the technology, there is still an entrance hurdle to using EMS in research projects. Prior devices are from the medical application field and they do not have the adjustment to be used without modification for HCI research. An initial effort to build control software and hardware needs to be done before using EMS as haptic feedback technology. Following the ubiquitous vision, EMS technology needs to be portable and lightweight. Moreover, a wireless communication to integrate the feedback technology and to communicate with other devices is necessary. This increases the flexibility and enables an easy interaction in new application scenarios or prototypes. There are no standards for protocols or interfaces to control EMS feedback parameters. Furthermore, it is not clearly defined how to use EMS feedback in prototyping and in user studies.

To tackle these challenges and to reduce entrance hurdles, enable flexibility and easy interaction the "Let your Body Move" EMS prototyping toolkit has been developed (following RQ1). An EMS prototyping process (Section 4.3.2), the toolkit implementation (Section 4.3.3) and a set of simple applications (Section 4.4) are presented. In a first evaluation, the toolkit was used in a workshop to investigate new ideas in EMS-based prototypes [194].

Such toolkits and guidelines help to reduce the entrance hurdle for other technologies and help to focus more quickly on the essential interaction techniques [142]. The developed toolkit is used to explore the idea of ubiquitous haptic feedback in HCI from different perspectives and to implement aspects that are discussed in the next section

3.5 Investigated Application Areas

The envisioned fields of applications for ubiquitous haptic feedback are notification, extending object properties, guidance, safety and prevention, assistive feedback, supporting rehabilitation or learning movements.

We selected three application fields and looked at the approach from different perspectives to explore and show the potential of EMS as haptic feedback. From these fields we implement four aspects using the EMS toolkit (Section 4.2) and investigate RQ2 - RQ5. Such examples cover interaction in virtual or mixed-reality situations, manipulation of the real world and

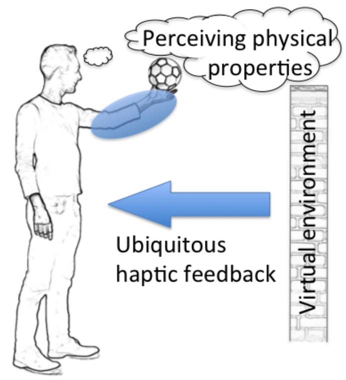


Figure 3.1: Ubiquitous haptic feedback lets the user perceive additional physical properties of virtual objects.

coding and transmitting abstract notifications. The way EMS can be applied and used as haptic feedback strongly depends on the application scenario. Therefore we introduce first the application field and then the specific challenges that need to be solved.

3.5.1 Haptic Extensions of Virtual Objects

In augmented reality (virtual or mixed reality) the visual channel presents virtual objects or extended physical objects. As discussed before, interacting in mid-air the user is not able to feel the object size, weight or surface structures, when no haptic feedback is provided. An example of a virtual object is an icon displayed in front of the user. The user can touch the object without feeling resistance or other specific properties, which is an unnatural behavior. Additional feedback can enhance the interaction by simulating the expected physical properties as shown in Figure 3.1. Extending this interaction with EMS instead of using common force feedback technologies requires the design of a new EMS-based haptic feedback. The location, timing and parameters of EMS to simulate physical properties need to be investigated. Therefore, the muscles that can be actuated with EMS to simulate these properties need to be identified.

However, the position of the applied EMS feedback and the resulting movement of limbs usually differ. Most muscles that actuate basic hand movements are located in the lower arm. EMS feedback might be well suited to free-hand interaction, following the notion of Nancel et al. [225]. Considering free-hand interaction brings further requirements such as the user's hand should not be covered with special feedback devices. Following the mid-air interaction example, the interaction surface or virtual objects could be unreachable for the user. When the user touches or grasps towards an object, the feedback needs to be activated. In general, the user performs different gestures (such as touching, grasping or punching) when interacting or exploring objects. These gestures should be also reflected in the feedback design. The feedback should also be related to the physical properties of the displayed object. For a well realistic EMS feedback, the different feedback parameters need to be explored. Finally, the EMS feedback should be compared to common feedback technologies such as vibration feedback.

However, when objects are displayed in a reachable distance in front of the user, the object could be used for input such as menus or buttons. Similar challenges appear as in 2D target selection [296]. The target could be occluded by a body part and it could be very small so the user does not see if she is hitting the target. A visual, tactile or a force feedback could give a response when the user has reached the surface of the target. In this case the different feedback modalities need to be investigated to find the best fitting feedback with regard to realism and selecting efficiency.

It is important to understand the differences between other feedback modalities when designing EMS feedback for virtual or mixed reality. Usually different feedback modalities work in the same scenario. The feedback designer needs to understand feedback abilities and find the best fitting technology for most realistic feedback for each application scenario. Simulated properties such as hard, soft, surface texture, friction, size, weight, rigidity, force or torque need to be investigated separately. Such object properties stimulate various nerves. Therefore the right haptic stimuli to simulate a property need to be found. The different haptic feedback channels need to be explored in a sense of how "natural" the feedback stimulus is perceived by the user and in which way such stimulus can be simulated and generated. Beside the realism of the feedback, it should be effective when using the object or target for input. The effectiveness is reflected through the movement time, error rate and throughput [95, 146]

The challenge is to find a feedback setting with the most realistic stimuli to make the interaction as natural as possible and with the most effective feedback for target selection (RQ2). In Chapter 5 a set of interactions with virtual objects are explored and extended with two haptic feedback modalities. We systematically compare EMS and vibration feedback in the context of free-hand interaction. With this finding in Chapter 6, these feedback modalities are used to support a 3D hand target selection task of virtual objects (RQ3). In a Fitt's Law based experiment the feedback modalities are compared [95]. With these two application scenarios we show how EMS-based haptic feedback can be used in mixed and virtual reality to enhance the interaction with physical object properties.

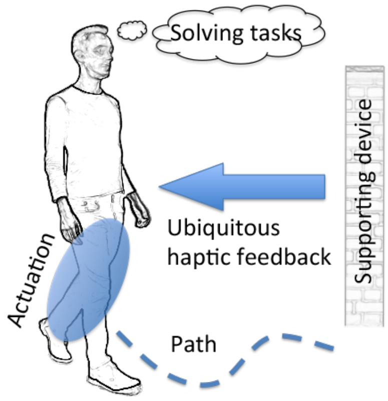


Figure 3.2: Ubiquitous haptic feedback supports the user by performing a task to free sensing capabilities and processing capacities.

3.5.2 Haptic Real World Manipulation

Interaction with the real world involves several senses such as visual, auditory or haptic senses. Sometimes the main task of a person involves their full attention. In contrast to the previous aspect, this approach focuses less on addressing the senses of the user to enhance interaction, but more on manipulating the user's body to free sensing capabilities. The user can be actuated to solve a task instead of transmitting information such an instruction. The perceptual system does not need to process the sensed information and the user does not need interpret those. This can free the sensing and processing capacities of the user shown in Figure 3.2.

For example, users of mobile devices often do not have the cognitive or visual capacities to focus on the surroundings and on the transmitted information. In mobile scenarios, users have to stop when they walk to interact with the device and continue walking afterwards. Additional visual feedback can be presented in the environment to tackle this challenge for example with projection [352]. This visual feedback could be overlaid by other visual influences such as textures of the projection area or daylight. Audio feedback could [351] be obscured by other background noise. In addition, the audio feedback could obscur important auditory information from the environment, such as an arriving car. Moreover, haptic feedback such as vibration [325] or actuation [213] is used to inform the user about the surrounding or guiding people. However, the user still needs to interpret information and map it to the interacting context. As discussed, EMS force feedback can move body parts. These movements or forces could prevent users reaching a dangerous area or guide the users to a specific point of interest. The users do not need to perceive or to process this information and move the body. The body is directly actuated and no cognition is required.

Pedestrian navigation tasks reflect this idea and the upcoming challenges as well. In the case of navigation the user still has to focus on the navigation task. Mobile devices are used for common pedestrian navigation. In public spaces such mobile devices involve the attention of the users and sidetrack them from the environment, which could result in accidents with other traffic participants [226]. When the user gets the navigation instructions presented visually it is necessary to perceive, interpret and map them to the real world. During this process the user focuses on the mobile device. When an update of the direction becomes necessary, the user manually changes the walking direction [315]. To shorten this process the walking direction could be directly manipulated with a voluntary force feedback to update the direction. This could free the auditory and visual capacity attend to the environment. Apart from attend to that, the information does not need to be interpreted and mapped to the real world, which reduces cognitive load and mapping errors. We call this approach *actuated navigation* and it is considered in Chapter 7. An investigation is needed to determine if the walking direction of pedestrians can be changed with EMS as force feedback (RQ4). This shows if the user's body can be manipulated in a real world scenario with ubiquitous haptic feedback to solve a task. An important area of study is whether or not the muscles can be used to change the walking direction. Further, the correct placement of electrodes must be ensured. It needs to be tested if the manipulation is strong enough to use it for *actuated navigation* tasks. Finally this manipulation of locomotion systems needs to be accepted by the users.

3.5.3 Haptic Notifications

In contrast to manipulating the user's walking direction or to providing subtle force feedback, the actuated movements are clearly visible to the user and other people in the surrounding. In this case the user becomes the output device and can display information or notifications. For example, the user's hand can be actuated to show a direction for guidance [315]. It is a simple pointing gesture that the user could follow. More complex patterns can also be used to code information, as is shown in Figure 3.3.

Interaction with other persons involves speech as well nonverbal elements such as body language. These nonverbal elements enhance the communication and make it more personal [68, 90]. In remote communication, these elements are often missing or are replaced by other symbols. For example when writing a text, emojis are used to enhance the text with emotions. Telephones are extended by a video streams to see the remote communication partner. Facial expressions could be decoded to give information about the emotional state of the communication partner [81]. However, in close relationships, body contact such as hugging or poking, is also used as nonverbal communication. Very personal information such

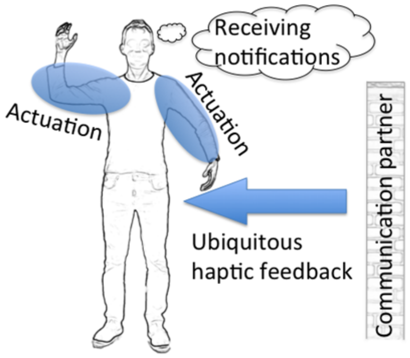


Figure 3.3: Ubiquitous haptic feedback lets the user perform a gesture to perceive notifications in an immersive way.

as emotions are usually exchanged. The way people express them is individually different. People who are familiar to each other usually know the body language of the other person, such as postures, when they are happy or sad. Technology may be used to communicate such physical closeness to remote living partners [77].

An end-to-end approach could involve remote living partners with non-verbal communication to measure and express emotions. Emotional gestures from the human body language could express a mental state. The gestures of the remote partner (sender) could be copied to the other partner (receiver). Again, the receiver becomes the output device of the sender and perceives the emotional information in an immersive and natural way by expressing the body language of the sender. For example, when the sender is sad or angry, the receiver performs a representing gesture with her own body. From the sender side sharing such private information could be done implicitly by measuring the mental state or explicitly by verbalizing the emotion and using symbols such as emojis. We call this approach *embodied emotional feedback*.

This approach opens questions how such a close communication could be supported and how such communication could look like using EMS (RQ5). It needs to be investigated if such a body language or gestures could be interpreted by the receiver and decode emotional information. Furthermore, it is unclear if EMS is powerful enough to let the user express such body language or emotional gestures. It needs to be investigated in which cases the sender would like to communicate the private information implicitly or explicitly. In Chapter 8 we investigate an end-to-end approach for communicating emotion and show a first step of a possible implementation. We show how emotional gestures sets can be applied using EMS and how they can be triggered using EEG (electroencephalography).

3.6 Closed vs. Open Control Loops

As discussed in Chapter 2, there are various technologies to achieve tactile and force feedback. The feedback could be applied in an open or closed control loop. Open loop feedback is a feedback sequence that is played back without considering how the condition or context is changing during the sequence. Closed loop feedback is updated with the conditions and context influence continuously.

Haptic feedback can be scaled with different types of factors. The feedback can be switched on and off or change the intensity over time. The feedback sequence such as performing a gesture could be pre-calibrated and played back or dynamically adjusted. To play back the gesture in an open feedback loop is simpler, since not all conditions and context need to be known for an adjustment. The expected feedback behavior of the user will be calibrated beforehand. During interaction the feedback is triggered once and will be played back as it was calibrated. Multiple elementary feedback behavior could be combined to a complex behavior. For example single movements can be combined to form a gesture. The influences between the elementary behaviors will be ignored. We call it *open feedback loop* and it works in many cases. This feedback loop will be used in most of the implementations. For a closed control loop the exact position of the body part, the whole context, and all feedback parameters such as intensity need to be known. In the case of moving body parts of a user several parameters need to be taken into account such as gravity, angle, position, supporting or counter force but also the habituation effect of the current, change of the skin resistance, muscles that influence each other or muscle fatigue. Therefore, in this work *open feedback loops* are used.

To explore feedback technologies in a new context, the initial effort to understand and build the technology is often the main challenge. This includes understanding the possibilities and the feedback technology. This is a time-consuming task, especially for complex and immersive technologies like EMS, in which a current is applied to the user body by a device. For testing new parameters, placements or types of electrodes fast prototyping is necessary. The device should be mobile and wearable to follow the ubiquitous haptic feedback approach.

In the next chapters we consider how EMS can be used safely in the context of HCI for haptic feedback and discuss important feedback parameters. It is shown how EMS can be used in simple application scenarios. For example to extend interaction with virtual objects through EMS feedback and to support users in everyday tasks and transmit abstract information to augment the user's abilities. Therefore in the next chapter we present how EMS can be enabled for HCI prototyping and demonstrate the use of EMS in simple application scenarios.

Chapter 4

Enabling EMS-based Prototyping

Nowadays, using EMS as a haptic feedback method requires extensive background knowledge. This includes knowledge about the design of circuits that generate or modify EMS signals, the choice of EMS parameters to achieve a certain effect, the placement of the electrodes, as well as the response behavior of different muscles. A lot of initial effort is typically spent in building custom hardware and software components [189, 315]. This raises the entry hurdle for HCI researchers who want to use EMS as a haptic feedback method. Easy and fast prototyping is hardly possible.

In other domains, such as cross-device interfaces, toolkits and frameworks like [98, 142] help to reduce the initial effort and enable researchers to focus on HCI-related questions quickly, e.g., regarding novel application scenarios and interaction techniques. To simplify the use of EMS in HCI research we present the "Let your Body Move" EMS prototyping toolkit (Figure 4.1).

The main purpose in developing this toolkit is (1) to reduce the entrance hurdle for other researchers that are new to haptic feedback with EMS, (2) fast prototyping hence, simple integration with other systems and (3) to run courses, tutorials, workshops and user studies to generate and evaluate novel ideas. The toolkit comprises the schematics of a hardware control module, software modules, sample applications, and a robust communication protocol for EMS parameters.

First of all in this Chapter we discuss EMS parameters that are adopted from the medical field and that work for the purposes of in our research. After that we discuss how EMS can be applied to the users and present samples of electrode placements, user individualities,

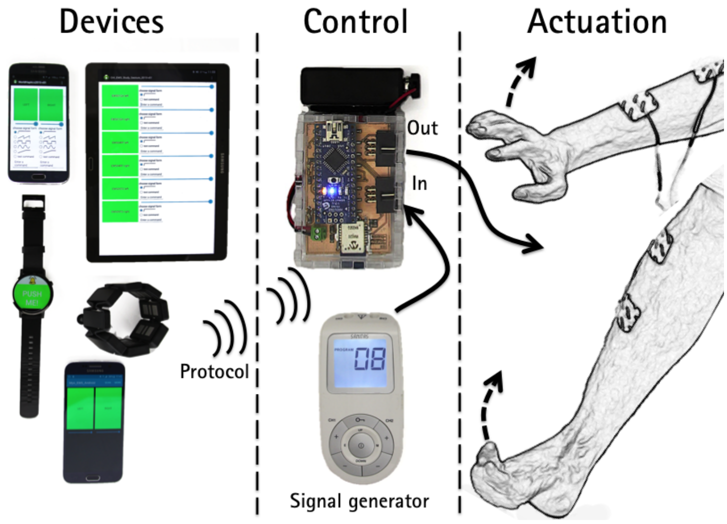


Figure 4.1: Overview of the EMS toolkit. Left: mobile and wearable devices that connect to the EMS control module; middle: custom control module and off-the-shelf EMS generator; right: actuation of muscles.

calibration of EMS feedback, parameters that should be reported for user studies and safety issues that need to be taken care of. Then the "Let your Body Move" toolkit is introduced. First we discuss the importance of toolkits and then we define the steps of a prototyping process to use the toolkit for investigating new ideas. After that, the hardware and software components of the toolkit are described in detail. Following that a set of sample applications to show how the toolkit can be used are presented. Finally we evaluate the instances of the toolkit in a workshop.

4.1 EMS Parameters

EMS is adopted from the medical field and it is used for rehabilitation and for fitness previously. As discussed in Section 2.3.1 EMS is known as under several names and has a broad application area. Again, EMS feedback ranges from a small tingling – similar to that generated by a vibration motor – to the contraction of a muscle, which results in the movement of a limb. Depending upon the amount of current used the receptors are stimulated and the user perceives this as feedback. A weak electrical current is generated by the EMS devices and applied to the user. A lower current only creates a tactile sensation that is noticeable at the place of the electrode on the skin. A stronger current leads to the contraction, as described before, and lead to a voluntary movement that is perceived as force. Depending on the intensity of the signal, the various different types of haptic feedback can be generated. To achieve comfortable haptic feedback the signal parameters need to be adapted to the particular user, muscle, and desired effect.

4.1.1 Tactile Sensation

Regarding the described meaning of EMS the tactile sensation arises as a side effect of the muscle's stimulation and is called electrical tactile feedback. The current crosses the skin and stimulates nerves and receptors as described in Section 2.1. Tactile feedback is felt at the position at which the current is applied. The perceived strength depends on the amount of current, pad size, and density of receptors in the skin. The tactile feedback can be used itself as silent and invisible feedback. In contrast to the force feedback (muscle stimulation) the feedback does not have a visual aspect. The signal parameters are similar to force feedback, but the intensity is lower and the electrodes do not need to be placed over a muscle.

4.1.2 Muscle Contraction

The weak current for EMS crosses the skin from the first surface electrode, flooding through the tissue and the muscle and back to the second electrode. The current stimulates the motor nerves that lead to the contraction of the muscle. The contraction lets the muscle tighten and pulls the tendon of a limb, which makes the limb move. This effect can be used to support a movement, such as to amplify grasping, or as a counterforce, to stop or slow down a movement (Section 2.3). Different elementary movements can be combined in an EMS gesture. In contrast to a natural contraction the muscle fibers are actuated continuously, which lets the muscle exhaust faster [148]. The actuation strength depends on the amount of current that is flooding through the muscle. Typically the muscle starts to twitch first. When the contraction is strong enough to overcome gravity the limb makes usually the full movement.

4.1.3 Amplitude

The strength of the electrical impulses (current) depends on the skin resistance and the voltage that is applied. The skin resistance can be influenced from hairs and skin hydration, as well as the thickness and characteristics of the underlining tissues. For electrical impulses of a duration longer than 10 ms, a current of 10-20 mA stimulates only the sensory nerve fibers,

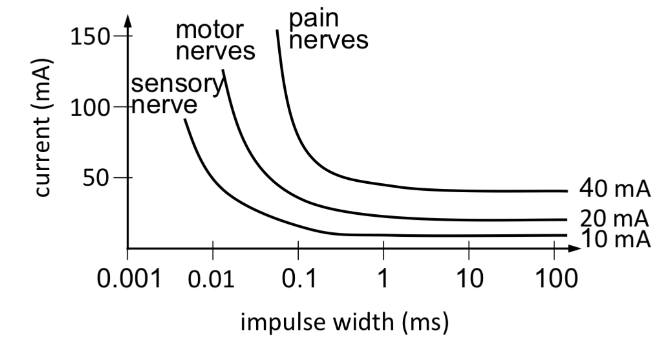


Figure 4.2: Gradient of the nerve stimulation over time [91].

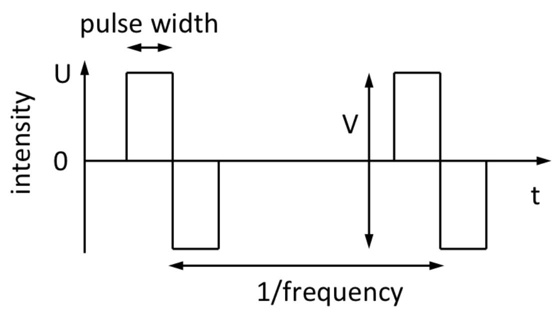


Figure 4.3: Impulse characteristics for designing EMS feedback.

a current of 20-40 mA in addition stimulates the motor nerve fibers, and a current of more than 40 mA also stimulates the pain nerve fibers [91] as shown in Figure 4.2. Which nerves are stimulated depends on many factors of individual users. To achieve a certain current the amplitude needs to be adjusted depending on the resistance of the skin, which differs widely across users and feedback positions. Therefore, the strength of the current needs to be calibrated for each user and muscle individually.

4.1.4 Impulse Characteristics

The electrical impulses can follow different characteristics as shown in Figure 4.3. Standard signal values for EMS are a pulse width of 30-800 μs, and a pulse frequency of typically 1-150 Hz [275]. The pulse intensity as discussed before depends also on the pulse width and pulse frequency. For very low frequencies (1-30 Hz) the muscle ticks for each pulse, for higher frequencies (30-60 Hz) the users can still differentiate each pulse. In our experience, a frequency between 70–100 Hz and a pulse width of 50 μs works well for a wide range of users. For TENS application higher frequencies up to 2000 Hz can be used [91].

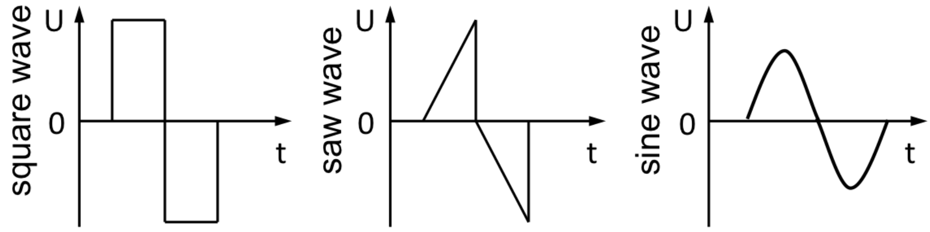


Figure 4.4: Typical EMS impulse forms that are generated by off-the-shelf devices.

4.1.5 EMS Signal Forms

The most common EMS impulse form is the square wave as shown in Figure 4.4. This waveform is easy to generate and works well in many cases. Most common EMS devices generate a square wave by default. Medical EMS devices have options to change the signal form, e.g., to sine, square, or triangular. Figure 4.4. The wave form should always have a positive and negative signal part, so that the current flows bidirectionally through the tissue. Different plus forms and theirs perception are discussed in [12, 32].

4.1.6 Skin Resistance

Depending on the position, the resistance of the skin, and the receptor density, varied as discussed in Section 2.1.3. The amount of hairs, skin composition and tissue density differs also over the body. These influence the skin resistance depending on the tissues and skin characteristics. Therefore a higher voltage is needed to get the same current, flowing through the muscle. The skin resistance follows roughly the electrical characteristics from an RC circuit [251, 330]. The skin parameters also differ between users. They also change within one user over time. For example, skin resistance changes with skin moisture, which is influenced by sweat.

4.1.7 Off-the-Shelf Devices

For workshops, prototyping and user studies of-the-shelf massage/EMS/TENS devices were used. They are battery driven and usually CE 93/42/EWG[1] (for medical devices) proved. The commodity EMS devices usually output a square wave as EMS signal. The EMS devices that

[1] CE `ec.europa.eu/growth/single-market/ce-marking`

we used in our studies generate pulse widths from 50-300 μs, and the pulse frequency in the range of 1-150 Hz. The intensity of the impulses is limited up to 200 mA and 100 V peak to peak at 500 Ω. Most of the devices allow setting the amplitude, the pulse frequency, and the pulse width. For example, the Sanitas SEM 43 [23] EMS devices were used in several user studies on program 8 TENS with a pulse width of 100 μs and a pulse frequency of 120 Hz. The TENS program delivers a continuously EMS signal and has individual settings for pulse intensity, width and frequency.

4.1.8 Feedback Patterns

Complex signal patterns can be generated from this basic impulse shape. The simplest possibility is to switch the impulse on and off over the time. The generated pattern can encode information to be transmitted haptically to the user. It may also be used to combine elementary movements to gestures. For example actuating the muscle that pulls the hand up in alternation with the muscle that pushes the hand down lets the user perform a wave gesture (Section 4.2.2). As a further pattern, the signal strength can be increased and decreased slower when the signal is switched on and off to smooth the actuated movements. Or the signal intensity can follow specific functions such as the sine or triangle function. With these parameters a variance of EMS output signal can be designed. In the following we describe how to apply EMS feedback to the user's set of muscles.

4.2 Applying Feedback EMS

4.2.1 Electrodes

Self-sticky electrodes are the most common and simplest to use. Other electrodes are suck electrodes and plate electrodes. Such electrodes are made of metal (textiles or plates), conductive plastic, or silicone. They are either inelastic or flexible [91]. The electrodes need a good conductivity to the skin. To reduce the resistance of dry or hairy skin salt solution or conductive gel can be used. The electrodes are sucked, sticked or wrapped to position over the muscle on the skin. Wearables electrodes could be glued or sewn on the textiles or woven into textiles as discusses in Section 2.3.3. Electrodes that are integrated in clothes also need a direct contact to the user's skin or a conductive intermediate layer between the textile electrodes and the skin. These electrodes can be attached to sportswear, to underwear, or also to special bandages as shown in Figure 4.5. Such textile electrodes are usually washable. Depending on

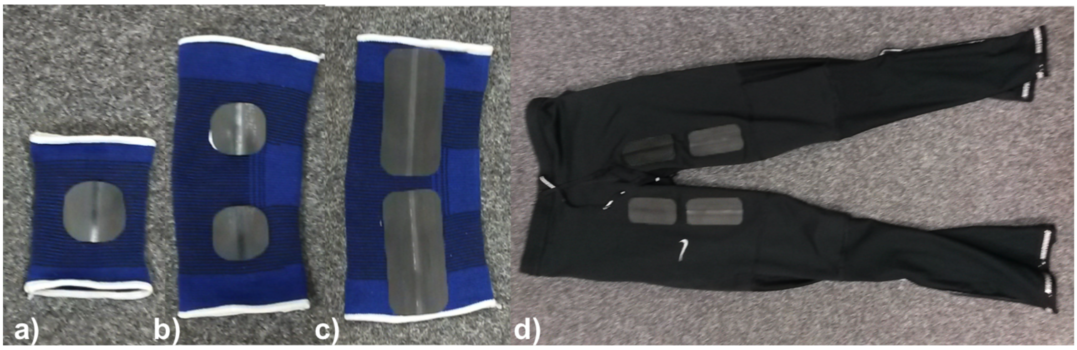


Figure 4.5: Silicone electrodes: (a) bandage for the upper arm to actuate the biceps, (b) bandage for the lower arm to actuate extensor digitorum, (c) bandage for the lower leg to actuate the tibialis anterior, and (d) sports trousers to actuate the sartorius muscle.

the muscles they are applied to, the electrodes may have different shapes. However, in many cases electrodes with a size of 40×40 mm work well. If the EMS signal is applied to a small muscle and the electrode size adapted, then the amount of current per area increases. This stimulates more receptors in the skin and increases the tactile feedback at the position of the electrodes. For very small electrodes this sensation can become uncomfortable. However, larger electrodes result in a larger dispersion of the current and other muscles may be actuated as well. There is a tradeoff between precise muscle actuation and the tactile side effects of small electrodes.

4.2.2 Muscles and Placement

For evoking a particular movement, to generate for example a force feedback, the pair of electrodes needs to be placed exactly over the muscle that is actuating the target joint. Thus the position of the EMS pads and the position of the effected movement differ. Some muscles are very close together, others overlaying each other. Again, the size and the position of muscles differ between users. Therefore precise electrode placement and calibration is crucial.

Hand up: The extensor digitorum muscle lifts up the hand, as shown on the Figure 4.10 (a). It is connected through a tendon to the upper side of the hand. When the electrodes are not properly placed on this muscle, the signal either actuates the extensor carpi ulnaris (lateral side) or one of the thumb extensors (medial side, extensor pollicis brevis or extensor pollicis longus), which move the thumb inside. The muscles in the lower arm are placed very tightly together and an exact placement is difficult. The effect also depends on the rotation and posture of the hand. The skin with the electrodes shifts differently to the muscles underneath.

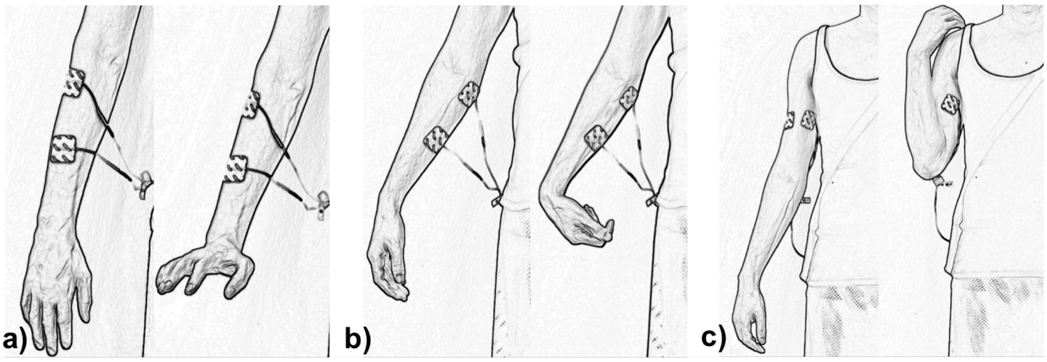


Figure 4.6: Placements of electordes and resulting movements for a) lifting hand up, b) pushing hand down and c) lifting lower arm up.

Hand down: The pads need to be placed over the flexor digitorum profundus, as this muscle pulls the wrist down (Figure 4.10 b). An imprecise placement also activates flexor digitorum superficialis, which bends the proximal interphalangeal (PIP) joints, i.e., it lets the upper finger segments claw. The flexor digitorum profundus does not actuate the thumb. To bring the thumb inside during this movement the thumb muscle (flexor pollicis longus) also needs to be activated. Actuating all these muscles together results in a fist.

Lower arm up: To lift the lower arm up the biceps brachii muscles (caput longum and caput breve) need to be actuated. On this larger muscle the pad may be placed vertically (proximal–distal) or horizontally (lateral–medial). Figure 4.10 (c) shows the horizontal placement. With the horizontal placement better actuation results are achieved, because the current crosses the whole muscle. However, the horizontal placement may result in a tingle in the palm of the hand, in which case the vertical placement should be chosen.

Arm up: The deltoid muscle primarily lifts the arm up. When actuating it together with the biceps brachii muscles, the arm moves a bit forward (Figure 4.7 a). To avoid this the shoulder muscles (infraspinatus and teres minor) can be actuated to pull the shoulder backward a bit. Depending on the user's fitness the deltoid muscle fatigues after a few actuations and can hardly lift the arm up.

Foot up: Activating the tibialis anterior muscle leads to lifting up the foot. The electrodes should be placed on the upper part of the lower leg on the outer side of the tibial bone (shinbone) as shown on the Figure 4.7 (b). The largest effect occurs, when the foot is swinging in the air. Longer electrodes that are placed vertically (proximal–distal) reduce the tactile side effect at the leg.

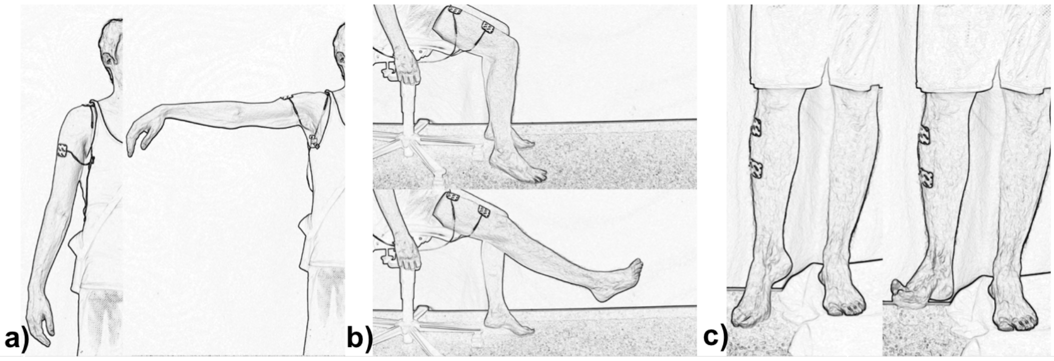


Figure 4.7: Placements of electordes and resulting movements for a) lifting upper arm up, b) lifting foot up and c) lifting lower leg up.

Leg up: When sitting the lower leg can be lifted up (moved ventral–proximal) by actuating the quadriceps muscle of the thigh. The quadriceps is a large muscle that can be reached easily by surface electrodes (Figure 4.7 c). This large muscle requires a relatively large current. Therefore, a larger pad should be used. Care should be taken when actuating this muscle while walking, as it easily blocks the leg, which may cause the user to stumble.

Actuating a single muscle results a single elementary movement. This elementary movement may support or counteract a voluntary movement performed by the user. For example, it might amplify a grasping motion or slow it down with a counterforce. Elementary movements may be combined to form a gesture.

4.2.3 EMS Usage

The above described elementary movements worked reliably for force feedback. Many other elementary movements and combinations of movements are possible [23, 49, 269]. Further movements can be carefully extracted from anatomic [362] or physiology [30, 125] literature. The reliability of EMS actuation depends on several factors.

The actuated muscle may change its form or it may move under the skin such that the surface electrode is no longer precisely placed over the muscle. If the electrode is placed on the boundary of the muscle, a periodic oscillation may occur, in which the muscle is repeatedly pushed away from the electrode while contracting, receives less current, relaxes, and moves back into the current. These effects need to be taken into account when elementary movements are combined to gestures or if force feedback should be applied during a voluntary motion of the user. Moreover, the muscle performance changes over time. Depending on the size and fitness of a muscle, after a set of repetitions or continued actuation muscle fatigue occurs [148]. Placing the electrodes on tissues with a lower resistance than the muscle will bypass the muscle. This can lead to unexpected effects such as actuating the biceps brachii muscles when one electrode is positioned on the lower arm and the other in the crook of the arm. In this case the pads need to be slightly repositioned.

4.2.4 Calibration

Every user is different! Because of anatomical differences a user-dependent placement of the electrodes for each muscle is necessary. The perception of signal strength, the maximum comfortable signal level, and the minimum level at which actuation starts, all differ widely across users. The skin resistance differs depending on tissue sickness, body fat percentage, skin moisture, and hair.

Typically, users do not have any prior experience using EMS. A calibration phase should start with a brief introduction to EMS and a discussion about the safety issues. When upcoming questions have been answered the users should be practically introduced to EMS step by step: Initially, a muscle should be tested that is easy to reach, such as the extensor digitorum on the posterior forearm. The experimenter should describe the expected effect beforehand and the users should be allowed to adjust the signal intensity level on their own. This helps to determine the maximum comfortable level for a particular user.

Then other muscles can be calibrated similarly by placing the electrodes and increasing the intensity level. The electrodes need to be placed at slightly different positions for each user, since the muscle position is user-dependent. Even small changes in position can result in a different movement. When the contraction does not appear, moves in a wrong direction or additional unintended movement occurs the electrodes need slightly repositioned. During the repositioning the EMS current needs to be switched off for safety reasons. A crosscurrent to other electrodes could occur when only one electrode of a pair is attached. After the repositioning the intensity should start again from a low level, since the same level could have stronger effect at the new position.

Also a fixed strength of the EMS signal can have a variable effect. As the muscle contracts, it changes its form, thereby shifting the relative positions of electrode and muscle. Therefore, the calibration process needs to take the intended movement into account. Furthermore, the timing of the elementary movements is crucial and has to be controlled thoughtfully.

During the calibration process the user should be asked to periodically inform the experimenter about her mental and physical state. The maximum comfortable level for each muscle should be recorded and never exceeded during the study. Finally, combined gestures can be tested with the calibrated strengths.

4.2.5 Reporting EMS Experiments

Important information that needs to be reported for reproducibility of EMS experiments include the used muscle or muscle group (with the function/actuation effect of the muscle), the placement of the electrodes, as well the types and sizes of the electrodes. Also the used EMS parameters, such as amplitude, pulse frequency, and pulse width, as well as measured current, should be reported per user. Voltage and current should be measured before and after the experiment, since the skin resistance can change.

4.2.6 Safety

There are potential medical risks that need to be taken into account when using EMS for generating haptic feedback [273]. The haptic feedback designer and also the user have to be aware of these potential risks. Feedback designers and users are required to consult the manual of the EMS device and to follow the safety recommendations carefully. The user's safety has the highest priority!

An important point for safety is that the electrodes must never be placed on the front torus near the heart. EMS devices must not be used in combination with a pacemaker or by people who have any heart disease. It is recommended that pregnant women, people with epilepsy, with cancer, after a surgery, with sensitive skin, or with a skin disease should not use EMS, or only after consulting their physician [23]. Moreover, extremely high EMS signals stimulate the nociceptors (pain receptors) [91]. The pain threshold depends on the user and on the position of application. Therefore, the maximum EMS level should be calibrated individually for each placement and should be always below the pain threshold. Reports from the domain of fitness training have shown that long activation periods with high EMS levels can result in muscular fatigue and overtraining of the actuated muscle.

Running EMS experiments typically requires the approval of a local ethics board. For our workshops at WorldHaptics [194] and CHI [195] on this toolkit and the associated prototyping process the participants filled in an informed consent form.

4.3 Let Your Body Move Toolkit

The "Let your Body Move" EMS prototyping toolkit (Figure 4.1) has the aim to decrease the initial cost to use EMS as haptic feedback. Further, the toolkit aims to achieve a fast prototype of new ideas and an easy integration in research projects to run user studies. However, a major concern with EMS research is safety. An important decision regarding the toolkit was thus to design it around existing massage/EMS/TENS devices as EMS signal generators. The toolkit was tested with four different commercial devices. A second fundamental aspect was to make the system as small and unobtrusive as possible to be able to use it in wearable applications. Moreover, the system is designed to easily connect to a wide range of mobile and wearable devices, such as tablets, mobile phones, and smartwatches (Figure 4.1). This is achieved by wireless communication over Bluetooth low energy (BLE). The output of the EMS device is sent to an Arduino-based control module.

The control module manipulates the EMS signal by modifying the intensities and on/off-times of two EMS channels. For safety reasons the control and communication circuitry is galvanically isolated from the EMS signal circuitry, which is connected to the user's body.

The EMS signal is switched off when the connection gets lost. A number of prototyping apps are provided, which run on Android-based tablets and mobile phones and allow Wizard-of-Oz studies to be easily conducted. Moreover, several example applications are provided that may serve as a basis for custom interfaces to EMS functionality, such as a runner's app that provides EMS feedback at particular points on the track. The circuit schematics and Arduino code of the control board, the Wizard-of-Oz control applications, and the example applications are provided as open source software [252]. Given the circuit schematics and the parts list, the fully assembled PCB board can be ordered from several manufacturers. This chapter may also serve as an introductory tutorial as we share my experiences in EMS parameter settings and skin electrode placements to achieve certain kinds of haptic feedback.

4.3.1 HCI and Haptic Prototyping Toolkits

The importance of toolkits is shown by the fact that prototyping toolkits help to make new technologies accessible and to focus on investigating new concepts and interaction techniques. For example, Houben and Marquardt [142] present *WatchConnect*, a prototyping platform for smartwatch cross-device applications. It simplifies investigating cross-device interaction between watches and desktop systems.

FeelSleeve [356] are tactile gloves that are attached to the back of a tablet to provide vibration effects based on the story the user is reading. Yannier et al. [356] show that tactile feedback increases comprehension and memorization. Pohl et al. [265] present a toolkit for simulating different surface structures with a tangible object. Ledo et al. [178] present the *Haptic Tabletop Puck*, which simulates haptic feedback by changing the friction of the device. They simulate different properties, such as softness, depending on the underlying texture. Ledo et al.'s toolkit covers the hardware-specific implementation with different layers of abstraction. Similar feedback is generated by *TeslaTouch* [17] and *FingerFlux* [345]. On the haptic and force-feedback side Brave and Dahley [38] present a device for haptic remote communication. Ha et al. [121] describe a haptic prototyping system for a single dial. The hardware prototype provides several patterns to turn the dial. They conclude that the system can be used for haptic prototyping in automotive, medical, and gaming contexts. *WoodenHaptics* [98] is a toolkit that implements a device similar to the *Phantom Desktop device*. It is an open source hard- and software toolkit that allows designers to investigate high fidelity haptic feedback. The *WoodenHaptics* toolkit can be used for haptic prototyping with a broad range of users. However, this device cannot be used in mobile contexts and has a limited interaction range. Most current haptic toolkits focus on very specific forms of haptic feedback or on specific interactions, such as dials [121], rolls [38], or sliders [310], or they are stationary [98].

The "Let your Body Move" toolkit is suitable for mobile and wearable interactions, can easily be connected to typical mobile devices, and is able to deliver a wide range of haptic feedback – from light vibrations to moderately strong movements. The cost of the toolkit components is below 100 USD. EMS is quite versatile with respect to the form of the signal as well as the placement of the electrode pads and the resulting movements. We believe that there are still many aspects that have not been considered yet and that there is particular potential in areas like learning movements, recognition, and recall such as envisioned in Section 3.3. A prototyping toolkit, such as *Let Your Body Move* can help to explore this potential.

4.3.2 EMS Prototyping Process

Before considering using the EMS prototyping toolkit in a particular project, it is important to clarify if EMS fits to the requirements for an envisioned scenario. The specific capabilities and limitations of EMS have to be considered. The design space of EMS is large, both in terms of the kind and range of effects it can create as discussed in pervious subchapter. Using the proposed toolkit requires an initial one-time effort, consisting of building the EMS control module (using the given schematic) and installing the control software on the Arduino. Each control board can handle two EMS channels. If more channels are needed, multiple instances of the toolkit's control module have to be built.

For the actual design process we recommend the following steps. This process is based on our own extensive experience in prototyping EMS-based haptic feedback. We assume that the design starts with an initial idea regarding an application scenario, such as a mobile application giving haptic feedback to runners, or regarding an interaction technique, such as giving haptic feedback in response to grasping virtual objects in a VR environment. The steps are:

1. Refine the role of haptic feedback in the application scenario or interaction technique.
2. Determine the parameters of the EMS design space to achieve the intended effects (EMS parameters, electrode placement, calibration requirements).
3. Install the Wizard-of-Oz control app on the experimenter's device (e.g. a tablet) and conduct a Wizard-of-Oz study.
4. Taking into account the lessons learned in the Wizard-of-Oz study, implement a custom prototype for the user's mobile device (mobile phone or smartwatch) that communicates with the EMS control module and logs events. Run a detailed study to evaluate the desired phenomena.
5. Iterate (refined prototype, Wizard-of-Oz study on specific aspects, EMS parameters and electrode placement).

The toolkit may be used as-is in brainstorming sessions in order to inspire Wizard-of-Oz prototypes. The toolkit helps in the quick production of working prototypes. We used this approach in a workshop setting (reported below), but considered it in a less common prototyping variant.

When the details of the role of haptic feedback in the envisioned scenario or technique have been clarified, the EMS design space needs to be considered. An example scenario would be a wearable application for joggers that actuate the runner's hand left or right to indicate directional turns. Important aspects to achieve the desired haptic effects concern the required EMS signal parameters, the placement and size of the electrodes, and user-specific calibration. The signal parameters include required and acceptable intensity levels and signal patterns (e.g., rhythms of movements to communicate a certain kind of information). These steps are in many cases sufficient prerequisites for an initial Wizard-of-Oz study that helps to validate the feedback concept or to try out quickly different feedback design ideas. The Wizard-of-Oz study can easily be controlled from the experimenter's Android phone or tablet in Bluetooth range of the user. However, this initial study already requires careful calibration of signal strength and electrode placement, as EMS strongly depends on the physiological characteristics of individual users.

The lessons learned can then be incorporated in the design of a custom software prototype for the user's device (e.g. the smartwatch of a jogger). A number of existing applications of custom prototypes may serve as a starting point for new software prototypes. The sensors of the user's device may be used to log specific events and reactions to haptic feedback. This setup can serve as the basis for a more extensive user study that aims to evaluate specific phenomena. Of course the design process allows for iterating on the prototype, specific aspects or new ideas for haptic feedback, as well as the modification of EMS parameters and electrode placement.

New constraints or requirements may arise, such as the need for another form factor or additional EMS output channels. While additional channels can easily be achieved by adding an additional EMS control module and EMS signal source, changing the form factor may call for a deeper modification of the hardware design. We consider this beyond the scope of the prototyping toolkit as we focus on simplifying the design process for HCI researchers, and because the existing form factor does not constrain the user severely. For example, as the system uses Bluetooth low energy (BLE), it can communicate wirelessly with an unmodified smartwatch. Again, the initial step to building the control board hardware needs an understanding of how to produce PCB circuits or order them from a web shop as discussed in the next subchapter.

4.3.3 Toolkit Implementation

The EMS prototyping toolkit is a composition of hardware, software, and methods to enable prototyping with EMS as shown in Figure 4.1. On the hardware side we provide a control module that manipulates the EMS signals of off-the-shelf EMS devices (Figure 4.8). It manipulates the strength and duration of the EMS signals and communicates wirelessly via Bluetooth low energy (BLE). The EMS control module is easy to build given the circuit schematics and parts list. The individual components are controlled by an Arduino Nano [2] over I^2C (Figure 4.9). We developed a simple ASCII-based protocol to modify the signal

[2] Arduino Nano: http://arduino.cc/

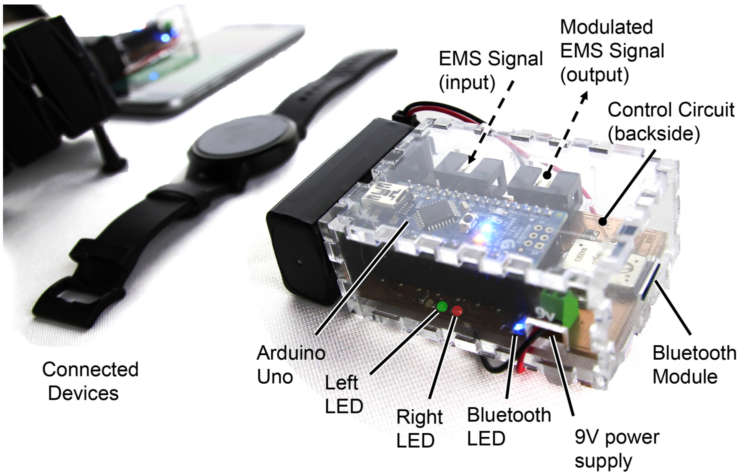


Figure 4.8: EMS control module: Overview of the components and functionality.

parameters. On the software side there are four simple Android prototyping apps implemented that communicate with the EMS module (Figure 4.1, left).

The schematics, parts list, the Arduino source code, and the source code of the Android apps are available online [252].

The toolkit is developed in several iteration steps. As shown in table 1.2 the first version switched the EMS signal only on and off and was not mobile. Later we added components for scaling the intensity of the EMS feedback. We also implemented the board with different communication components such as for WiFi. Regard to the focus on mobiles and wearables we used for the latest version BLE. The size of the hardware was reduced over the iteration steps. The software was also improved step by step to run reliably.

4.3.4 Toolkit Hardware

We typically use the Breuer Sanitas SEM 43 [23] as the signal generator. However, we tested the system with other EMS devices. The control module reduces the signal intensity of the EMS device. The EMS device is calibrated with the maximum acceptable intensity for a particular user. For safety reasons we designed two galvanically isolated circuits, the EMS circuit and the control circuit. The EMS circuit is connected to the signal lines of the EMS device and the human body, as shown in Figure 4.8, right. The control circuit is connected to the Arduino (Figure 4.8, left), but also to the BLE module, and a 9V or USB power supply.

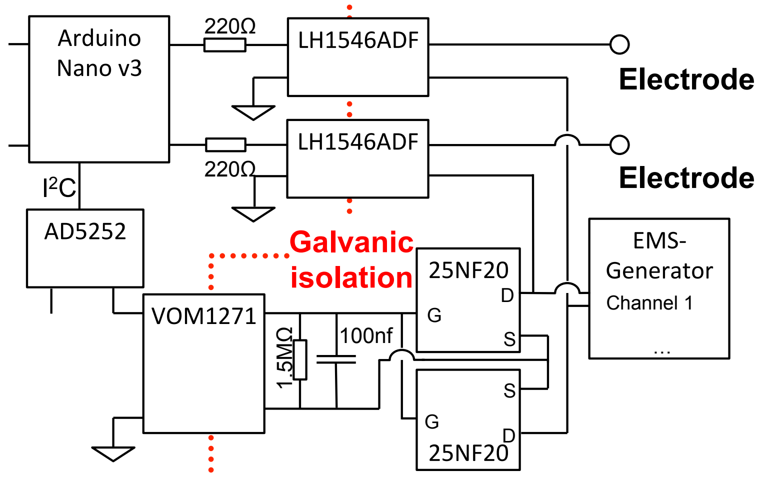


Figure 4.9: Circuit of the EMS control module for one EMS channel.

EMS circuit: The galvanic isolation of the EMS circuit is implemented with an optically isolated MOSFET driver (VOM1271[3]) as shown in Figure 4.9. It generates a current to drive two MOSFETs (25NF20[4]) in the EMS circuit, which reduces the signal intensity of the EMS signal and switches it on and off. One MOSFET is used for the positive and one for the negative half-wave of the EMS signal. These MOSFETs are connected to one channel of the EMS device (EMS generator). The regulated resistance of the MOSFETS should be between 100 Ω and 10 kΩ, because otherwise the EMS device switches off automatically. For safety reasons we also included two photo relays (LH1546ADF[5] in Figure 4.9, top-center) to instantly cut off the EMS circuit when switching the module off. The photo relays are connected on one side to the MOSFETs and to the EMS device and to the other side to the EMS electrodes. The second channel has an analogous structure. In case the current of the control circuit fails, the user's body is isolated from the EMS device.

Control circuit: In the control circuit the input of the MOSFET driver is leveled by a 1 kΩ I²C digital potentiometer (AD5252[6]). The Arduino controls the photo relays and the Bluetooth communication through a standard BLE chip[7]. When the Bluetooth connection fails, the EMS channels get disabled. For the BLE module and for each EMS channel we added a control LED (Figure 4.8).

[3] VOM1271 `http://www.mouser.com/ds/2/427/vom1271t-244790.pdf`

[4] STD25NF20 `http://www.mouser.com/ds/2/389/DM00079534-470123.pdf`

[5] LH1546ADF `http://www.mouser.com/ds/2/427/lh1546ad-254173.pdf`

[6] AD5252 `http://www.mouser.com/ds/2/609/AD5251_5252-246267.pdf`

[7] RN4020 `http://www.mouser.com/ds/2/268/50002279A-515512.pdf`

Command	Values	Sample	Description
Channel	0-1	C0	Set channel 0 or 1
Intensity	0-100	I56	Set intensity in %
On-Time	1-50000	T2000	Set the on time in ms
Activate/Go	G	G	Activate the command

Table 4.1: EMS Control Protocol (ECP).

4.3.5 Protocol of the Toolkit

As long as the EMS modules are not connected they announce their Bluetooth name. Based on the name the prototyping apps can find the device and connect to the "EMS-Service-BLE1" service. The service accepts ASCII strings to change the EMS parameters. The protocol of the service is shown in Table 4.1.

For example, if the message "C0I100T750G" is sent to the service, channel 0 will be activated at full intensity for 750 ms. Resending "G" activates the same channel with the previous parameters again. Each parameter can be changed individually. If a new "on-time" message is received while a channel is active, the new time will be updated immediately, even if it is shorter. For example, if the signal is on and the new time is set to 50 ms, it will deactivated after 50 ms. The maximum on-time that can be set is 1000 ms. For safety reasons we use a relatively short on-time of 750 ms and resend "G" before it expires to keep the signal alive. When the application fails to renew the lease, the EMS channel stays active until the on-time expires. The protocol can easily be extended to add further commands, e.g., for changing the service name or the connection code. However, this basic protocol is sufficient to generate a wide variety of feedback. For example, it is possible to generate slow movements (by slowly increasing the signal strength) or oscillating movements (by modulating the signal with the sine function).

4.4 Application Scenarios

Since the EMS module uses BLE it can connect to any device that supports BT 4.0 or higher. The sample apps were extensively used for prototyping and in multiple user studies. We have successfully run these apps on Android devices, such as tablets, mobile phones, and smartwatches. Below, the four presented prototyping apps, which can easily be extended: (1) an app for Wizard-of-Oz prototyping that can connect the EMS module and apply different

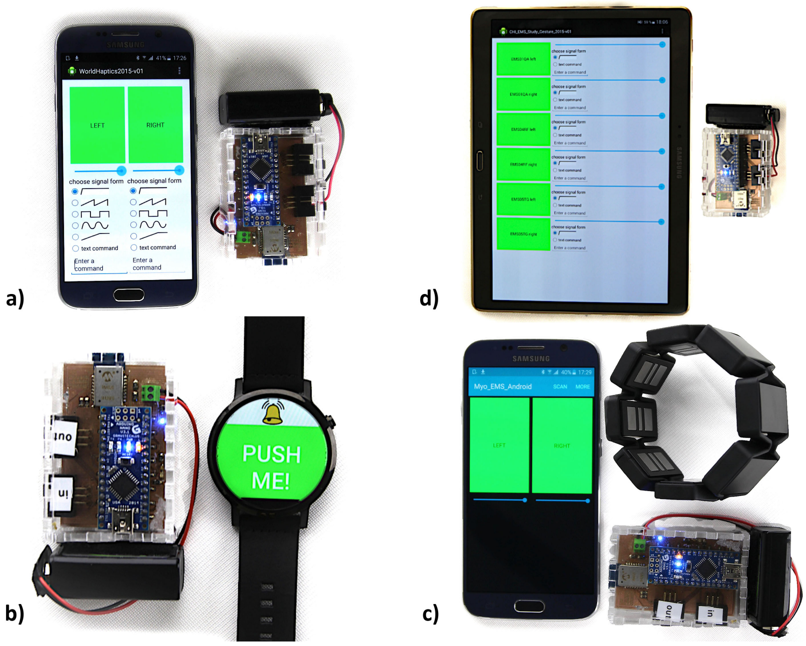


Figure 4.10: Sample apps to run the toolkit: a) Wizard-of-Oz Prototyping App, b) Connecting Multiple Devices App, c) Myo Remote Control App, and d) Event Triggering App.

parameter sets, (2) an app for connecting multiple devices to actuate a set of muscles, (3) an app that connects to a bracelet wearable device, and (4) a smartwatch app.

4.4.1 Wizard-of-Oz Prototyping

The Wizard-of-Oz prototyping app can connect to one EMS module and activate two channels (Figure 4.10 a). The uesed EMS device can generate two independent signals. Four electrodes are needed to actuate two muscles. The app activates a channel while the user presses a button. The signal intensity may be adjusted with a slider. Different patterns may be chosen: Immediately on, square wave signal with a 1 s period, sawtooth signal (linearly increasing intensity, then off and starting again), sine wave signal, and inverse sawtooth signal (linearly decreasing, then on). Finally, there is a text field for sending custom protocol messages as described above. Each time the button is pressed, one custom message is sent.

4.4.2 Connecting Multiple Devices

Actuating multiple muscles requires additional control modules and EMS devices. This is useful for more complex haptic feedback, like grasping or lifting an object. Each button activates one channel while it is pressed as shown in Figure 4.10 (b). It is also possible to change the intensity and use individual messages. The app can be used as a "gesture keyboard" using chording: Each key actuates a muscle and the gesture can be played like on a piano.

4.4.3 Myo Remote Control

The remote control app shows how to use data from external sensors such as the Myo[8] to control muscle activation (Figure 4.10 c). In this case the mobile device serves as a gateway between the EMS module and the Myo device. The Myo device detects simple gestures of the hand through EMG (electromyography) at the lower arm. This setup enables a remote control for another person: By attaching the EMS pads to one person and having the Myo device worn by a second person,the detected movements of the second person can then be transmitted to the first person and replayed or otherwise mapped.

4.4.4 Event Triggering

The smartwatch app runs on a Moto 360[9] and extends that device with force feedback as shown in Figure 4.10 (d). For specific notifications, such as an alarm, it can actuate a muscle. In this sense the user becomes the output device for notifications. For example, when an alarm is ringing the user starts waving the hand. Different movements or rhythms may be used for different kinds of notifications.

4.5 Toolkit Evaluation

To evaluate the toolkit we conducted a one-day workshop with 10 participants (2 female) at the WorldHaptics [194] conference. The goal of the workshop was to investigate application scenarios involving haptic feedback and to teach researchers from different disciplines how to use EMS. In preparation for the workshop we built 11 instances of EMS control modules

[8] Myo 360 `http://www.myo.com`

[9] Moto 360 `http://www.motorola.de/products/moto-360`

Figure 4.11: A participant lifts the thumb up with the other hand.

and deployed the Wizard-of-Oz app on 11 Android tablets and mobile phones. The workshop consisted of a design session on how to generate application scenarios and a hands-on Wizard-of-Oz prototyping session to test the proposed ideas.

4.5.1 Workshop Procedure

The workshop started with a detailed overview of EMS in HCI research. We explained how EMS works and how to safely use it. We followed up with an EMS experimentation session, in which every participant had the chance to feel the involuntary muscle contractions that it caused. All participants got a prototyping toolkit consisting of an EMS module, four self-adhesive electrodes, an EMS device, and a mobile device with the Wizard-of-Oz prototyping app. We asked the participants to perform a simple wave gesture and ended this session with an EMS-based aloha wave.

With the experience of how EMS works, we ran a 10 minutes brainstorming session. The brainstorming was done with different general topics in mind, e.g., providing physical properties, transmitting information, and assistive systems. Each group selected one scenario and realized it in a simple Wizard-of-Oz prototype. After understanding which muscles they needed to stimulate to cause a certain movement, the participants combined the elementary movements to EMS-based gestures.

At the end of the day the prototypes were presented in a plenary session. We video-recorded the prototyping session and the final presentations for later analysis.

Figure 4.12: A participant controls a grasp and release gesture.

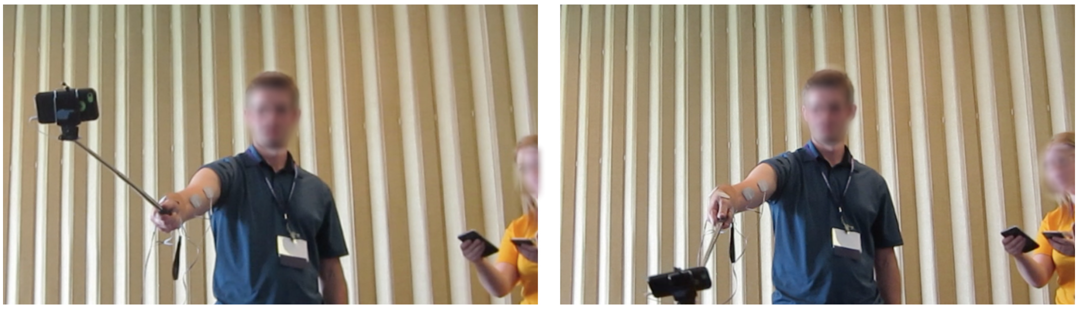


Figure 4.13: A participant controls another participant to take a photo.

4.5.2 Results

We analyzed the video recordings of the prototyping session and the final presentation to identify the sub-results and see which application scenarios the participants tried with the Wizard-of-Oz app. During prototyping the participants tried different scenarios such as single grasping, lifting the thumb up, changing the face expression, and remotely controlling a person to take a photo.

The participants divided their initial ideas first into several different elementary movements such as opening and closing the hand and lifting the arm up. Then they tried each movement one after the other. Finally, they combined the movements to complete gestures like grasping and releasing. One participant lifted his thumb up and described it as the “easy” app. He used it to describe that something is “nice.” He used a muscle of his right hand to flex the thumb shown in Figure 4.11. The participants of Group 3 divided their initial idea first into several different elementary movements such as opening and closing the hand and lifting the arm up. They then tried each movement one after the other. Finally, they combined the movements to complete gestures like grasping and releasing (Figure 4.12). Group 1 and 2 acted similarly. Before Group 2 came up with their final application scenario they tried a

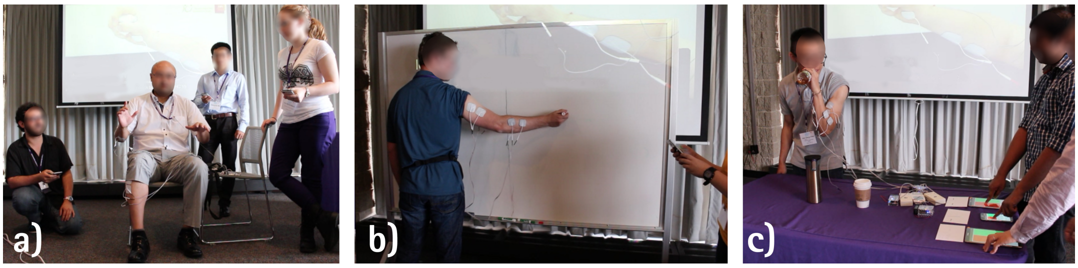


Figure 4.14: Final results of EMS-based a prototyping session (a) learning scenario “piano-player”, (b) game scenario “play pictionary”, and (c) healthcare scenario “diet control app.”

remote control for a “selfie stick” shown in Figure 4.13. They also broke down their gesture into elementary movements and combined them for the remote control. They used the biceps and triceps to move the stick left or right, and the muscles in the lower arm to lift the hand up. Group 1 started to actuate the hand, then the upper arm, and finally they added more body parts, such as the foot. The groups acted straightforward to investigate the prototypes. For some participants it was hard in the beginning to find the right muscle. By performing the required movements they explored the rough position of the muscle. Afterwards they placed the electrodes and tested the position while slowly increasing the intensity. When it was not the expected effect they replaced the electrodes until they got the right movement.

After the prototyping, Group 1 investigated a learning, Group 2 a remote control, and Group 3 a healthcare scenario. Group 1 with four participants called their learning scenario “piano-player.” The “learning device for piano” proposed to help a piano player to coordinate and time key hits, vertical movements over the keyboard, and handling the piano foot pedal (Figure 4.14a). To implement this idea they used six muscles. They explained that the leg muscles are “to control the pedal movements up and down” and the muscles in the arm “to control wrist movements.” Finally, they used the shoulder muscles for “translating across the piano.” During their presentation they used new wordings such as “my shoulder is online.” One participant was actuated while the other three controlled two muscles each. They first demonstrated each actuation of the combined movement sequentially and then simultaneously.

Group 2 with three participants investigated the “Play Pictionary” game scenario. They mentioned, that “this is a new step of Pictionary [...] after you game a little bit, you can control your friends while they will play Pictionary.” Group 2 introduced a remote painting approach, where two players control one other player who paints the picture (Figure 4.14b). One muscle is used to lift the hand up and one to push it down to draw vertical lines. To draw horizontal lines the muscles in the upper arm pushes the hand left (biceps muscles) and right (triceps muscles). Each player used one control module to actuate two muscles for drawing each dimension. For drawing, both players tried to synchronize the drawing. The group named this as a “fun game” with a completely new kind of gameplay.

Group 3 with again three participants composed a healthcare scenario that they called “diet control app.” This application supports people for balanced diet and helps to avoid unhealthy food shown in Figure 4.14c. The participants explained, “when it comes to a healthy option” ... “then you will take it” and an “unhealthy [option] will be avoided.” In the scenario the user had to choose between different drinks. When trying to grasp an unhealthy drink the hand was pushed away. On the other hand healthy drinks will be grasped and lifted up automatically. Further when the user was just across a healthy drink “it will pull your hand down a bit.” They mentioned that the environment needed to be tracked to detect the location of each object. Group 3 used five muscles: Two muscles in the lower arm were used to grasp the bottle and one to open and push the hand away from the drink. For lifting the hand the biceps muscles were used. Finally for pushing the hand down toward to a drink the triceps was used.

To activate the movement one participant controlled the three muscles of the hand using two devices. The other participant lifted the hand up or pulled it down. While investigating the scenario the participants investigated a kind of music book to activate the right muscle at the right time.

General Observations

The participants quickly got familiar with the toolkit and with EMS as a haptic feedback method. During the workshop the participants used most of the functionality of the toolkit as well as all of the provided devices. In most cases the participants were able to locate a muscle for a certain movement, place the electrode pads, and actuate the muscle with the toolkit.

The participants used the actuation time (on/off) as main manipulation factor. Usually, when the muscle starts to move it makes the full movement until the actuation is switch off. A precise and smooth movement or holding at a certain position was hard to achieve. To precisely control the speed and the amount of movement a closed control loop is necessary, as well as a way to adjust the intensity of the muscle contraction. It took the participants some practicing to find the right timing to combine the elementary movements to a full gesture.

For the final presentation one group used two devices and the other groups used three. All groups came up with non-obvious ideas from different areas. We observed new wordings, such as “shoulder is offline.” The main challenges the groups faced were related to the timing to perform gestures and the precision of the actuation. For the timing the participants used multiple devices side by side and actuated one muscle per finger. The precision problem was more difficult to solve. The participants’ strategy was to avoid very precise movements in their prototypes. For example Group 2 did not implement filigree finger movements of piano players. They rather focused on gross movements like moving the arm across the keyboard. Most of the movements and gestures that the participants tried to actuate worked reasonably well. To be as inclusive as possible, the workshop was thematically quite broad. We believe that more specific ideas would have been generated in a more focused workshop, considering, e.g., specific scenarios, specific muscle groups, particular gestures, or particular application scenarios from everyday life.

4.6 Discussion

The prototyping toolkit and process described in this chapter aim to lower the entry hurdle for using EMS-based haptic feedback in HCI research. There is an initial effort in producing or ordering the EMS control module. The Eagle files for the circuit and the parts list are available on the Let Your Body Move ToolKit bitbucket project Web site. After this initial step fast prototyping with a wide range of haptic feedback is possible. The results from the workshop show that the toolkit can be used in prototyping sessions with very little overhead. We successfully used the same toolkit and prototyping process in several user studies to perform simple movements as well as complex gestures. Moreover, the toolkit is applicable for generating EMS-based haptic feedback in mobile and wearable usage scenarios as well as in virtual environments.

However, the presented toolkit does not shift the responsibility away from the experimenter. When using EMS safety issues should always be a prime concern. Ethical aspects need to be kept in mind as well.

The Arduino software and the Android apps can be extended with new functionality. Bluetooth makes it easy to connect new devices and to realize further application scenarios. For example, a mobile phone may act as a gateway for remote communication. The circuit may also be extended to more channels or other wireless communication channels such as WiFi. The toolkit can be integrated early in to the environment and produce feedback when the users need it to support interactions.

4.7 Conclusion

This chapter gives an overview of how EMS can be used systematically in HCI. We presented a set of typical EMS sample parameters that work reliably in several studies that will be discussed in Chapters 5 to 8. The presented samples electrode placements for the elementary movements will be used in the following Chapters. In Chapter 8 we show how elementary movements can be combined to actuated gesture sets. We discuss calibration requirements and safety aspects that are important when running EMS-based workshops, prototype sessions and users studies. Further we present the full working *Let Your Body Move* toolkit for EMS-based haptic feedback. We show the wide range of EMS-based haptic output in mobile and wearable situations. The software components and hardware schematics are available and can be adapted to new scenarios. The toolkit and associated prototyping process considerably simplify the usage of EMS-based feedback in mobile interactions. Because it uses BLE for communication the toolkit can easily be combined with mobile and wearable devices, such as mobile phones, wristbands, and smartwatches.

The proposed toolkit was evaluated in a workshop setting. After a brief introduction the participants were able to develop interesting application ideas using EMS as a haptic feedback technology. The participants were able to use most of the features of the toolkit successfully. However, the evaluation also uncovered certain problematic areas, such as the difficulty of temporal and spatial precision in Wizard-of-Oz prototyping. An idea to overcome these problems is to provide scripted Wizard-of-Oz inputs rather than completely manual control.

In the following chapters we show how EMS haptic feedback can be used to investigate interaction paradigms. In Chapters 5 and 6 the toolkit is used in an early form to apply the feedback. In Chapters 7 and 8 the apps that are discussed are used to run parts of the user studies.

Chapter 5

Simulating Object Properties

With the advent of the Nintendo Wii controller[10] and the Microsoft Kinect[11], mid-air interaction in front of (large) displays have become increasingly popular. Much effort has been put into making body and gesture recognition robust and accurate [289] and, consequently, novel applications emerged both in the research and in the commercial sectors. To make such interactions convincing and immersive, multiple modalities are required. However, considering haptic feedback for mid-air interaction, it is still in its infancy and existing solutions restrict the user in several ways. Controllers like the Wii do provide vibration feedback, but require the users to hold the controller in their hands. Moreover, this approach has limitations in providing more advanced haptic feedback, such as for creating the illusion of holding a physical object. Further approaches to make simulated physical objects realistic include gloves [231] or exoskeletons [78]. As discussed in Section 2.2.2, those devices are in general cumbersome to wear and operate, particularly in public environments.

5.1 Free-Hand Interaction

In this chapter we focus on haptic feedback for free-hand interaction without encumbering the user's hand. The aim is to make free-hand interaction more realistic and convincing by providing haptic feedback in a way that is easily applicable in daily life. When a surgeon needs the flexibility and the tactile sense of the hands to handle surgical instruments the

[10] Nintendo Wii: `http://www.nintendo.com/wii/what-is-wii/`

[11] Microsoft Kinect: `http://www.xbox.com/enUS/kinect`

Figure 5.1: Free-hand interaction with haptic feedback: A user receives haptic feedback when approaching an object shown on the screen.

hand cannot be covered. Therefore the wrist and the lower arm are a particularly good body positions for applying haptic feedback in free-hand interaction. Wristband devices are already popular for life logging applications (e.g., Nike+ Fuelband[12], Jawbone Up[13]).

Today, vibration is the most popular technology for haptic feedback and is integrated into many mobile devices (Section 2.2.1). However, there is still a considerable knowledge gap about the perceived qualities of EMS feedback compared to feedback based on vibration. At the same time, EMS provides several advantages compared to vibration. It does not require any mechanics, making it cheap and easy to integrate with everyday objects (e.g., clothes or wristband). Furthermore, it is more variable with regard to the characteristics of the feedback.

In this chapter, we provide a comparison of EMS and vibration as feedback methods for free-hand interaction. First we discuss the design space of haptic feedback for free-hand interaction. We use this design space as a basis to present two studies that compare EMS to vibration feedback. The first experiment investigates (a) the differences in feedback strength for both EMS and vibration, and (b) identifies which levels of feedback strength between vibration and EMS correspond to each other. Then we used the results for a follow-up experiment, where we investigated how to select the feedback intensity for EMS and vibration in a way that reflects (a) different types of interactions (touch, grasp, punch) and (b) different materials (soft, hard) in free-hand interactions with large displays. In these experiments, different objects were shown on a large screen and we asked the user to perform a certain free-hand interaction (e.g., virtually touching a stone in mid-air – see Figure 5.1). The results show that users rate the

[12] Nike+ Fuelband: `http://www.nike.com/FuelBand_SE`

[13] Jawbone Up: `http://www.jawbone.com/up/international`

appropriateness significantly higher for the EMS feedback on hard material. The contribution of this chapter is to present results from two studies that investigate how to design haptic feedback to best reflect different types of interaction with different materials.

5.2 Haptic Feedback in Free-Hand Interaction

Several research projects looked at providing haptic feedback for interacting with remote systems and in virtual environments [116, 124, 300]. Free-hand, mid-air, and full-body gestures are getting more popular since infrared and depth camera-based tracking systems such as the Kinect, LEAP Motion[14], PrimeSense[15], and Xtion[16] become affordable and easy to use. Moreover such systems apply to body parts or the full body of the user so the user becomes the controller herself.

As discussed haptic feedback can make interaction with the remote system more realistic for the user [300]. In most cases, where such haptic feedback technologies are used, the user is restricted to a fixed position and rather bulky apparatus are required (Section 2.2.2). For example, Nikolakis et al. [231] compare stationary haptic feedback devices for manipulating objects in a virtual reality environment. To make the feedback mobile, the haptic system is moving in front of the user during interaction [234]. However, those haptic feedback systems, usually hand and forearm, restrict both the tactile sense and the mobility of the hand [101]. Hence, such systems are usually cumbersome to wear for a long period of time and of course users rarely wear gloves in the summer [169, 234] . On the other hand vibration feedback is well understood in research as well as in commercial products (Section 2.2.1). For example in motion-intensive interaction techniques (e.g., gestures), small, portable devices can be used, that require the user to wear gloves or markers [180]. Ooka and Fujita present a device, that aims to make grabbing and manipulating virtual objects more realistic [239]. Moreover, vibration has been used in many products for example it has been added to the touch panel of a mobile device [102]. Nevertheless, vibration feedback is still subject to research.

Following the notion of Nancel et al. [225], we use the term *free-hand interaction* to describe interactions based on mid-air gestures [3, 18] that neither need a physical connection to the display nor a handheld controller. Free-hand interactions are characterized by not limiting the degree of freedom for hand movements or the perception of tactile stimuli.

[14] LeapMotion: `http://www.leapmotion.com`

[15] PrimeSense: `http://www.primesense.com`

[16] Xtion: `http://www.asus.com/Multimedia/Xtion`

Different forms of free-hand interaction have been investigated, focusing on the restriction of sensory capabilities and social acceptance such as Obrist et al. [235] ultrasound feedback and the AIREAL [297] and AirWave [119], as discussed in Section 2.2.2. These approaches are limited in applications distance (ultrasound less than 10 cm, AIREAL 1 m and AirWave up to 3 m) and feedback strength. Moreover, they are not suitable for multi-user interaction and the environment needs to be augmented to provide feedback.

A large and inflexible apparatus impedes the user with regard to mobility and during interactions based on body posture or free-hand gestures. Small and mobile systems usually obscure the hands and restrict the tactile capabilities. User-independent systems require the surrounding space to be instrumented. As a result, such systems are usually limited with regard to feedback strength, interaction distance, and number of users. To tackle these issues we investigate the use of electrical muscle stimulation (EMS) for free-hand interaction. We compare EMS to vibration, one of the most popular haptic feedback modalities that can be easily applied to users due to its low cost and high social acceptance.

5.3 Design Space for Free-Hand Interaction Feedback

For designing feedback in free-hand interaction and to be able to provide a comparison taking important dimensions into account, we have sketched a design space for creating haptic feedback for free-hand interaction. This design space is used later on to explore specific dimensions without confounding different aspects. Based on a literature review, we identified the following dimensions of the design space. The design space can be applied for different types of tactile and force feedback as presented in Section 2.2.

Feedback technologies: There are many different technologies available that induce haptic feedback. One of the most common feedback technologies is vibration feedback that is used in almost every mobile phone, tablet, or game controller. Other feedback technologies include EMS feedback or air currents. Such technologies have different abilities to provide feedback ranging from tactile prickles on the surface of the skin or physical haptic movements of limbs.

Sensing capabilities: The haptic sensing capabilities are based on the different nerves in skin, tissue, and muscles all of which are stimulated by touch, pressure, and heat (Section 2.1.2). Again, the number of nerves varies at different positions on the human body. Therefore, some positions are more sensitive to haptic feedback than others. This lack of sensitivity can be adapted by the size of the stimulated area. Furthermore, the sensitivity changes over time because of the habituation during the stimulation. Further, the sense of the feedback also depends on the size of the stimulated area.

Position on the body: In cases where haptic feedback is applied through a device on the user's body, a number of different positions are possible. These include the fingers, the forearm, the upper arm, the torso, the head, the legs, and the feet. Applying feedback to each of these positions works differently and the choice of a position usually depends on the action for which feedback should be applied (playing football vs. grabbing something with the hands).

Stimuli characteristics: When applying the feedback, the following characteristics have an influence on haptic perception: the strength of the applied stimuli, the duration, and the stimuli form over time. The form of the haptic stimuli can follow the characteristics of being steady, alternating (on/off), or an increasing or decreasing sequence. Combinations of these stimuli create different rhythms over time, that can provide an illusion of physical properties or surface behavior of virtual objects.

Feedback type: Haptic feedback can be used for different purposes. We define feedback that is used to make the user aware of a certain status (e.g., that has executed an action) as *supportive*. Compared to this rather implicit form, we define *informative* as feedback to transmit information (i.e., similar to Morse code). In addition, this can be used to transfer information in a way that privacy is protected Finally, it can be used for warnings, for example, the feedback is provided as soon as users leaves the area in which they can be optimally recognized by a sensor (e.g., Kinect).

Content characteristics: The content characteristics that are simulated through the feedback are important as well. This is in many cases a continuum, such as simulating soft or hard surface, a smooth or rough surface, or a slow or fast movement.

Input gesture The feedback that is provided to the user depends on the gesture that is performed to achieve a realistic feedback. There are several gestures that can be done in mid-air (e.g. virtually touch or grab).

5.4 Prototype

We developed an EMS feedback and a vibration feedback prototype to explore the *feedback technologies* dimensions of the design space. Both prototypes apply their feedback on both forearms (*position on the body*) to keep the hands and wrists free (cf., Figure 5.2). This is particularly useful if the prototypes need to be embedded into clothing later. The

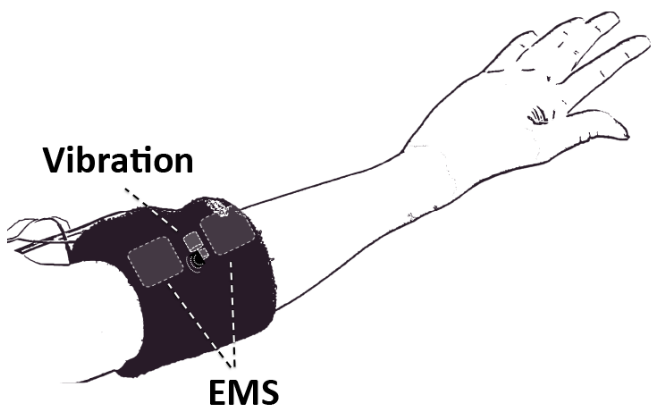


Figure 5.2: Vibration and EMS feedback placed on the forearm.

communication of both prototypes is realized with an Arduino Uno[17] that controls each of them independently. For both prototypes, the *impulse characteristic* is a simple on/off pattern of 750 ms, following the findings of Lopes and Baudisch [189]. The communication between the prototypes and the control software is realized using a WiFi-module. Both prototypes and the Arduino Uno controller weigh together about 580 g including battery. Furthermore, we would like to emphasize that with these prototypes the focus is on free-hand interaction as a special form of mid-air interaction [225]. In contrast to free-hand interaction, a later development may also include forms of interaction that require users to hold a device.

5.4.1 EMS Feedback

For EMS feedback we used an early version of the "Let Your Body Move" toolkit (Section 4.3 and used a Prorelax TENS+EMS DUO [272] device as EMS signal generator. The device uses a pulse width of 260 μ s and a constant pulse frequency of 60 Hz using a stable modulation scheme with a sawtooth waveform. In total, the device has 24 different strength levels. In a pretest, we explored the different levels and identified 10 different levels (1-10) that could be suitable for providing haptic feedback on the forearm. Regarding the impulse-time intensity curve in Figure 4.2, we discarded level 1 and 2 (current lower than 10 mA) as well as level 10 (lower current than 40 mA but uncomfortable for users). The standard deviation (SD) is within 6 % of the current. An overview can be found in Table 5.1. The device controls the different levels of current depending on the user's skin resistance. For applying the feedback to the user, two 40×40 mm self-adhesive electrode pads were used (Figure 5.2). These pads

[17] Arduino Uno: `http://arduino.cc/`

	Vibration		EMS	
Level	Speed (rpm)	SD	Current (mA)	SD
1	1390	0.51	4.10	0.25
2	2960	0.67	7.24	0.30
3	3876	0.53	10.12	0.23
4	4590	0.65	12.74	0.21
5	5267	0.73	14.50	0.18
6	5835	0.59	18.50	0.28
7	6274	0.65	19.06	0.28
8	6748	0.61	19.64	0.28
9	7274	0.49	21.82	0.17
10	7959	0.63	23.22	0.21

Table 5.1: Speeds of the vibration motor and corresponding currents for EMS.

were placed within a distance of 2 cm on the forearm over the flexor digitorum profundus (Section 4.2.2). The EMS impulse leads to a contraction of the muscles of the forearm, which forces the hand and middle finger to move upwards.

5.4.2 Vibration Feedback

The vibration feedback prototype uses a motor with a maximum speed of 8.000 rpm (at 7.5 V) and an asymmetric weight of 2 g. Following the EMS prototype, the vibration motor strength was divided into 10 levels. The levels range from 1390 rpm to 7959 rpm (cf., Table 5.1). The standard deviation (SD) is smaller than 0.04 % of the speed. The motor was placed within a wristband to fix it on the forearm during usage. To make users perceive both types of haptic feedback in the same place, the vibration motor is located between the EMS electrodes.

5.5 Study 1: Investigating Intensity

In the first step, we conducted a study investigating the intensity of EMS and vibration. We used two tasks to gain comparable levels of EMS and vibration feedback and to evaluate how easy EMS signals of different levels can be distinguished.

5.5.1 Participants and Procedure

In total, we invited 12 participants (8 male and 4 female) to take part in this study. They were aged 20 to 33 years ($M = 25.01$, $SD = 3.89$) and, except for one, right-handed. First, we provided participants with a brief introduction to the study. We attached the devices to the dominant arm (cf., Figure 5.2). To make participants familiar with the feedback to expect during the study, we applied sample EMS and vibration feedback, including the entire range of intensity levels. We chose the EMS levels from very low to still acceptably strong feedback.

In the study, participants had to adjust the intensity of the vibration feedback to match the intensity of the given EMS feedback. Participants were able to replay EMS and vibration feedback with the chosen intensity. Then, the participants started with the tasks to (1) map the vibration level to EMS level and afterward to (2) distinguish different EMS levels. Then, they filled in a questionnaire with 5 items rating scales ranging from 1 (totally positive) to 5 (totally negative).

5.5.2 Task 1: Generating Corresponding Intensity Levels

To evaluate EMS and vibration feedback in an application scenario, it is necessary to get corresponding feedback strengths. Therefore, we applied specific EMS levels to the users (levels 3 to 9) in a counterbalanced order. The user's task was adjusting the vibration level to the given EMS level until the user perceived the feedback similar for both feedback technologies. There was no time limit and participants were able to perceive EMS and vibration feedback repeatedly. Each EMS signal was presented five times in a randomized order to each participant.

For EMS levels 3 and 4, the lowest vibration level was already perceived to be more intensive. For the remaining levels, there is a close to linear correlation. Hence, we decided to use EMS levels 5 and 8 and the corresponding vibration levels 2 and 6 for study 2.

5.5.3 Task 2: Distinguishing Vibration and EMS Signal

In many cases, different strengths of haptic feedback are required (e.g., for different actions or content items). Hence, it is necessary to create feedback that users can distinguish. In this task, participants should differentiate which level is more intense. Two different EMS signals were provided after each other. We used EMS level 6 as a baseline and a second signal with a level between 3 and 9. Thus, we have a difference of 0 to 3 levels. The order in which the

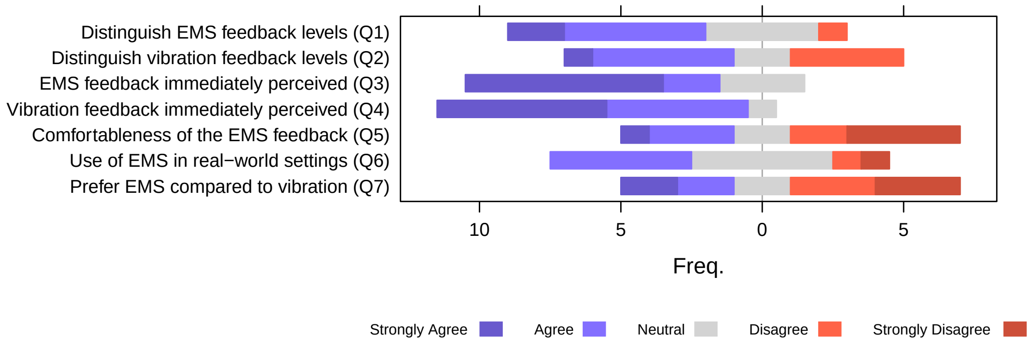


Figure 5.3: Results of the questionnaire ranked on a 5-point Likert scale.

signals are presented to the user is counterbalanced to the position in which the baseline is presented (as first or second stimulus).

The success rate is 60% for one level of difference, 90% for two levels, and 100% for three levels. Thus, we used three levels of difference in feedback strength for the second study.

5.5.4 Questionnaire

The results of the questionnaire show that participants felt that they can distinguish the different feedback-levels easily as shown in Figure 5.3 (Q1 EMS: Median $(M) = 2$, median absolute deviation $(MAD) = 1$, Q2 Vibration: $M = 2.5$, $MAD = 0.5$). Furthermore, both kinds of feedback are perceived immediately (Q3, Q4). Questions about the comfort (Q5 $M = 3$, $MAD = 1$) and whether participants felt that EMS could easily be applied in a real-world setting (Q6 $M = 2.5$, $MAD = 1$), received average results. Asked for their preferences, participants did not have a clear preference for one of the methods (Q7 $M = 3.5$, $MAD = 1.5$, 1 = EMS, 5 = vibration).

5.5.5 Limitations

We acknowledge the following limitation of the study. The system automatically adjusts the current depending on different skin resistances. However, the system is limited to a specific spectrum that it can compensate. That is, it cannot compensate the current for all possible variations in resistance. So it is possible that a user with very dry skin (i.e., skin resistance of more than 700 Ω) subjectively perceives level 5 (with a current of 13 mA) to be lower than a user with very wet skin (i.e., skin resistance of less than 400 Ω) perceives level 4 (with current of 14 mA).

5.6 Study 2: Exploring Haptic Feedback

The aim of the second study was to find out how feedback should be designed to best reflect (a) the gesture a user is performing (such as grabbing an object) and (b) the properties of the object the user is interacting with (e.g. whether it is soft or hard). In this way we aim to lay the foundation for more realistic and distinguishable haptic feedback. We tested EMS and vibration feedback types, each with a low and a high intensity level (EMS_{low}, EMS_{high}, $vibration_{low}$, $vibration_{high}$)

As has already been discussed in the design space, a number of gestures could be used for free-hand interaction with content on the screen. In this study we focus on three common gestures: grabbing, touching, and punching (hitting hard) an object. With regard to the object characteristics, we focus on the distinction between soft and hard objects as having two opposite types of material behavior.

5.6.1 Participants and Procedure

In total, we invited 20 participants for the study (13 male and 7 female). They were aged from 21 to 62 ($M = 27.55$, $SD = 8.61$). All participants were right handed.

We tested in our study the two feedback methods (vibration and EMS) and two materials characteristics (hard and soft) with three different gestures ('mid air touch', 'mid-air punch' and 'mid air grasp'). Again the EMS and the vibration device were attached to the participants' dominant arm (Figure 5.1). We used two well-known metaphors as stimuli for representing material characteristics (i.e., a stone for hard and a sponge for soft material). Further, we focused on parameters, which the users could be differentiated clearly. We used level 5 and 8 for EMS and for vibration level 2 and 6 as feedback intensity, based on the findings from the prior study. We showed each participant an interaction object and an interaction technique on the screen and asked them to perform the gesture for the object (e.g. grasp a stone). The participants were asked to perform the technique like they would interact with a real physical object. For example, the 'mid-air touch' participants were supposed to perform a full hand touch gesture in the air in the same manner as touching a physical stone or sponge in front of them. In total, we have six conditions with 3 different interaction techniques on two different materials.

The study is designed as a within-subject study, thus, each participant performs all conditions with both haptic feedback methods. All conditions are grouped by interaction technique and interactive object. The order of all combinations of materials and gestures are permuted with

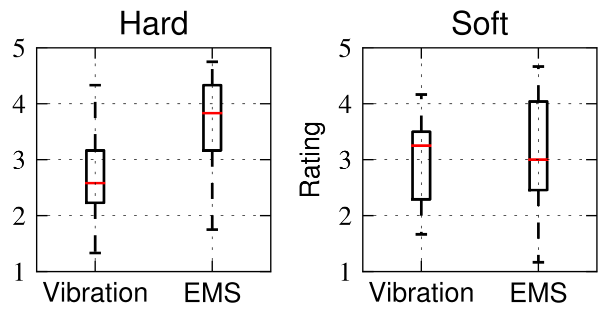


Figure 5.4: Comparison of EMS and vibration feedback for (left) hard and (right) soft material.

a latin-square. For each material and gesture each user got all feedback conditions in all possible permutations in a counterbalanced order.

In each group, the participants perceived haptic feedback with high and low intensity using the EMS and vibration feedback, again, in a counterbalanced order. We placed the participants 1.20 m standing in front of the display, so the participants could not reach the display. The Kinect was placed directly in front of the display. The user was asked to test the gestures first, then the four feedback modalities, and afterwards both together. We advised participants that the point of feedback and the gesture movement should fit together. When the users were comfortable with the feedback signal and gestures we started the study. The trail phase was up to 3 minutes. As shown in Figure 5.1 the material was displayed on the screen and the user was asked to perform the gesture, in the direction of the visual object. When the user lifted up their arm they received the haptic feedback on the lifted arm. After performing the gestures the users were asked to rate the fitting of the feedback for the interaction and the material on a 5-point Likert scale (1 = not fitting at all, 5 = perfect fit). After 24 trials the users were asked to complete a final questionnaire. Finally, we conducted semi-structured interviews to obtain more qualitative feedback.

5.6.2 Results

The 20 participants performed all 24 conditions and perceived the EMS feedback 1173 times (median *(M)*= 58.65, standard deviation *(SD)*= 19.23) and the vibration feedback 860 (M = 43.00, SD = 10.43) times.

From the questionnaire we found that eight of the participants had experience with free-hand interaction as they previously used the Microsoft Kinect. All of them use vibration feedback

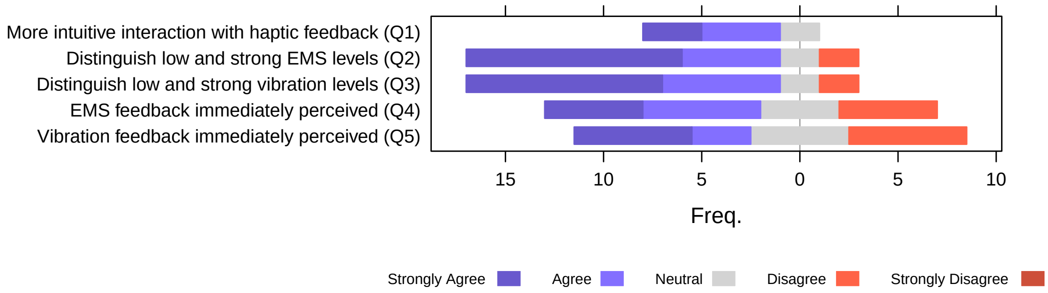


Figure 5.5: Results of the questionnaire ranked on a 5-point Likert scale.

on their mobile phones and 70% use force-feedback on a gaming console. Furthermore, they agreed that force feedback makes the interaction with virtual objects more intuitive as shown in Figure 5.5 (Q1 $M = 2$, median absolute deviation *(MAD)*= 0 – 5 Point Likert scale, 1 strongly agree to 5 strongly disagree). Only one participant had reservations against the use of EMS.

All users are able to distinguish the EMS and vibration feedback. We asked them how well they can differentiate between the low and the strong feedback (Figure 5.5). For both devices, the ratings are high, EMS performing slightly better (Q2, $M = 1$, $MAD = 0$) compared to vibration (Q3, $M = 1.5$, $MAD = 0.5$). Furthermore, we asked the participants whether they experienced any delay in the feedback. For EMS, the average score for the delay is $M = 2$ (Q4, $MAD = 1$), for vibration it is $M = 3$ (Q5, $MAD = 1$).

The participants rate EMS feedback better than vibration feedback (aggregated over all feedback strengths, interaction techniques, and interaction objects). For comparing hard and soft material we aggregated all gestures and strengths. As shown in Figure 5.4 (left), EMS is perceived better than vibration for interacting with hard material. A Wilcoxon signed-rank test showed that this difference is statistically significant, $Z = -2.931$, $p = 0.003$.

The comparison of EMS and vibration for soft material (Figure 5.4, right) is not significant. Therefore the difference of EMS feedback and vibration feedback is based on the displayed material.

5.6.3 Qualitative Feedback

Semi-structured interviews with the participants after the study revealed that they can imagine using EMS feedback to extend visual feedback on interaction with a wide variety of materials, including not only hard and soft material, but also cold and pointed material.

Furthermore, they envisioned several application areas. For example, when controlling robots remotely, EMS can provide information about when an obstacle is hit. It can also tell the user how much power is needed to lift a target to make this remote interaction more realistic. Furthermore, participants suggested using this approach for assistive systems. For example, EMS could be used when an athlete and a trainer are not collocated to provide feedback on whether or not a movement is correctly executed. Feedback could even go so far as to address a particular muscle. They talked about using the feedback in interactive games and for physiotherapy.

5.6.4 Limitations

We acknowledge the following limitations of the study. Again, the perceived feedback strength of EMS depends on the skin resistance and the user's sensitivity. For this reason, we divided the feedback into high and low in the second study. However, we envision of EMS systems as personal devices that only require a one-time calibration or can control the feedback current more accurately. In semi-structured interviews participants reported that the direction of movement was more like a magnet than a resistance. Other participants did not notice the direction of the muscle movement.

5.7 Experience with Haptic Feedback

The analysis of the design space shows that a variety of different dimensions need to be taken into account when providing haptic feedback. First, an appropriate feedback technology needs to be chosen. The results from the study show not only that participants liked EMS feedback, but that they also considered it to provide more realistic feedback when interacting with virtual objects having different properties (hard, cold). The findings suggest that EMS is a particularly well suited technology to provide haptic feedback. This is also backed by the fact that the power required for this method is rather low and we envision that due to its form factor it can be easily integrated in small artifacts or clothing as discussed in Section 2.3.3.

This allows the feedback to become ubiquitous and it can extend the interaction with virtual objects by physical properties in free-hand interaction in everyday scenarios.

Another property of EMS that was mentioned by the participants that could be explored is the ability to preserve private feedback. Compared to vibration, it is impossible for others to see or hear EMS tactile feedback. As a result, we envision future security-critical applications, such as ATMs, to employ EMS. An authentication application could, for example, provide a number of haptic authentication patterns, where users need to press a button as they feel their personal pattern. Such an approach would make frequently used attacks, such as shoulder surfing, impossible.

5.8 Conclusion

In this chapter, we took a first step towards understanding the potential of EMS as haptic feedback with the focus on free-hand interaction. We present the design space of haptic feedback in free-hand interaction with an early version of the “Let Your Body Move” toolkit. Based on the design space and the EMS parameters (Section 4.1) we compared EMS to the currently most popular feedback technique, vibration feedback, in two user studies. In the first study we calibrated the feedback strength of EMS to similar level of vibration. This allowed the second study to compare EMS and vibration feedback when the users interact with gestures and with objects that have different physical properties. The results show that EMS is perceived to be superior in particular conditions, such as for interaction with hard material.

In addition, with a simple placement of two electrodes to actuate a single muscle (flexor digitorum profundus) the users perceived a further positive effect on the interaction. The user feedback indicates that users are willing to wear EMS haptic feedback technology to perceive additional haptic feedback to simulate object properties. Interaction in virtual or mixed environments can benefit from EMS feedback to simulate physical properties in scenarios such as gaming. This interaction can take place in every-day scenarios such as in a mobile context in a public space, when interacting with displays that are not reachable by the user. Since the EMS feedback technology is wearable it can be activated wirelessly in interaction scenarios when it is necessary to support an interaction from the environment that tracks the movements and actuates the user.

In interaction with such environments target selection is one of the most important tasks. It requires a precise coordination of the hand in 3D space and comes along with further interaction cues. Haptic feedback might support this interaction. The feedback needs adequately to represent this precise and delicate interaction. In this chapter we have shown that EMS goes further than vibration feedback with regard to the feedback variability. In the next chapter we investigate EMS for target selection tasks and compare it again to vibration feedback.

Chapter 6

3D Target Selection

Target selection is a core task not only for user interaction on 2D displays, but also for 3D interaction with virtual reality (VR) and mixed-reality systems. 2D pointing and selection is well understood, yet in 3D it is more complex and therefore less well investigated. It is has repeatedly been a research focus of prior work [8, 29, 67]. 3D pointing techniques require movements in 3 axes with a virtual hand or cursor to select a target, and the movement typically covers all three degrees of freedom (3DOF). In contrast to 3D, 2D selection requires control of only 2DOF. Typical 2D selection devices are associated with a mouse cursor or a touch input device. Furthermore, there is currently no standard for 3D selection or input devices and techniques such as the ISO 9241-9 standard [146] in the 2D domain. To improve the comparability between user studies, the most recent work uses a 3D extension of the ISO 9241-9 methodology. This methodology has been used to demonstrate the benefits of visual feedback methods [321]. 3D displays or projections with shutter glasses as shown in Figure 6.1 are used for virtual and mixed reality environments. Interaction with 3D stereo displays introduces additional issues such as the vergence-accommodation conflict [136], which makes the target selection more difficult [43, 319].

General user interface guidelines frequently include appropriate feedback as a desirable criterion. Previous 3D pointing experiments use highlighting to provide additional feedback, when the cursor or finger selects a potential target object. Another option is haptic feedback, which helps participants to haptically perceive target depths and may improve performance [56]. On the other hand, its absence may affect one's ability to find the true depth of targets [319]. Another factor that affects selection is that the user may occlude small targets with the finger, or other body parts. The so called "fat finger" problem [334] in 2D touch input is also due

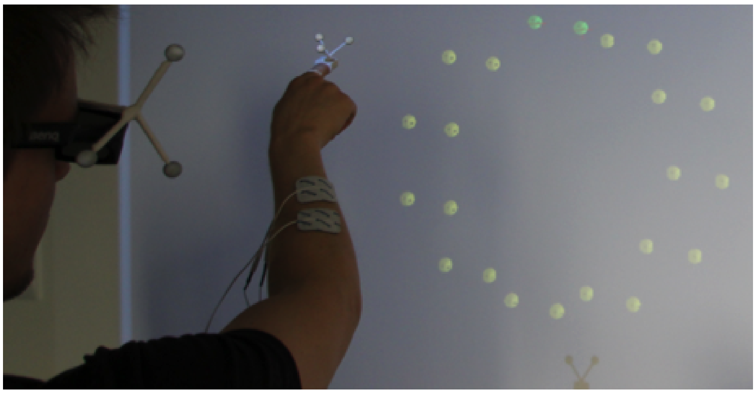


Figure 6.1: User interacting with a 3D scene. The head and finger trackers are visible, as well as the EMS electrodes.

to the occlusion of targets by a finger. The problem applies also to 3D. Yet, when moving a finger to a 3D target, the situation is worse. If a finger is behind an object floating in space it may still appear to be in front of it from the viewpoint of the user, due to the occlusion of the display by the finger (or other body parts). Within the vision that is discussed in Section 3.5.1, in this chapter haptic feedback is used for target selection to face these issues.

In this chapter we introduce EMS-based target selection for 3D displays or projections with shutter glasses. Due to the lack of standardized experimental methodologies, the effect of haptic feedback with vibration or EMS has not been investigated.

6.1 3D Target Selection

One of two main approaches in 3D selection is the virtual hand-based techniques used for virtual finger, hand or 3D cursor-based selection techniques [2, 34, 67, 270]. The other approach is ray-based selection and is outside the scope of this work. Virtual hand-based techniques rely on the 3D intersection of the finger, hand or 3D cursor with a target. Such selection requires that the user also picks the correct distance, i.e., visual depth, for a target. In such techniques, color change is most commonly used as additional visual feedback [2].

In this work a 3D extension of the ISO 9241-9 standard [146] is employed, based on Fitts's Law [95], similar as illustrated in Figure 6.2. Recent 3D pointing studies have used this paradigm ,e.g., [43, 43, 319, 320]. The movement time (MT) is proportional to the index of difficulty (ID) and depends on the size W and distance A of targets:

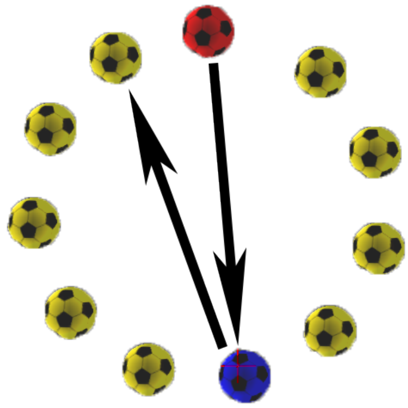


Figure 6.2: ISO 9241-9 reciprocal selection task with eleven targets. The next target is always highlighted in blue. Targets turn red after they have been missed and green if they have been hit. Participants start with the top-most one. The arrows indicate the pattern in which the targets advance.

$$MT = a + b \cdot ID, \ \ where \qquad ID = log_2(\frac{A_e}{W_e} + 1) \qquad (1)$$

Throughput (TP) depends on effective measures, and captures the speed-accuracy trade-off [33]. The so called effective index of difficulty (ID_e) is described by the log term. The average length of the projected movement is called the effective amplitude (A_e). W_e is the effective width and is computed via the standard deviation of the projections SD_x and of the selected positions onto the task axis. It is the line between the adjacent targets. W_e is adjusted by multiplying 4.133 to the SD_x regard to [203, 321]:

$$TP = \frac{log_2(\frac{A_e}{W_e} + 1)}{MT}, \ \ where \qquad W_e = 4.1333 \cdot SD_x \qquad (2)$$

6.1.1 Haptic Feedback in Pointing

The effect of haptic feedback has been evaluated, with tactile and force feedback devices (Section 2.2. In an early Fitts's Law study, a substantial difference was observed in conditions with a low index of difficulty [335]. Arsenault and Ware [9] found that haptic feedback reduced the time of inter-tap intervals while sitting. Wall et al. investigated 3D object selection in a system with stereo graphics and haptic feedback. They identified that accuracy was higher, but found no improvement of the selection time [336]. Lehtinen et al. [180]

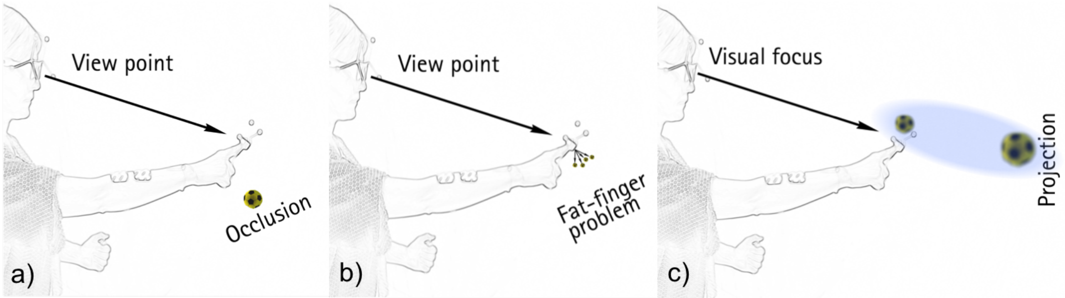


Figure 6.3: Addressed 3D pointing issues: The user a) occludes the selecting target, b) selects a small target, and c) focuses on the finger and sees the target blurred.

used different vibration patterns for guiding users to a target in pointing tasks and found it to be beneficial. Also, Corbett et al. [60] showed that 3D pointing with haptic feedback is significantly faster than without haptic feedback, but vibration feedback was slightly slower than the non-feedback condition. 3D selection with haptic feedback while standing was evaluated by Pawar and Steed [244] using a large haptic device in a CAVE (cave automatic virtual environment). They established that "hard" force feedback was slower then "soft" feedback for selection tasks. The effect of haptic feedback through EMS for selection tasks has not yet been investigated. In this chapter we investigate this and compare it with vibrational feedback. Visual highlighting and no additional feedback were used as a baseline.

6.2 Feedback Issues in 3D Pointing

Issues affecting 3D pointing have been studied before [307, 321], we reviewed the most relevant problems in the following.

6.2.1 Occlusion and the "Fat Finger" Problem

Large screen-based displays suffer from an inherent cue conflict. First, the finger or hand of the user can occlude objects shown on the display, even if they are positioned to "float" in front of the user's finger or hand relative to the viewer (even in monoscopic or head-tracked displays). Typically, the user's hands are raised in front of the target to interact or select such virtual objects (Figure 6.3 a). Transparent displays in front of the hand just reverse the issue by always occluding the hand. The tip of the finger can occlude targets of similar or smaller size. This is well known as the "fat finger" problem in touch interaction [334], but also applies directly to 3D selection (Figure 6.3 b). To address this, we displayed a cursor slightly above the tracking sleeve worn on the index finger. We moved the cursor as close as possible to the finger, while still enabling the participant to see the targets clearly. Note that this still leaves the problem that the hand or even the arm of the user can occlude one (or more) targets, especially during downwards motion.

6.2.2 Stereo Viewing

Stereo displays introduce additional cue conflicts. The human visual system is unable to focus simultaneously on objects at different distances (e.g., a finger in front and a target at the back).

The display is typically further away than the 3D content the user interacts with. Such stereo systems suffer from the so called vergence-accommodation conflict [307, 321]. When a target appears in front of the screen, the users still have to focus their eyes on the screen, to see the target in sharp focus. Then, the focus is either on the selecting finger or on the target during a target selection with a finger. Thus, the user sees one or both blurred [42] (Figure 6.3 c). Similarly, the double vision effect (diplopia) can also be found in stereo touch-screens [328]. This effect impacts the selection of a target, as the user may steer the finger to the wrong position in the 3D space. The user needs to correct the movement or might even miss the target completely [184, 230].

6.2.3 Selection Feedback

Several cues, including tactile feedback and stereo viewing, indicate to the user that she has touched a target in the real world. In virtual or mixed realties only a subset of such object properties are presented. In such environments the whole user, or parts such as the finger or the head, is tracked to interact with the virtual objects. In the absence of haptic feedback or force feedback, a tracked finger that selects a 3D target will just pass through it. In stereo viewing the finger occludes at least one of the shown images and thus also collapses the 3D illusion: The target is still seen behind the finger. Therefore other feedback methods such as highlighting become necessary [43, 319]. When the user reaches the target it then changes color or triggers a sound. The user sees or hears if the target is correctly selected, even if the finger is visually in front or behind the target. It also helps, if the user has to differentiate between small targets. This form of visual feedback has been shown to have a positive impact on pointing performance [321].

6.2.4 Haptic Feedback

Haptic feedback is used in many cases as additional, or even in place of, visual feedback. One classic scenario is where visual feedback is not possible, such as for blind people. Another common use case aims to increase realism by adding force feedback as discussed in Chapter 5. Vibration and EMS feedback technologies are currently lightweight and mobile enough to be practical. Both consume very little power (in the milli-Watt range) and work even with fast motions. Research on object selection with pointing has used vibration as a feedback modality in different positions on the body (lower arm, hand and finger tip) [60, 180, 358]. EMS can similarly be used to provide selection feedback, and could be compared to vibration and visual feedback.

A small vibration motor is attached to the fingertip of the user. For EMS, we attach the electrodes at the index finger muscles in the lower arm. The user then perceives the applied stimulation in the finger and at the lower arm. Increasing the stimulation through EMS causes the finger muscles to contract and the finger to move. In this work the stimulation is limited to cause no, or only imperceptibly small, finger movements. The main motivation for this is that (sufficiently) larger finger movements would make it difficult or even impossible to select small targets successfully, as it might appear that the finger is pushed away from the target. Yet, and even though the finger itself does not move, the EMS stimulation still provides the sensation of the finger hitting an object.

6.3 Evaluation of Target Selection

To compare the different forms of feedback we consider here, none, visual, vibrational, and EMS, we built an appropriate prototype and designed a Fitts's Law study based on ISO 9241-9 [146].

6.3.1 Participants

We recruited 12 participants (3 female) from a local university mailing list with ages ranged from 21 to 32 (average = 25.5, $SD = 3.1$). All participants were right handed and had an average height of 1.79 m ($SD = 0.09$). Except for one, all had used 3D technology before and watched at least one 3D movie at the cinema in the last year. Only three of the 12 participants watch 3D movies at home. Seven participants had used haptic feedback devices (such as a game controller or joysticks) before, six of them in 2D games and two in 3D games. Six of

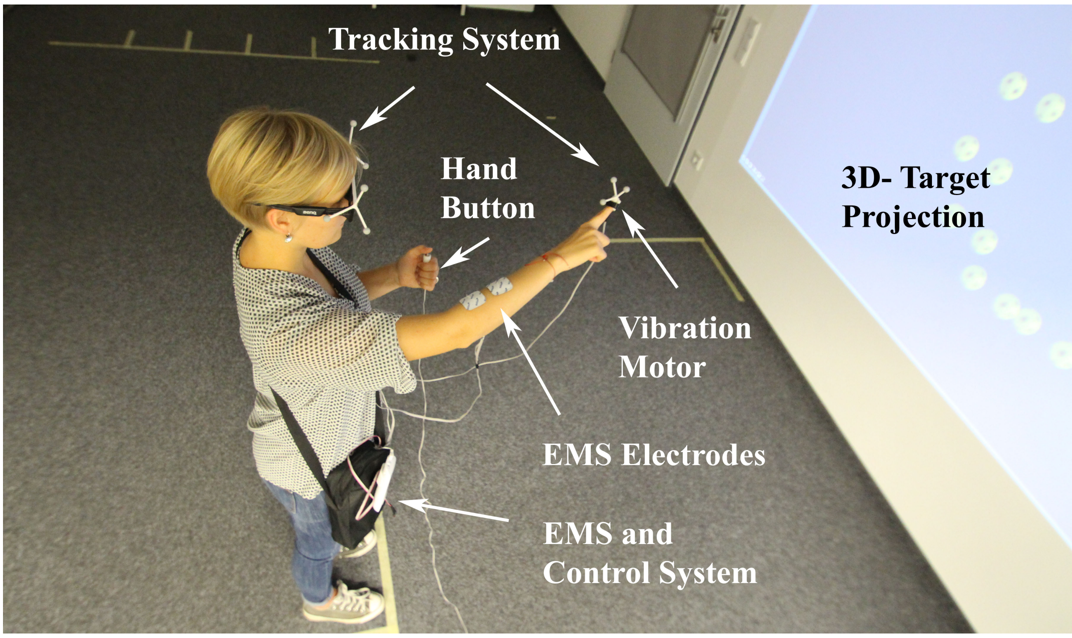


Figure 6.4: A participant standing in front of the 3D projection and performing a task. While performing getting Non-feedback, EMS, vibrotactile or visual feedback. When selecting a target the hand button will be pressed.

the 12 participants had experienced EMS before, for previous user studies, physiotherapy and massage purpose.

6.3.2 Apparatus

To perform this experiment, we set up a virtual reality system and added vibration and EMS feedback.

Hardware

The software ran on a Windows 8.1 PC with a 3.5 GHz Xeon CPU, 8 GB RAM and a ATI FirePro V graphics card. For stereo display a BenQ W1080 ST short throw 3D Projector with 128×800 resolution and 120 Hz were used together with BenQ 3D shutter glasses. The size of the projection screen was 3.26 m×1.9 m and the user stood 2 m away from the screen. For 3D tracking we used ten Naturalpoint Optitrack Flex13 cameras with the Motive Tracker software. The system was calibrated to an accuracy of 0.32 mm.

To enable the participant to indicate selection, we integrated a Logitech mouse button into a 3D printed handle. The optical tracking targets were mounted onto a custom, 3D printed, finger sleeve. This sleeve contained also the vibration motor. For head-tracking the tracking targets were attached to stereo glasses, again via 3D printed mounts (seen in Figure 6.4). The user wore a small bag (with a shoulder strap), which contained the control electronics for the vibration motor and the EMS toolkit with the Arduino Uno for access via WiFi (seen in Figure 6.5). We created a custom application in Unity 4. We used the iminVR MiddleVR 1.4 plugin for stereo display and to interface with the tracking system for the head and finger position. The target and study logic was implemented through custom Unity scripts. We also created scripts to interface with the vibration and the EMS device through the WiFi interface of the Arduino. Additional scripts were then used to log all information necessary for the analysis.

Visual Feedback

In all conditions the user sees a $1 \times 1 \times 1$ cm cross as cursor approximately 1 cm above the finger sleeve. For the visual feedback condition the target is highlighted in green when the cursor is inside the target.

Vibrational Feedback

A vertical coin vibration motor (KF2353[18]) was mounted at the user's finger within the tracking sleeve below the fingertip (Figure 6.4). The motor is 1 cm long, vibrates up to 9,000 rpm, and consumes 90 mA at 2.3V. The vibration motor is attached through the finger sleeve (with the optical tracking markers) and hook-and-loop fasteners to the finger. This reduces the sound and also helps to ensure that the feedback is only felt on the fingertip. With this mounting method, the sound of the vibration motor is very low, too small to be easily audible in the lab environment. The vibration motor is controlled with an Arduino Uno. The Arduino Uno is connected to the main computer via an RN-XV-171[19] WiFi chip. The Arduino is powered by a 9V block battery and worn together with the EMS-system in a side bag.

EMS Feedback

For the EMS feedback we used a simple version of the "Let your Body Move" EMS prototyping toolkit (Chapter 4) with a Beurer SEM43 [23] device as EMS signal generation. This version of the toolkit switched the EMS signal on and off via two optical relays. This toolkit version has a RN-XV-171 WiFi chip to connect to the main computer, visible in Figure 6.5. Whenever the user's finger "hits" a target the toolkit applies the EMS feedback.

[18] KF2353 `http://www.mouser.com/ds/2/321/28821-Flat-Coin-Vibration-Motor-Documentation-369707.pdf`

[19] RN-XV-171 `http://www.microchip.com/mymicrochip/filehandler.aspx?ddocname=en558075`

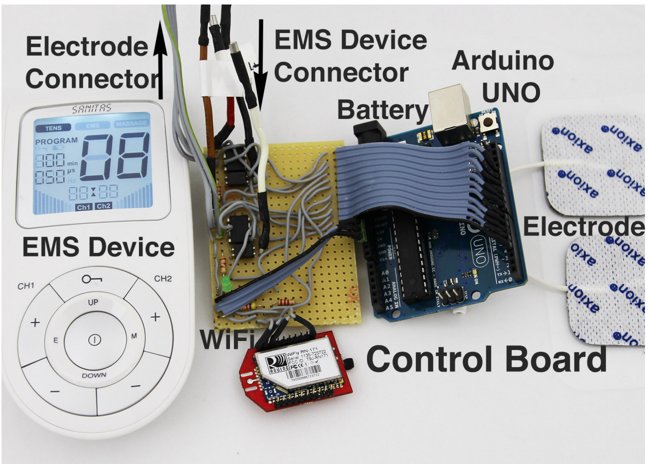


Figure 6.5: EMS Toolkit with Arduino Uno, WiFi unit and control board to switch on/off the EMS signal.

We used 50 μs duration and a frequency of 80 Hz as parameters for the EMS toolkit. We calibrated the intensity of EMS for each user individually and the calibrated currents are shown in Table 6.1. We placed 40×40 mm self-sticking electrodes on the extensor digitorum muscle. When the user holds the index finger in a pointing position as shown in Figure 6.4, this muscle lifts the index finger up, which simulates the sensation of hitting a (light) physical object. During calibration of the EMS intensity we scaled the intensity down to a level where the finger itself does not move, but the user still perceives the sensation of the finger moving.

End-to-end latencies

The responsiveness of each condition was tested 20 times, 10 times for the transition to "on" and 10 times to "off". This was done by recording both a finger and the display with a camera, computing the delay in terms of frames and then averaging the results [318]. The visual feedback condition, i.e., the end-to-end latency of our Unity-based virtual reality simulation, was measured to be 54.6 ms and $SD = 5.24$. Our projector likely caused a substantial part of this latency. The end-to-end latency of the EMS condition was 61.8 ms and $SD = 4.76$ and the vibration condition 66.6 ms and $SD = 6.39$.

6.3.3 Experimental Design

The study had two independent variables: 4 feedback types and 3 target depths, for a 4×3 design. The four feedback types where: non-, EMS, vibration and visual feedback. Target depth varied from 40 to 60 cm from the user's position. Targets were arranged in circles of

20 cm, 25 cm and 30 cm diameter, with sizes of 1.5 cm, 2 cm, and 3 cm. Similar to previous work [318], we positioned targets within the same circle at the same target depth. The order of all of the above conditions and factors was determined by Latin squares to minimize learning effects. In total, our experiment had thus $4 \times 3 \times 3 \times 3 = 108$ target circles with 11 targets each. Thus each user performed 1188 target pointing tasks and we recorded 14256 trails overall.

6.3.4 Procedure

We introduced the participants to the context of the study and asked them to fill a background questionnaire about their relevant experience and an informed consent form. Then, we connected them to the EMS toolkit, by placing the electrodes on the extensor digitorum muscle and put the tracking target onto their index finger. We run through the calibration process as discussed in Section 4.1.

We initially stimulated the index finger of the participant so that it lifted up by approximately 1 cm, which ensured that we had identified the right muscle for the finger. Then, we decreased the EMS signal until the finger was not moving anymore, but made sure that the participants still felt the EMS feedback. We measured the current and voltage of the calibrated level. Finally, we took a photo of the positions of the placed electrodes for later analysis.

The participants were placed 2 m in front of the screen. We asked them to stand relaxed, but not to move around during the study. They were equipped with the 3D glasses and with the finger sleeve for tracking and vibration feedback. Participants wore the finger sleeve and EMS electrodes in all input conditions (Figure 6.4). The software turned the haptic or visual feedback on as long as the cursor was within the target. If the user clicked the button held in the other hand while the cursor was in the target, a “hit” was registered. Otherwise a selection error was recorded. In the “non”-feedback condition, no feedback was provided. In the visual feedback condition, the target changes color when the cursor enters the target and back when the target is left. The EMS-feedback or vibration feedback worked analogously. Before the start of the main study, users were given a few training trials (between one and three), until they felt comfortable with the particular condition. After the participants had completed all targeting trials they were asked to fill a second questionnaire.

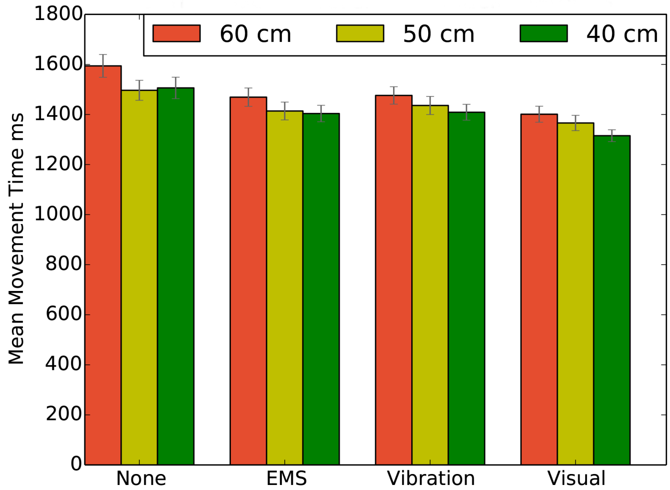


Figure 6.6: The average movement time for all conditions and three depth levels.

6.3.5 Resultes

First we discuss movement times, errors, throughput, and then the feedback current we recorded for each participant. As the data for movement time was not normally distributed, we log-transformed the data for time before the statistical analysis. Also, the outliers beyond 3 standard deviations from the mean in terms of time and target position were filtered. This removed 350 trials or 2.46% of the data, which typically corresponded to erroneous double-selection episodes. Subsequently a repeated measures ANOVA was used to analyze all results.

Movement Time

The ANOVA identified a significant effect for movement time $F3,33 = 5.9$, $p < 0.005$. According to a Tukey-Kramer test, only the no-feedback and visual feedback conditions were significantly different. The average movement times for the no-feedback, EMS, vibration and visual feedback conditions were 1522 ms, 1449 ms, 1465 ms, and 1387 ms, respectively. In terms of depth of targets, there was also a significant effect $F2,22 = 10.86$, $p < 0.001$, with the two levels closest to the user being significantly faster to select than the ”deep“ level.

Error Rate

ANOVA identified a significant effect for error rate $F3,33 = 6.05$, $p < 0.005$. According to a Tukey-Kramer test, the EMS, vibration and visual feedback condition was significantly better than no-feedback condition. The average error rates for the non-feedback, EMS, vibration and

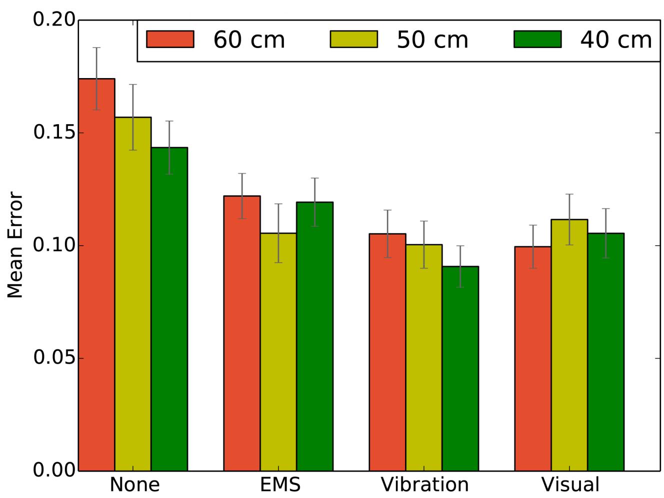


Figure 6.7: The Error rate of all conditions and three depth levels.

visual feedback conditions were 15.3%, 11.3%, 9.8%, and 10.5%, respectively. For target depth, there was no significant effect on errors $F2,22 < 1$.

Throughput

ANOVA identified a significant effect for throughput $F3,33 = 3.58$, $p < 0.05$. According to a Tukey-Kramer test, only the no-feedback and visual feedback conditions were significantly different. The average throughput values for the no-feedback, EMS, vibration and visual feedback conditions were 3.19, 3.28, 3.29 and 3.37, respectively. For target depth, there was a significant effect on throughput $F2,22 = 6.73$, $p < 0.01$. The targets further from the user had again significantly less throughput than the closer two levels.

Feedback Current

The stimulation from the EMS was perceived differently by different users, depending on their skin resistance, muscle performance and the position of the electrodes (see Section 4.1). We recorded the current and voltage for each user after calibrating the finger to exhibit no (or only minimal) motion. We also took pictures of the electrode positions for each user.

Subjective Results

The participants could differentiate between the haptic feedback methods as shown in Figure 6.9 (Q1, median (M) = 01, 1 strongly agree to 5 strongly disagree, with median absolute deviation (*MAD*) = 0). All three feedback methods were ranked as reasonably realistic with

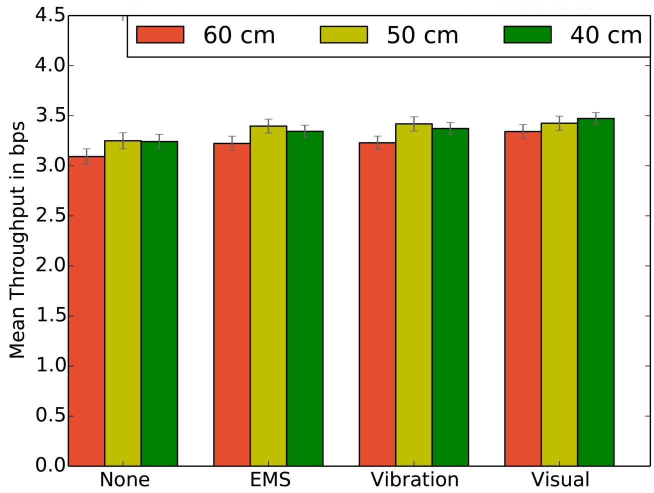


Figure 6.8: The throughput of all conditions and three different depth levels.

User	EMS Level	Current (mA)	Voltage (V)
1	3	20.91	39.80
2	5	24.71	62.16
3	4	24.48	80.27
4	4	24.60	107.22
5	3	23.25	65.96
6	5	21.13	97.27
7	2	16.55	50.31
8	4	23.14	99.95
9	2	15.43	67.19
10	3	19.90	85.08
11	3	17.66	82.73
12	5	25.16	119.63
Average	3.58	21.41	79.80

Table 6.1: Stimulation level, current, and voltage used with the EMS system, for all users.

a median of 2 (Q3-Q4, $MAD = 1$). When we asked for the perception on delay in the feedback, the EMS feedback and visual feedback were ranked with a very low delay (Q5, Q7 $M = 1$, $MAD = 0$), followed by the vibration feedback (Q6, $M = 1.5$, $MAD = 0.5$). Also the position of the feedback was ranked as appropriate. A median of 2 for EMS feedback at the lower arm (Q8, $MAD = 1$) and median of 1 for the position of the vibration motor at the fingertip (Q9, $MAD = 0$). We also asked how well the participants were able to map the EMS impulses to the virtual 3D objects. The participants almost universally agreed on this (Q10, M=1.5, MAD=0). The participants were asked if they got used to the EMS impulses

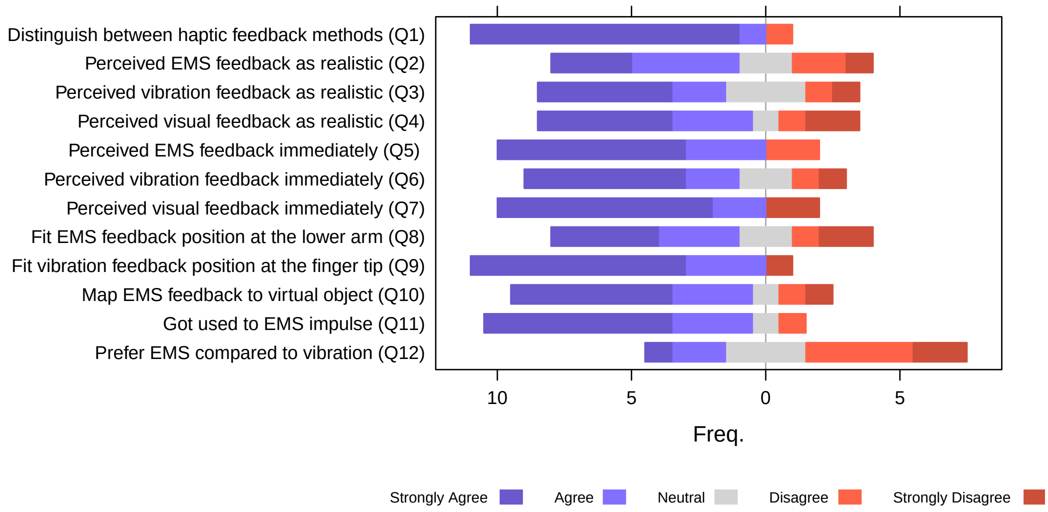


Figure 6.9: Subjective results of the questionnaire ranked on a 5-point Likert scale.

and we again found agreement (Q11, $M = 1$, $MAD = 0$). In the direct comparison between EMS and vibration feedback, participants slightly preferred vibration with a median of 3.5 (Q12, $MAD = 0$). Finally, two thirds of the participants (66%) agreed that they could imagine using EMS feedback in everyday life. The application areas mentioned by participants were general 3D interaction, games, and notifications, such as warnings or time indicators. While most of the participants were comfortable with the EMS impulses, four of them reported at the end of the study that the EMS impulses were too strong and sometimes moved the finger out of the targets. This may be caused by the skin conductance or muscle response changing substantially over time and depending on the posture. Regular re-calibration during prolonged use could address this limitation.

6.3.6 Discussion

The results of our study show that pointing with visual feedback is faster than no feedback, suffers less from errors, and has also higher throughput, albeit only 5% more. Other recent work [321] also found a significant decrease in error between these two conditions, but did not find a significant difference in throughput between visual feedback and no feedback. Overall, the visual feedback conditions perform better than the haptic feedback conditions, but not significantly. This is not unexpected, as it has already been shown that the visual feedback is faster than the haptic feedback [111]. The results for vibration and EMS feedback are not significantly different from those of visual feedback, nor from the non-feedback condition. Different to the study in [60], our results show that vibration was more effective that no feedback, but again not significantly so. Although the lack of a significant difference does not "prove" equality, these results still indicate that vibration and EMS both provide viable alternatives for feedback in 3D pointing and that both alternatives do not have a significant cost in terms of throughput. However, users ranked both conditions very positive. Thus, both feedback modalities were reasonable additions to visual feedback. Additionally, users mentioned that they would like to use EMS feedback in games and other scenarios. The practical experience of the user study shows that EMS as a feedback technology still has some drawbacks. First, it is important to place the electrodes directly over the actuated muscle, so other muscles are not stimulated by accident. The photos that we took after the calibration show that the electrodes are placed in very similar locations across participants. In case of a perfect calibration the posture of the hand and arm plays also a role as discussed in Section 4.1. This is the reason why we calibrated the EMS level in the same posture as used for pointing. Second, skin resistance between the users varied and changes how much the muscle needs to be actuated. Table 6.1 illustrates the diversity of current settings across users after the calibration, with settings ranging from EMS level 2 to 5 and current between 15.43 mA and 25.16 mA. Again, we calibrated the stimulation to a level were finger movement was just not visible.

However, a minority of participants reported that their finger was pushed away from the target in the EMS condition. One possible explanation is a potential change of skin resistance over time, which could be addressed with recalibration. Another explanation is a change in pointing posture during the experiment. The participants reported that when they tighten their finger that they could "counter" this minimal movement. Given that the end-to-end latencies of the different conditions fall into a range where only negligible effects in terms of throughput have been reported [243], we believe that the differences in latencies are not a (significant) confounding factor.

6.3.7 Conclusion

In this chapter we presented a first evaluation of a lightweight, low-energy haptic feedback system to assist 3D hand target selection with vibration and EMS. We found that both vibration and EMS are reasonable alternatives to visual feedback. In this area there are still several open questions, such as how haptic feedback performs in pointing tasks where the targets have different visual depths, or even when targets are straight behind each other (which poses challenges for the visual condition). We believe that the toolkit we created makes it easier to investigate these challenges. This chapter shows that EMS feedback can support users during target selection in virtual environments.

Overall, the last two chapters have shown the potential of EMS feedback to extend the interaction with virtual objects in free-hand interaction and for target selection. It was used to simulate physical object properties and as additional selection feedback. In both cases, EMS was raked similar to vibration feedback or even better. However, EMS has a wider range of feedback and the force feedback position differs from the application position. In ubiquitous computing scenarios this feedback can be used to extend interaction with virtual objects on interactive surfaces that are not reachable by the user, as discussed by Mark Weiser [344], and also in 3D environments. Furthermore, when the user needs to select items, it can be used in addition to visual output as selection feedback. The EMS feedback is attached to the user and can be activated from the environment when it is necessary in different situations and locations. As next step, we will investigate how people's movements can be manipulated in real world scenarios to reduce visual distraction.

Chapter 7

Actuated Walking

Navigation systems have become ubiquitous. While today we use them mainly as commercial products in our cars and on our smartphones, research prototypes include navigation systems that are integrated with belts [326] or wristbands [157]. These systems provide explicit navigation cues, ranging from visual feedback (e.g., on a phone screen) via audio feedback (e.g., a voice telling the direction in which to walk) to tactile feedback (e.g., indicating the direction with vibration motors on the left or right side of a belt). At the same time ubiquitous haptic or force feedback is rarely used.

An obvious drawback of such solutions is the need for users to pay attention to navigation feedback, process this information, and transform it into appropriate movements. Moreover, navigation information may be misinterpreted or overlooked. The need to cognitively process navigation information is particularly inconvenient in cases where the user is occupied with other primary tasks, such as listening to music, being engaged in a conversation, or observing the surroundings while walking through the city. To avoid intrusions into the primary task we envision future navigation systems to guide users in a more casual [264] manner that, in the best case, does not even make them aware of being guided on their way.

As a new kind of pedestrian navigation paradigm that primarily addresses the human motor system rather than cognition, we propose the concept of *actuated navigation*. Instead of delivering navigation *information*, we provide an *actuation* signal that is processed directly by the human locomotion system and affects a change of direction. In this way, actuated navigation may free cognitive resources, such that users do not need to attend to the navigation task at all.

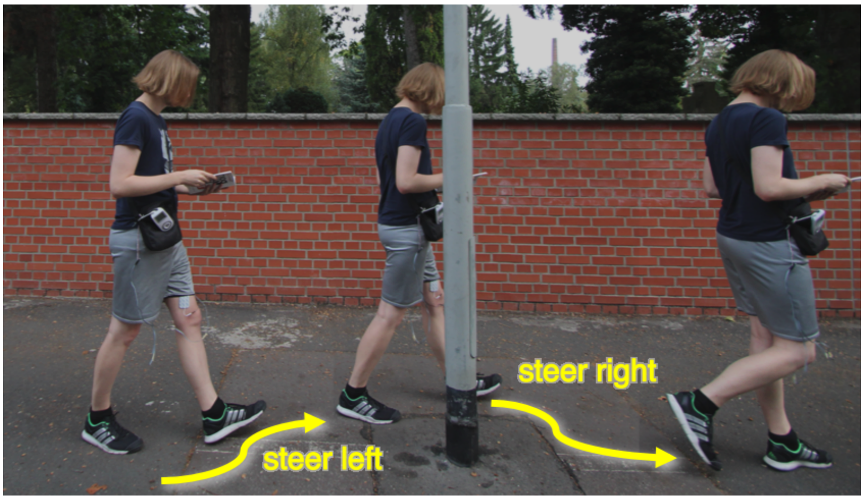


Figure 7.1: A user is absorbed in his reading, not noticing the lamppost. Actuated navigation automatically steers him around the obstacle.

In this chapter we take a first step towards realizing this approach by presenting a prototype based on electrical muscle stimulation (EMS) to guide users. In particular, we apply actuation signals to the sartorius muscles in the upper legs in such a way that the user slightly turns in a certain direction. With the presented system the user stays in control or can give it away: The system does not cause walking movements, but only slightly rotates the leg in a certain direction while the user is actively walking. The user can easily overwrite the direction by turning the leg. If the user stops, the system does not have any observable effect, as the EMS signal is not strong enough to rotate the leg when the foot is resting on the ground.

The contribution of this chapter is twofold. First, we introduce the notion of actuated navigation and present a prototype implementation based on electrical muscle stimulation with the “Let your Body Move” toolkit. Second, we present findings of (a) a controlled experiment to understand how walking direction can be controlled using EMS and (b) a complementary outdoor study that explores the potential of the approach in an ecologically valid setting.

In the following, we discuss the properties of actuated navigation and present the two studies in detail. The results show that our approach can successfully modify a user’s walking direction while maintaining a comfortable level of EMS. We found an average of $15.8°/m$ deviation to the left and $15.9°/m$ deviation to the right, respectively. The outdoor study shows that the system can successfully steer users in a park with crowded areas, distractions, obstacles, and uneven ground. Participants did not make navigation errors and their feedback revealed that they were surprised how well it worked.

7.1 Pedestrian Navigation

Pedestrian navigation systems and mobile city guides have been widely researched in the past [1], with a focus on how to present rich map information on small displays and how to support the user in matching the current position and orientation to the displayed information.

Approaches include providing photorealistic panoramic images from 3D city models rather than symbolic 2D map data [219], automatically rotating virtual maps to correspond to the user's orientation in the real world [292], and coupling paper maps to virtual information using mobile augmented reality approaches [222].

It is widely recognized in the literature that navigation and wayfinding tasks can put a high cognitive workload on users and distract from the environment. Reducing workload and distraction are prime concerns of pedestrian navigation systems [134, 219, 261] and are the main motivation for our work.

7.1.1 Tactile and Haptic Navigation

To reduce the reliance on the visual and auditory modalities, particularly as users engage with processing cues from the physical surroundings, vibration feedback has been suggested as an alternative. Jacob et al. present feedback on the mobile phone as soon as it is pointed to the correct direction [149]. However, this requires active exploration of the surroundings to enable guidance. Pielot et al. developed a haptic compass for off-the-shelf mobile phones worn in the pocket [261]. The target direction is encoded with a two-pulse vibration pattern. NaviRadar [281] is able to communicate arbitrary directions around the user based on a radar sweep metaphor. Another approach is to present the direction by applying vibration feedback to a specific position on the body. Users then map the body position to the direction they need to take. This has, for instance, been done with two vibrating wristbands [157]. To provide directional information, Tsukada and Yasumura [326] used a belt containing eight vibrators equally spaced around the user's torso. The system activates the vibrator that matches the target direction. To achieve more fine-grained direction indication Heuten et al. [134] extended this approach and developed a spatially continuous tactile display by interpolating the intensity between adjacent vibrators.

Haptic navigation systems generate a force to convey direction. Amemiya and Sugiyama [4] built a handheld indicator that provides direction cues to the user via a pseudo-attraction force. The force is generated by a linear micro-actuator that moves a weight quickly in the navigation direction. It then moves back slowly such that the user does not sense it. HapMap [145] also displays direction haptically: A servomotor in a handheld casing (formed like a piece of handrail) tilts right or left to generate a perceivable torque. Pull-Navi [170] is a head-mounted device that communicates direction by pulling the ears in 3D. PossessedHand [314] actuates the hand with EMS to indicate walking direction haptically.

7.1.2 Augmented Walking

Active manipulation of walking has been explored for navigation and to enhance the walking experience. Gilded Gait [313] aims at simulating different ground textures by providing tactile feedback through multiple vibrators embedded in insoles. The user can perceive deviations from the path through modified or missing tactile feedback. CabBoots [100] is an experimental system that tilts the soles of shoes to guide the user left or right. This approach requires relatively strong actuation forces and mechanics to achieve tilting.

Most closely related to idea of "Actuates Walking" are Fitzpatrick et al. [96] and Maeda et al. [205] who manipulate the user's sense of balance through galvanic vestibular stimulation (GVS). By applying GVS, the vestibular system is disturbed so that the user automatically sways in a specific direction. In this approach, a small DC voltage is applied between the mastoid processes (positioned behind the ears) such that a current of 0.5-1.0 mA results. This leads to a decreased firing rate in vestibular afferents on the anodal side. GVS lets people sway towards the anode. GVS modifies human behavior directly. No attention is required. GVS can be used to modify walking direction. However, it has been found that visual input overrides vestibular disturbances [96]. The latter reported walking experiments from a starting position towards a target with eyes open and shut. In contrast to the in this work presented actuated walking approach, it takes the detour over the sense of balance instate of directly influence the locomotion system. GVS affects the sense of balance and mainly causes swaying of the upper body in a particular direction, whereas my approach actuates human muscles and effects a leg rotation in a particular direction. Except for GVS, the presented approaches require the user to perceive, interpret, and react on the output of the navigation system. In contrast, we propose to actuate the human locomotion system via EMS directly, such that the user does not need to concentrate on the navigation task.

7.1.3 EMS-based Augmented Walking

EMS has been investigated to actuate limbs for a long time in rehabilitation Section 2.3.1. With respect to the lower limbs work in rehabilitation focus on correcting foot drop, which

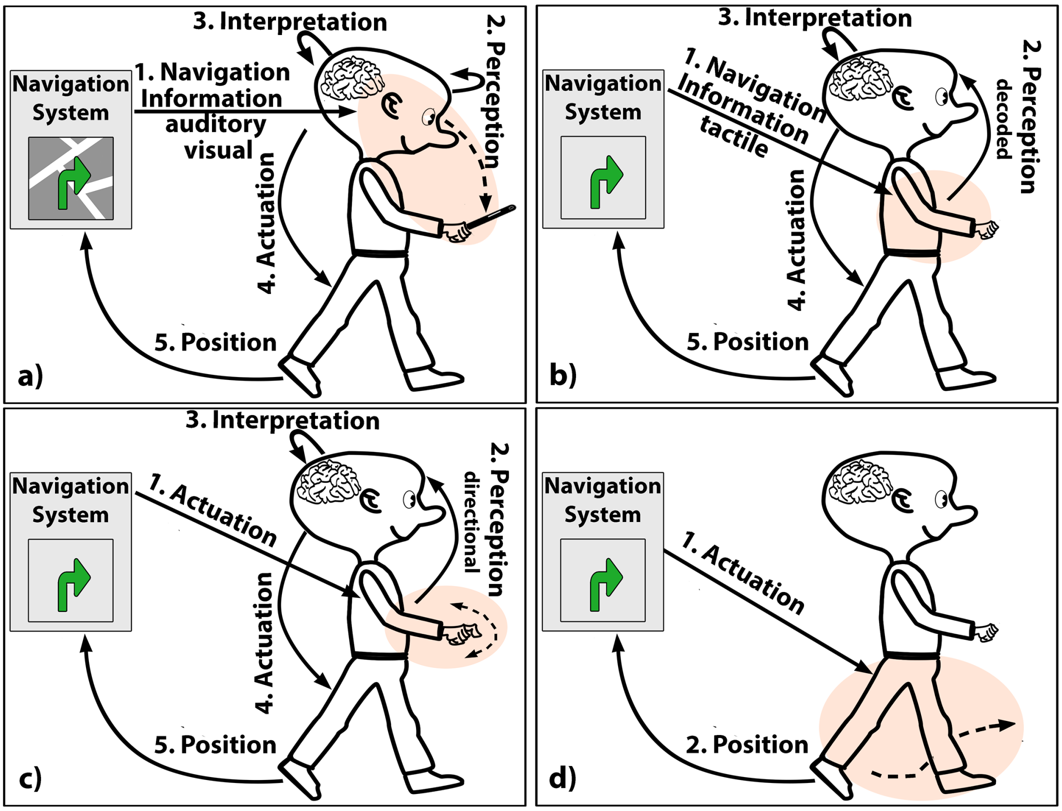


Figure 7.2: Pedestrian navigation using (a) visual or auditory output, (b) tactile output, (c) actuation of the hand as an indicator, and (d) direct modification of walking direction (in our case actuation of the human locomotion system).

denotes the inability to raise the forefoot. A proposed treatment is to apply EMS to muscles at the front of the tibia during the swing phase of gait to flex the forefoot, synchronized by a heel-switch [198]. Other applications with regard to the lower limbs include knee joints movement, cycling, standing up, keeping body balance, and walking (Zhang [361] for a review). For the latter three tasks, research is still at the simulation stage. Controlling walking, for example, is an extremely difficult task because many independent muscles have to be controlled in a coordinated way and a joint may have multiple degrees of freedom. Moreover, the muscles respond in nonlinear and time-varying ways to electrical stimulation such that closed-loop solutions are necessary. Further problems are time delays between signal and response and muscle fatigue. EMS, particularly when applied through surface electrodes, has different characteristics from voluntary control signals, which leads to rapid fatigue. Moreover, not all of the muscles in the lower body are accessible or can be selectively activated when using surface electrodes.

Significant research effort went into restoring gait, which requires selectively stimulating multiple muscles in the affected leg [20]. A simpler task than complete artificial control of lower limbs is to correct the gait of partially impaired patients. EMS has been used for faster recovery and to improve gait.

In this work we do not attempt to fully control walking, the goal is just to influence the direction of walking. This involves an outwards rotation of the leg that corresponds to the intended walking direction [128]. For example, if the human intends to go to the right, one part of turning is that the right leg is slightly rotated outwards. The actual rotation happens in the swing phase of the leg, so that the foot that is put on the ground points into the new direction.

To achieve the same effect with EMS, we first identified the muscles that lead to an outward rotation of the leg. A number of muscles are involved in this activity [128]: m. gluteus maximus (intimate), dorsal parts of the small glutei medius / minimus (intimate), m. quadratus femoris (intimate), m. gemelli (intimate), m. obturatorius internus (deep), m. obturatorius externus (deep), m. piriformis (intimate), m. iliopsoas (deep), and m. sartorius. Unfortunately, except for the musculus sartorius, all of these muscles are either inaccessible for electrode pads, because they are deeply embedded in tissue, or are partially located in intimate zones of the body. We thus focus on the sartorius (Figure 7.1), which is a long and thin muscle that runs across the upper and anterior part of the thigh. It is connected to the pelvis and to the upper tibia. Contraction of the sartorius leads to flexion of the hip and the knee joints. Stimulating it electrically while walking leads to lateral rotation of the leg and therefore to a change of the walking direction.

Another possibility of modifying the walking direction would be to shorten the step length on the side in which to rotate. To achieve this, EMS could be used to block the large muscles on the front and back side of the thigh. Yet, this will likely impact on gait stability, which is why we leave exploring this opportunity for future work.

7.2 Pedestrian Navigation through Actuation

Pedestrian navigation systems sense the position and orientation of the user and give directions to guide the user towards a goal or along a route. There are a number of different options of how to convey navigation information to the user that we discuss in the following.

7.2.1 Classification of Navigation Systems

The most widely used modalities are *visual and auditory* output (Figure 7.2 a). Here, symbolic information, like arrows overlaid on a map or verbal instructions, are presented to the user. This information can be more or less abstract, but has to be perceived and interpreted before the appropriate motor commands can be issued. Interpretation often involves mapping the symbolic instructions to the real world. Although the visual and auditory senses have a high bandwidth they are typically already engaged with acquiring information from the world around the user, and the additional navigation information interferes with this real world information.

To shift perceptual load off the visual and auditory senses, *tactile navigation systems* have been developed, in which, for example, vibration output is applied to different body parts to indicate points at which the user has to turn left or right (Figure 7.2b). The tactile channel has lower bandwidth than the visual and auditory channels, but in many cases tactile feedback at decision points along the route suffices for successful navigation. Simple vibrotactile output is limiting, however, in that it does not easily convey precise direction. Here, as in (a), the information has to be perceived and interpreted before it can be mapped to motor commands.

As shown by Tamaki et al. [314], *muscle stimulation systems* allow directional information to be conveyed, which can be used for navigation (Figure 7.2c). In this case, the hand is directly actuated and moved towards the target direction. The human hand is used as an output device. It serves as an indicator of the navigation direction. Still, the user has to perceive the movement through visual and haptic channels (proprioception), interpret it, and walk into the indicated direction. Moreover, the hand cannot be placed in the pocket. Since navigation information can be easily observed by others, the concept may lead to issues with regard to privacy and social embarrassment. However, the mapping is direct and simple. The feedback is multimodal (haptic and visual) and the actuation of the hand will immediately draw the user's attention.

The option we propose is depicted in Figure 7.2 d). The approach is based on muscle stimulation. In this way we convey navigation information through *actuation* rather than through communicating a direction. While doing so is, in general, also possible using GVS [96] or CabBoots [100], we apply an EMS signal in such a way as to slightly modify the user's walking direction towards the target direction. The approach directly manipulates the locomotion system of the user. We believe this approach minimizes cognitive load, since neither perception, nor interpretation, nor voluntary issuing of motor commands are necessary to adapt the direction. Still, users perceive the directional signal. If the user stops, the system output has no observable effect. Moreover, the signal is weak enough that the user can override it and walk in a different direction if desired. The navigation signal cannot be observed by others as it is delivered privately to the user.

This approach frees the sensory channels and cognitive capacity of the user. The user may be engaged in a conversation, observe the surrounding environment during sightseeing, or even write an SMS, and is automatically guided by the navigation system. We refer to this experience as “cruise control for pedestrians.” Of course, the positioning technology has to be accurate and robust to allow for high-precision navigation. Moreover, obstacles and threats have to be reliably recognized by the system. These issues are beyond the scope of this paper. Instead we focus on the possibility of controlling the user while minimizing the cognitive load.

7.2.2 Information vs. Actuation

The fundamental difference to most prior approaches is that our solution solely relies on actuation. The information approach refers to the user’s perceptual system (“input”) and information processing capacity. The actuation approach primarily addresses the human motor system (“output”). Option (c) is a hybrid variant that provides information through actuation (hand movement indicating direction). With information delivery, the human cognitive system has to process the information and respond to it. The user has a higher degree of control in that the information may be ignored. On the other hand information can also be overlooked or misinterpreted. It is the responsibility of the system designer to make the navigation information as easily interpretable and the mapping to the task as direct and natural as possible. Moreover, the information delivered by the system may interfere with other information in the surroundings of the pedestrian.

In the case of delivered actuation, no cognition is required. Rather, deviating from the navigation path requires counteracting the system-generated force. Reacting flexibly to changing goals can be achieved by observing user behavior, recognizing the intent to take a different path, and resetting the navigation system accordingly – or directly communicating with the user. The result would then be a shift from automatic actuation to explicit communication and goal setting.

7.2.3 On-Body vs. Environmental Feedback

The device that outputs navigation information may be placed on the user or in the user’s vicinity. For pedestrian navigation systems the main options are handheld or wearable devices.

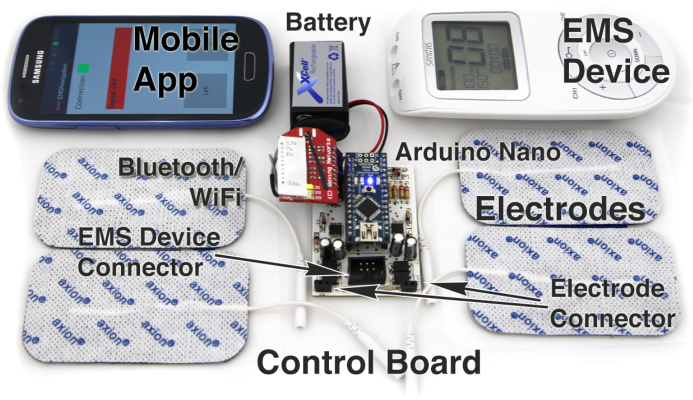


Figure 7.3: The toolkit used for the navigation prototype including the EMS device, self-adhesive pads, the wireless communication, and a mobile device with control apps.

Handheld devices typically use the visual and auditory channels and have the additional disadvantage that they occupy the user's hands. Holding the device all the time is tiring and problematic if, for example, the user carries a bag. With handheld devices, visual output is delivered on the device screen or through a microprojection. In the latter case navigation cues may be projected on the ground. Electronic displays and especially microprojections are problematic in direct sunlight. Visual output may also be delivered via head-mounted displays. Auditory output is typically played via speakers or headphones. Tactile output requires stimulation of mechanoreceptors in the skin.

Visual output has high switching costs between the real world and the navigation information on the display. Switching cost may be reduced for head-mounted displays if the virtual information is integrated with visual information from the real world, as in augmented reality systems. Auditory output has low switching costs but requires earphones for privacy, which shields the user from the surroundings to some extent. Tactile output has low switching costs and retains privacy. However, all of these options draw the full attention of the user and require a significant amount of cognitive processing.

A major advantage of on-body feedback is that it can, in general, be more easily perceived by the user. While environmental feedback needs to compete with a lot of objects in the user's field of view, on-body feedback is much less likely to interfere with other cues. As a result, users could more easily focus on the primary task. On the downside, on-body feedback requires actuators to be worn and may be more intrusive.

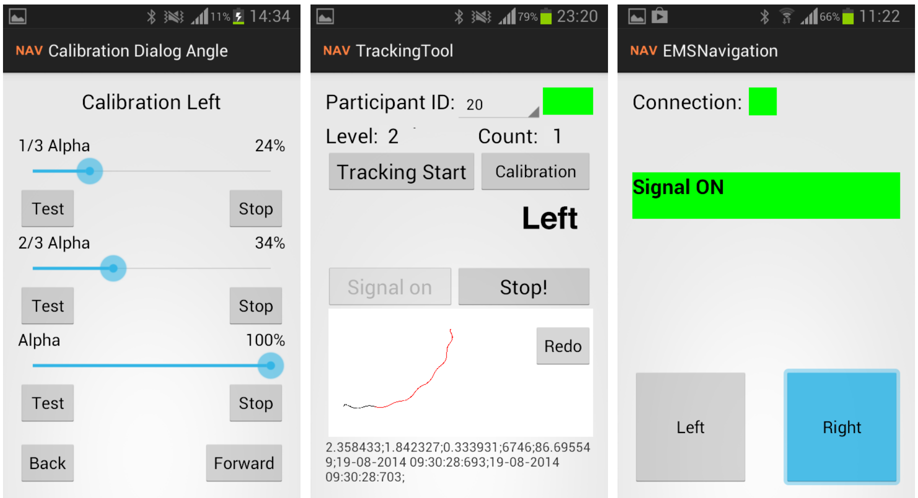


Figure 7.4: Apps to calibrate the user's leg (left), control a single trial in the lab study (middle), and remote-control of the user's walking direction in the outdoor study (right).

7.3 Navigation Prototype

To investigate the concept of actuated navigation we used the "Let Your Body Move" toolkit with different impulse forms, intensities, and activation times. It connects to a mobile phone running the usual navigation software. The actuated navigation prototype consist of a set of control applications to support (a) a lab experiment investigating change of direction during single walking trials, and (b) an outdoor study in which users were guided along marked and unmarked trails.

7.3.1 Toolkit Settings

For the prototype a earlier version of the "Let Your Body Move" toolkit is used as the described in Section 4.3. In contrast to the latest version it uses externally a Bluetooth 3.0 module for communication, and digital potentiometers[20] to control the signal of the EMS device. The control board is able to switch the two channels of the EMS device on and off as well as to reduce the signal intensity in 172 steps. The EMS signal is generated with Beurer Sanitas SEM 43 device [23] on TENS program no. 8 with a frequency of 120 Hz and a pulse width of 100 μs. To apply the EMS signal self-adhesive electrodes with a size of 50×90 mm were used. These larger electrodes reduce the tactile sensation. The wearable navigation prototype with the used toolkit is shown in Figure 7.3.

[20] 41HV31-5K http://www.mouser.com/ds/2/268/20005207A-259170.pdf

7.3.2 Control Applications

The toolkit is controlled by 3 customized apps: (1) a calibration app, (2) a study app, and (3) a navigation app. The apps run on a Samsung Galaxy S3 Mini and are connected to the toolkit. The apps use the text based protocol to send EMS parameters (Section 4.3.5).

Calibration App. The calibration app (Figure 7.4, left) adjusts the strength of the applied EMS signal. It is used for calibrating and storing user-specific intensities. Furthermore, the app records current and voltage levels during the study.

Study App. Via the study app (Figure 7.4, middle) different user-specific settings are selected. It records precise positioning data from a Naturalpoint OptiTrack infrared tracking system. The application is also responsible for controlling the EMS hardware during the study.

Navigation App. The navigation app (Figure 7.4, right) serves as a remote control in the Wizard-of-Oz outdoor navigation study. It simply contains two buttons similar to the the Wizard-of-Oz app (Section 4.4). As long as one of the buttons is pressed, actuation is applied and the user is steered towards the selected direction.

7.4 Lab Study

The goal of the lab study was to understand how to control walking direction using EMS. As other muscles that are relevant for leg rotation are either inaccessible or are located in intimate areas, we focus on the stimulation of the sartorius muscle. There are a number of parameters and characteristics that need to be identified. These include the optimal position of the EMS electrodes on the thigh, the maximum level of stimulation that still feels comfortable, and the degree of directional change during walking that can be elicited. We also aim to investigate whether different levels of stimulation can be mapped to different rotation angles. Finally, we aim to analyze whether direction control while walking has negative effects on gait, such as instability.

7.4.1 Participants

We recruited 18 participants (13 male, 5 female) aged between 18 and 27 (M=22.1, SD=2.3) via university mailing lists and at a sports club. According to the questionnaires, 12 of them are doing sports regularly. 10 participants regularly use pedestrian navigation systems on their phone (Google Maps, Apple Maps, and OsmAnd). All of them look onto their phone

Figure 7.5: Placing the pads on the musculus sartorius (left), measuring the angle of deflection corresponding to EMS intensity (middle) and an equipped user on the starting position (right).

screen for navigation, one uses audio. None of the participants ever used tactile feedback for navigation. 8 of the 10 users said that navigating distracts them from other tasks, such as from traffic, from conversing with friends, from listening to music, and from talking on the phone. Five participants previously used EMS for massages, pain relief, training, participating in studies, and testing EMS out of curiosity. None of the participants used EMS regularly.

7.4.2 Experimental Design

The study was designed as a repeated measures experiment. The independent variables were the intensity level of the EMS actuation (strong, medium, weak, off) and the starting position of the user (left, middle, right). Users starting from the left position were guided to walk right and vice versa. The starting position also determined the leg with which users started to walk (left leg for starting right and vice versa). When starting from the middle, no feedback was applied and users started once with the left leg and once with the right leg. This resulted in 3 (left position; strong, medium, weak intensity) + 3 (right position; strong, medium, weak intensity) + 2 (middle position; left leg, right leg; EMS off) = 8 conditions. Conditions were counterbalanced and repeated 5 times each, resulting in 40 trials per user. As the dependent variable we measured the user's head trajectory (position and orientation).

7.4.3 Setup and Procedure

As participants arrived, we provided them a consent form that they had to read and sign. Also, we explicitly told participants that they could abort the study at any time. We asked them to change before the actual study. We measured the diameter of their thigh and tested for their primary leg. They then proceeded with the calibration for the main part of the study.

Calibration

First, the deviation angle and the level of voltage and current were measured. One electrode pair was attached to each leg of the participant and connected to the EMS device (Figure 7.5, left). The EMS signal was controlled through the mobile application described in the previous section. As the actuation is not strong enough to happen while the user is standing on the ground, but only happens during the leg's swing phase, the leg had to be able to move freely during calibration. To this end, for calibration users stood on a pedestal with one foot while holding on to a tripod with one hand (Figure 7.5, middel). The other leg was hanging freely and did not have floor contact. The EMS signal was then applied and modified until the maximum comfortable level for the user was reached with respect the to Section 4.1. We measured the rotation angle of the foot with the OptiTrack system and markers on the shoe.

After having determined the maximum angle and intensity, we reduced intensity to achieve 2/3 and 1/3 of the maximum angle, respectively. For example, if the maximum angle was 30°, we determined the intensity values for 10°and 20°(Figure 7.4, left). Both legs were calibrated independently in this way. The user-specific parameters were stored in the control application for later use in the actual study. Apart from the calibration, we measured the current and voltage for each leg and angle. To this end, the EMS system and the user were attached to a test circuit with two digital multimeters.

Walking Study

The second part of the study constitutes the walking tasks. We set up 10 cameras in a 4×6 m tracking area. To maximize the trackable walking distance, the starting points were either on the left or on the right of one sideline. For the baseline condition (no actuation) participants started from a central position.

Participants were equipped with a tracking cap (Figure 7.5, right). The OptiTrack system continuously sent the 3D position of the user to the study app via WiFi at a rate of about 30 Hz. To keep participants from focusing on a point in the room and steering towards that point we blindfolded them with an eye mask. In this way, users also did not know the starting point, which could have led to an anticipation of the direction.

The EMS signal for each condition was applied using the study application. For applying signals to the left leg users were asked to start walking with the right leg and vice versa. After the third step the EMS actuation signal was applied. This procedure ensured that the signal was applied during the leg swinging period and at roughly the same position for each participant. For the baseline without actuation users started with either the right or left leg in alternating order. Finally, participants filled in a questionnaire and were debriefed.

7.5 Results

Quantitative results are based on an analysis of the calibration data, the walking trials, and an analysis of the direction changes. We excluded three participants during the calibration process. P5 did not feel well and aborted the study. On P8 and P13 the EMS system did not show any effect. Due to technical problems, data from P4 had to be excluded from the analysis of direction changes.

7.5.1 Quantitative Results

Figure 7.6 provides an overview of the data that were recorded during the walking trials. We used this data to quantify the effects of different levels of EMS actuation. Prior to further data analysis we smoothed the data using a Gauss filter, thus removing the deflection caused by head movement.

Figure 7.5.1 shows the directional change in degrees per meter. The left graph shows an overview. The strong, medium, and weak actuation conditions have been combined for left and right, respectively. First, the median change within each user was computed, then the mean across users. The mean change is 15.8°/m to the left and 15.9°/m to the right. There is a relatively wide spread and the data are skewed towards 0°/m stemming from the fact that the actuation showed only a small effect for some of the participants. A Friedman test shows that the differences between left actuation, no actuation, and right actuation are significant on the 5%-level ($\chi^2(2)$=24.571, p<0.001). A post-hoc test with Bonferroni correction shows that left, off, and right are pairwise significantly different. Randomization tests on matched samples with Bonferroni correction applied come to the same result.

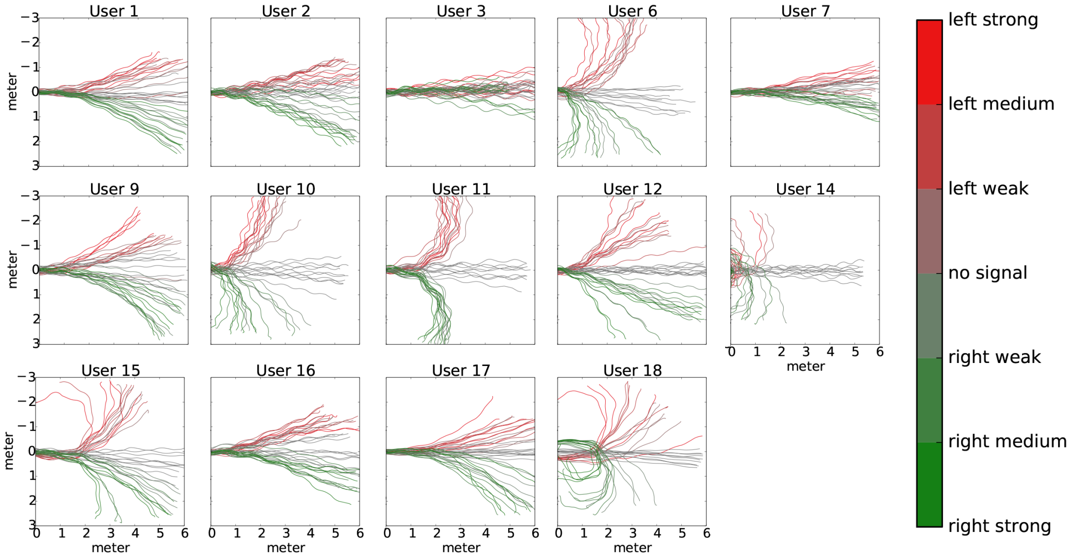


Figure 7.6: Plots of the raw data from all conditions and all users.

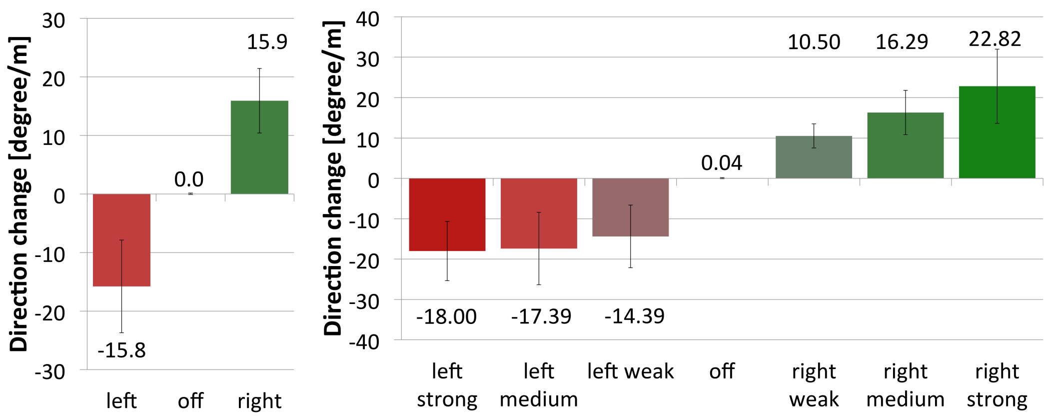


Figure 7.7: Direction change in degrees per meter of the overall direction (left) and divided into the different EMS levels (right). Error bars show standard error.

The right of Figure 7.5.1 shows the directional change for each condition separately. There is a tendency of stronger actuation showing larger directional change. However, again the variation is strong and does not precisely follow the calibration (which aimed for full angle at strong actuation and 2/3 and 1/3 of full angle at medium and weak actuation). Comparing all seven conditions, a Friedman test reveals a significant difference ($\chi^2(6)=57.245, p<0.001$). A post-hoc test finds that the left conditions are pairwise different from the right conditions and off-condition is different from the right conditions and the left conditions. There are no pairwise differences among the left conditions, and no pairwise differences among the

	Angle in degree/m		Radii in m	
Participant	Left	Right	Left	Right
14	-128.98	100.13	-0.44	0.57
18	-33.11	101.23	-1.73	0.57
11	-26.88	30.53	-2.13	1.88
6	-26.46	26.46	-2.17	2.17
10	-17.67	24.98	-3.24	2.29
15	-27.56	9.85	-2.08	5.82
9	-7.73	9.41	-7.41	6.09
17	-4.88	11.60	-11.74	4.94
1	-4.08	3.75	-14.05	15.30
12	-3.18	1.87	-18.04	30.60
16	-2.00	2.20	-28.65	26.04
7	-1.08	2.32	-52.96	24.67
2	-0.55	3.36	-103.74	17.05
3	-0.23	1.04	-253.61	55.02

Table 7.1: Directional changes and turning radii of each user.

right conditions. Randomization tests on matched samples with Bonferroni correction applied identify the same pairwise significant differences.

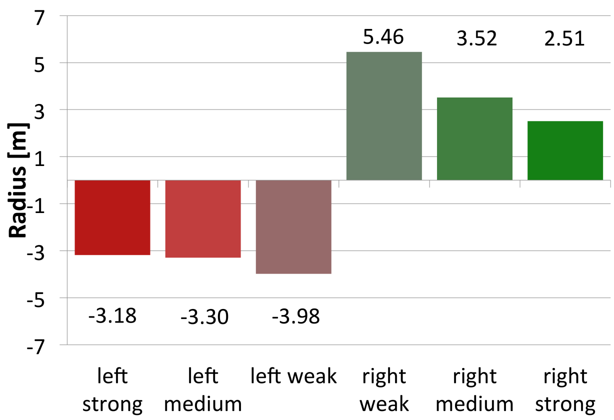


Figure 7.8: Associated radii of the direction changes divided into the different EMS levels.

For steering pedestrians around corners the turning radius is relevant. As can be seen in Figure 7.6, while actuation is active users move on a circular path. If the tracking area had been large enough and the actuation had continued, the test participants would have moved in circles. The above results relate a length of 1 m on the circle arc to a rotation of $\alpha°$. This translates into a radius $r=\frac{180}{\alpha\pi}$. The radii associated with the above direction changes are shown in Figure 7.8. As expected, the smallest turning radii of 3.18 m for left turns and 2.51 m for right turns are associated with strong actuation. These radii are sufficient for navigation in public spaces, such as streets and parks, and even in indoor spaces, such as in airports, train stations, or shopping malls.

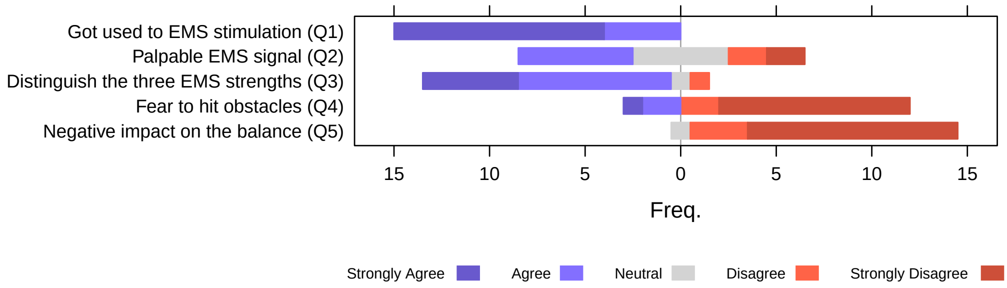


Figure 7.9: Subjective results of the questionnaire ranked on a 5-point Likert scale.

However, there was a large variability of achieved radii between subjects. Table 7.1 shows the mean directional changes and turning radii for each participant, ordered by decreasing effect size. For this table the medians of the trials for each condition and user were computed. Then for left and right the stimulus levels were chosen that worked best for that subject. Three groups of participants can be identified: The first six have rather small turning radii, the next five have medium turning radii that appear to be sufficient for course navigation, and the last three have very large turning radii, which would not be sufficient for successfully steering them.

7.5.2 Questionnaire

After the 40 walking trials we asked participants to fill in a questionnaire (5-point Likert scale, 1= strongly agree, 5=strongly disagree, Figure 7.9). All participants strongly agreed that they got used to the stimulation after a few walking trials with a median *(M)* of 1 and median absolute deviation *(MAD)* of 0 (Figure 7.9, Q1). Furthermore, we were interested in the quality of the stimulation signal. We received mostly neutral responses for the question whether the signal was palpable during actuation (Q2, *M*=3, *MAD*=1). Users agreed that they could differentiate the 3 different strengths on both legs (Q3, *M*=2, *MAD*=0). All participants described that they could clearly feel the EMS signal. Additionally, 9 participants said that they would use such a system in everyday life for pedestrian navigation. They did not fear running into an obstacle when wearing the eye mask during the trials (Q4, *M*=5, *MAD*=0). Finally, they did not find actuation to have a negative impact on balance (Q5, *M*=5, *MAD*=0).

7.5.3 Qualitative Results

During the experiment we observed two major challenges. First, we found that holding the leg in a relaxed manner during calibration was crucial for achieving the desired effect. Second, the placements of the electrodes required high precision. If electrodes were placed too far off the muscle (>0.5 cm), either no actuation was possible or other muscles, such as the musculus quadriceps femoris were actuated, which led to the leg being fixed in its position.

7.6 Pedestrian Navigation Study

Having acquired an understanding of the fundamentals of EMS-based control of walking direction in the lab, we performed a study to gain insight into how well the approach works in a real environment. We invited 4 male participants ($mean = 25.3$, $SD = 1.3$). Three of them are right-footed and do sports 8 to 20 times a month. All use phone-based navigation systems up to 5 times a week. To observe participants in context and be able to flexibly react to the environment we opted for a Wizard-of-Oz study in which the experimenter followed the participant and manually triggered actuation signals. The study was video-captured for post-hoc analysis. Participants were equipped with the EMS prototype.

7.6.1 Study Design

The study took part in a park (appr. 380×400 m) with many paths and meadows. This allowed the study to be conducted in a safe environment, which at the same time provided a multitude of different paths. We defined two different routes. Note, that participants were unaware of these routes

- Route 1 had a length of 991 m and included 7 right turns and 9 left turns. The route followed existing trails and took participants about 12 minutes to complete (Figure 7.10, left).
- Route 2 was 552 m long and ran mainly across lawn. Since there were no marked trails we defined landmarks that users needed to pass. The route included 8 left and 4 right turns and took participants on average about 7 minutes to complete (Figure 7.10, right).

7.6.2 Apparatus and Procedure

As participants arrived at the lab, we described the study and had them fill in a demographic questionnaire and a consent form. We calibrated the EMS system using the same procedure as described above, before walking over to the park. Participants were asked to walk casually and to just let the turns happen, as triggered by the actuation. Furthermore, we asked them to pay attention to any obstacles, potholes, and bumps – particularly when walking on lawn, and to stop or circumvent these as necessary. We then began with the walk. The experimenter followed the participant and triggered actuation at turning points, using the navigation app described earlier (Figure 7.4, right). After the participants completed both routes, we conducted a semi-structured interview, which we audio recorded.

Figure 7.10: Routes for outdoor study (left turns marked red, right turns marked green): Route 1 on existing trails with a length of 991 m (left) and route 2 across country with a length of 552 m.

7.6.3 Results

We recorded 88 minutes of navigation videos and 30 minutes of audio interviews. In the following we report on findings from observations and interviews made during the study. From our data we identified five categories, in which we grouped our findings, namely general experience, steering and direction changing, comparison to other navigation systems, mental load, and ethical concerns.

General Experience

Overall feedback on the navigation system was very positive. All participants stated that they were quite surprised by the *"very good performance of the system, particularly for narrow curves"* (P2). Asked about their experience and thoughts in the beginning of the test, some participants were concerned of giving away control to the navigation system. For example, P0 reported that at first he was *"afraid of running into obstacles when not changing direction in time."* P0 reported a situation on a small bridge where he was *"afraid of walking into a man sitting on the floor there."* However, the experimenter guided him smoothly around the man, making the participant feel *"much more relaxed in the following."* We explored in which situations the navigation system works best. P1 stated that the system worked best in situations where he *"walked in a relaxed manner."* Furthermore, the ground texture seemed to have a strong influence. Participants reported that even ground (e.g., pavement) worked significantly better than bumpy ground or walking in high grass.

Steering and Direction Changing

P0 said *"I was walked in the [right] direction."* P2 reported that *"only the actuation and not the tactile feedback changes the direction."* Similarly, P3 estimated that 90% of the direction changing came from the actuation and *"maybe 10% from feeling [the signal]."* Participants also found it *"interesting not to know in which direction the system was guiding me next."* P3 stated that *"changes in direction happened subconsciously."* P0 said that he was thankful that the experimenter steered him around the puddles and people.

Furthermore, we wanted to learn about the degree to which people could still control their walk while using our system. Here, participants stated that they could always change the direction themselves and stop at any time.

Comparison to Other Navigation Systems

All participants could imagine using the system in practice. They felt the system to be best applicable for walking and jogging. Moreover, participants were not concerned of using such a system in traffic. Asked about the differences to commercially available navigation systems, participants particularly liked the fact that they were not provided with visual feedback, thus, *"freeing capacities"* (P1). P3 particularly liked that he could focus more on the environment compared to traditional navigation systems.

Mental Load

Participants stated that while in the beginning they were consciously aware of the feedback, they *"did not think about it anymore after just a few minutes"* (P1, P2). In general, participants reported the navigation to be very subtle so that they could easily focus on their surroundings. An interesting comment was provided by P0 who stated to *"concentrate less on the close environment after some time."* In a similar manner, P2 stated that he did not solely focus anymore on the direction he was walking into. In contrast he found the system *"particularly useful in situations where [he] wanted to use his smartphone."* He would even try out reading some text during the test, using the system like an autopilot. Afterwards he stated that only *"one still has a bit of an eye for the surroundings [...] enough for orientation."* These findings suggest that an emphasis needs to be put on designing the system in a way such that it reliably detects potentially dangerous situations and warns the user, for example, through a secondary feedback channel.

Concerns

Finally we were interested whether users had any concerns of being controlled by an application. Surprisingly, none of the participants came up with such concerns. All of them felt that being controlled was ok, since they could at anytime take over control and 'override' the system. P1 compared the system to the *"cruise control in the car,"* where users could regain control at anytime.

7.7 Discussion

7.7.1 Application Scenarios

Delivering actuation signals for pedestrian navigation has a wide range of applications. It is particularly useful if the user is cognitively engaged with other tasks, needs to receive precise information privately, or if several users need to be spatially coordinated to reach the same destination that goes even further then discussed scenarios in the Section 3.3.

In sports, for example, actuated navigation may steer long-distance runners via different jogging trails on different days for increased variety and enjoyment, or to choose the optimum path to reach a particular training goal the electrodes could be integrated in sport suites as discussed in Section 2.3.3. In team sports, actuated walking may coordinate the orchestration of team actions. New variants of team sports may be devised in which the coach or an external player may influence the moves of the team. Coordinated action is also relevant for firefighters, who may be steered through a building towards the relevant spot. Coordination of larger crowds is also conceivable. Imagine visitors of a large sports stadium or theater being guided to their place, or being evacuated from the stadium in the most efficient way in the case of an emergency. Actuated navigation may help disoriented elderly people to find their way home. Actuated navigation may be part of tourist and city guides to allow visitors to focus on the sights rather than on the navigation task as they walk through the city. Finally, it may facilitate serendipitous encounters in public places. In all these examples, actuated navigation is unobtrusive, private, and may be overridden if desired. The force feedback to change walking direction of the pedestrian should be always and everywhere available.

7.7.2 Limitations

EMS was used to investigate the actuated navigation approach. Although EMS (in the form of functional electrical stimulation) has been used for some time in rehabilitation, its use in the general public is not yet widespread. However, EMS is gaining popularity as a fitness training method. Current EMS systems are still somewhat inconvenient, in particular regarding the placement of the electrodes. In the experiments an exact placement of the electrodes was needed. There are individual physiological differences and small placement differences can deteriorate the intended muscle stimulation. Simple single-pad surface electrodes were used. In rehabilitation, multi-pad electrodes have already successfully been deployed. Via machine learning techniques, the optimal activation of a subset of the pads can achieve optimal control of the intended muscle. It may be possible to integrate future multi-pad electrodes in underwear (Section 2.3.3), obviating the need for separate placement of surface electrodes.

The lab experiment showed that open-loop control is not sufficient to achieve a precise angular change of the walking direction, as this depends on many parameters, like the weight of the user, the resistance and impedance of the skin, and the state of the muscle. Systems that aim to enable precise control, even of a single muscle, require closed-loop systems with sensors that feedback the state of the limbs and joints as discussed in Section 3.6. However, for actuated navigation it is sufficient to set an acceptable level of muscle stimulation and control the amount of change via the duration of muscle stimulation.

We found that for a small percentage of our test users EMS had very little or no effect on walking direction. Given the data from the study we can only speculate whether this was due to sensor placement, higher skin resistance, physiological differences in muscle position, or unconscious counteracting against the small directional force generated by EMS. These questions have to be investigated further in future work.

7.8 Conclusion

In this chapter EMS was used to lay the foundation for future navigation systems that aim to reduce the users' mental load. Opposed to prior approaches we focus on user actuation rather than conveying navigation information. We provide a proof of concept implementation, showing the feasibility of this approach. The initial lab study shows that EMS-based actuation can change users' walking direction. In a subsequent field study pedestrians were successfully "cruise controlled" along two routes across a public park in real world scenarios. Feedback from the study participants suggests that the approach works reliably and that the modification of the direction came mostly from the actuation rather than from the user's perception of the tactile stimulus.

From a safety perspective it is particularly important that the participants could easily "override" the EMS actuation, which may be important as obstacles appear along the trajectory of the user. Furthermore, participants had no concerns with regard to being controlled by the system and use EMS for navigation.

In the future this approach needs to be extended by a feedback loop for outdoor navigation (e.g., through precise positioning and visual obstacle detection) to navigate the user automatically towards a target destination. This will allow the system to be tested in an everyday-life setting.

This work shows the potential and challenges to manipulating users in their real environment. A task, in this case a navigation task, could be automated to free mental resources of users to let them focus on the environment or on another task. With this approach the secondary tasks (e.g. navigation) can be banned to a background task and cognitive resources can be used for the primary task, for example for sightseeing. In contrast to Chapter 5 and Chapter 6 the users were actuated to do a task rather than to extend a virtual object with physical properties to support the interaction. In this work the path in the real world is extended by a force to guide users. With this new way of guiding no display such as on a phone or on a smart watch is necessary, the user just walks and ends up at the destination. In the next chapter we will go a step further and investigate how emotion can be implicitly detected and expressed though EMS gestures.

Chapter 8

Communicating Emotions

More and more people are living in long-distance relationships – often because they cannot easily find workplaces in the same city or are sent abroad temporarily [181, 183]. In such situations couples struggle with maintaining social connectedness, typically by relying on text messages, social media, and voice communication [66]. Exchanging intimate information about one's emotions is an important maintenance behavior in long-distance relationships [200], but it is not well supported by current technology.

The advent of novel sensing and actuation technologies enables a new quality in communicating emotional feedback. Not only do these technologies allow for a wide variety of emotions to be implicitly collected, i.e., without an explicit trigger by the sender, but these emotions may also be perceived in a more natural manner. Hence, it is communicated through stimulating parts of the human body such as with body language or emotional gesture. This direct approach omits the need to verbally express the emotion. The recipients interpret the familiar body language that leads to similar sensations experienced by the partner. This kind of intimate coupling could support empathizing with the partner.

We propose an approach to communicate nonverbal abstract states of the sender to a receiver through actuating the receiver to perform a representative gesture that reflects the sender's emotional state. The state of the sender is implicitly measured. The performed gesture allows the receiver to perceive the information in an immersive way and to understand the notification intuitively. The transmitted state could be a symbolic repression of an object, a position, a mental model or, as considered in this chapter an emotional state.

Darwin described in 1872 that emotions are communicated nonverbally by body language [68]. Remote communication with nonverbal expressions needs a sensing component that detects the state and sends it to the receiver. The receiver has an output component, which in case of haptic feedback could be an actuator. Using body language, the actuation component makes the body of the user perform a representative expression such as a posture or a gesture [90, 245]. Beyond natural body language, sign language also uses abstract symbols such as gestures to communicate nonverbal information to another person. There are specific signs to communicate the emotions in a similar way. These gestures can increase empathy towards the remote partner, which can help to understand the partner and to come into a similar emotional state such as feeling sad when the partner feels sad. In long-distance relationships such a system can support the partners to communicate emotions

In this chapter we investigated how such abstract notifications could be implicitly sensed and transmitted to the receiver allowing the receiver to perceive this as an immersive emotional notification. For example the recipient's body can be actuated to perform a gesture for sadness, to express that the sender is feeling sad. To investigate this approach, a prototype is implemented to sense the state of the sender, transmit it to the receiver then the receiver perceives this transmitted state.

If this set up is one-directional, it leads to awareness of the affective state of the other person. If the communication of affective states is set up in a bi-directional way a feedback loop is necessary, with mutual effects on both partners. We call this kind of setup *embodied emotional feedback*: The recipient's own body experiences and portrays the affective states of the sender with an intuitive mapping of these states.

The prototypical implementation of the embodied emotional feedback is using EEG (electroencephalography) on the sensing side and EMS (electrical muscle stimulation) on the receiving side. On the sender side, the human body reveals affective states through measurable signals, such as heart rate, blood pressure, skin conductivity, muscle tension, facial expressions, pupil diameter, voice, body movements, posture, and electroencephalography signals (e.g., [45, 46, 48, 51, 118, 214, 360]). EEG has been used to implicitly capture the changes of emotional states with good reliability [31, 50, 51, 58, 185, 207, 229]. On the receiver side, a lightweight wearable force feedback is needed to actuate the body language or gestures. EMS feedback is used to modify muscle tension, provide tactile feedback, and even actuate the human body (Section 2.3).

Hence, these are suitable technologies to realize emotional awareness between two persons without the need for explicit intervention of verbal communication. In particular, we implicitly obtain information about a user's emotional state, e.g., whether getting amused, sad, or angry (or *none* of these) and then convey this information through intuitively understandable muscle activations. The receiver displays the body language in a natural way. The receiver herself is the "output device" to express the emotional state. For body language we gathered a set of body gestures used to express certain emotional states from the literature and compared them to sign language gestures of these states.

To explore the approach of embodied emotional feedback and evaluate the prototype, we conducted three user studies concerning (1) the input side (EEG), (2) the output side (EMS), and (3) the end-to-end connection. In an initial study various movie snippets that evoke particular emotions [229] are shown to the user and the resulting EEG signals are collected. A machine learning classifier on these EEG signals is trained, based on questionnaires about experienced emotions. For emotional output two gestures sets were composed from a literature review. The focus was on how the body naturally reveals emotions and how sign language expresses emotions. In the second study we evaluated how users rate the fit of our designed actuation-based gestures to particular emotions. Finally, we invited pairs of users (couples, friends) to our lab. One person was asked to watch the movie clips. EEG signals were collected and classified as emotional change of a state. Then these measured states were sent to the other person and mapped to EMS actuation signals of the gesture. The results show that the participants experience *sign language gesture set* more reflecting the emotion than *composed gesture set*. Interviews revealed that participants liked the implicit sharing of emotions and felt the embodied output more immersive than common notifications (e.g., text messages). However, they wanted to stay in control about which emotions they want to share, e.g., only positive emotions with friends or also negative emotions with the partner.

This chapter contributes the concept of implicitly sensing the abstract state of the user, transmitting it to the receiver and letting the receiver become the output device to replay the state with body language. *Embodied emotional feedback* is a new way of sharing emotions over a distance that implicitly senses emotional states, communicates them to another person, and actuates the recipient's body as a result of these states. We implemented *emotion actuator*, a prototype to realize this idea and we designed two actuated gesture sets to display emotions. In three studies we evaluated the concept and the prototype.

8.1 Remote Emotion Communication

Prior research presents various approaches to achieve emotion communication and connectedness. Lottridge et al. [196] explore what remote couples lack from existing communication technologies as well as what they want to share and how. They identify *empty moments* (waiting, walking, waking up) as a design opportunity for sharing emotions. Hassenzahl et al. [129] review design concepts and technologies that aim at creating relatedness. They present six strategies for creating a relatedness experience: awareness, expressivity, physicalness, gift giving, joint action, and memories. Dey and Guzman [73] discuss the design of presence displays for awareness and connectedness. Kaye et al. [160] propose the concept of *minimal intimate objects*, which allow communicating intimacy by sending a very simple one-bit message to the long-distance relationship partner. The ambiguity of the one-bit message affords reinterpretation by the receiver.

MobiMood is a mobile system for explicitly sharing emotions among friends [57]. Emotishare [348] is a platform for sharing and responding to explicitly reported emotional states among friends. Social media are commonly used to share emotions [19]. People tend to restrict more intense and negative emotions to private channels and share positive emotions more widely. We can support this observation from the findings of the studies. Perttula et al. [249] report an EEG-based prototype for mood sharing on a public map among visitors of a large-scale event. The moods of many visitors were visualized on this map to facilitate social navigation.

Various projects aim at augmenting mobile phones by an emotion channel. Cui et al. [62] use front-camera recordings of emotional reactions to received content to implicitly capture and transmit emotions. It is interesting here that the system does not try to recognize the emotion but just captures it and returns it to the sender. Park et al. [240] implement remote touch in phone conversations: The *Poke* system uses an inflatable surface on the phone's front that receives index finger pressure input from the back side of the other phone. A long-term study found that users developed vocabularies for expressing and understanding emotions. CheekTouch [241] is a mobile phone based prototype for explicitly exchanging affective touch behaviors (pinching, stroking, patting, slapping, kissing and tickling) through vibrotactile patterns on the cheek.

Several works link pairs of interactive tangible objects, such as picture frames [53, 167], lights [6], beds [77], pillows [55], and teddies [97] for communicating emotion.

Höök [139] investigated bodily persuasion through *affective loop* experiences, which employ physical and emotional interactions. An interaction with a sensor-equipped doll is reported. Particular gestural interactions with the doll (e.g., shaking it back and forth) influence the emotion of a game character (e.g., anger). It was found that the experience of performing the gesture and the game character's feedback also have an effect on the user's emotion, leading to an *affective loop*. In this work, the recipient's body is actuated through implicitly sensed emotions rather than active gestural input.

Fagerberg et al. [250] draw on theories of movement and emotional expression to design a set of affective gestures for emotion input. Sundström et al. [309] propose *eMoto*, a system in which a user can explicitly input emotional states using pressure on a handheld token and the amount of movement of that token. Pressure is mapped to the valence axis, movement is mapped to the arousal axis. In contrast to these works, we use movement as an output modality.

United-pulse [346] are rings worn by a couple that play the heartbeat of the partner. Gooch and Watts [115] present three prototypes, like a robotic grasping hand, that support hand holding over a distance. Tsetserukou and Neviarouskaya [324] present a device for remotely reproducing emotions of another person through a haptic device worn on the chest.

8.2 Embodied Emotional Feedback

Embodied emotional feedback involves implicitly sensing emotional state changes and displaying them by actuating the recipient's body. The approach also involves recognizing emotions from physiological data and transmitting them from the sender to the receiver. The roles of sender and receiver may change depending on the direction of the information flow over the bi-directional channel. In the literature there are examples of explicit as well as implicit forms of emotional input. Implicit emotion sensing has the advantage of not interfering with the emotional experience, yet it lowers control. The user does not need to reflect their own stage and does not need to verbalize it. A possible solution is to ask for the user's permission before sending a detected emotion or to share specific emotions with specific recipients only.

Another aspect of implicit emotion sensing is that it is not necessary to verbalize the experienced emotions. The recipient becomes the output device of the sender's emotion. We hypothesize that this leads to a stronger sense of immersion and intensity and, possibly, a more intuitive understanding of the received emotion, compared to other output modalities. One reason for this expectation is that it has been shown that gestures are closely linked to emotions. Performing a gesture may even evoke a particular emotion [174]. Also when a person is more involved in a situation, in particular in a partnership, the empathy and resulting feeling of the other person can increase. Therefore body language that represent the emotion need to be elicited and output gestures need to be designed. In the following we describe the components of embodied emotional feedback.

8.2.1 Measuring Emotions

In a first step the emotions that should be communicated need to be measured. Different methods exist and the selection of a recognition method depends on the targeted theory of affect, the emotions of interest, context, as well as the intended goal of the evaluation [107]. These methods can be either subjective or objective.

Subjective methods include structured and non-structured questionnaires and self-assessments. Examples are the Positive and Negative Affect Schedule (PANAS) [341] and the Self-Assessment Manikin (SAM) [36]. Objective methods employ physiological and non-physiological sensors. A popular method is using cameras and image analysis algorithms to detect facial expressions based on Ekman's theory of emotion [81], which suggests a link between facial expressions and affective states [360]. Additionally, electromyography (EMG) recordings are used to recognize emotions from facial expressions [46]. Other methods measure heart rate [15, 133], skin conductance [294, 312], respiration rate [133], pupil response [242], or electroencephalography signals (EEG) [58, 107, 185, 229] to recognize emotions. Objective methods overcome some drawbacks of subjective ones, the physiological responses of individuals vary and are sometimes not easy to interpret. Also, the prior emotional state is usually not considered. Rather the emotional change is compared to a baseline or calibration phase. However, Picard argues that a universal solution to this issue is not required if a user-dependent solution is possible [260].

There are several ways of implementing the sensor side. Current research efforts show that classifying emotions from facial expressions can achieve accuracies up to 80–90% under controlled conditions [45]. Psychology explicitly separates physiological arousal, the behavioral expression (affect), and the conscious experience of an emotion (feelings) [31]. Facial expressions and voice are related to the behavioral expression, which can be consciously changed or adapted and its interpretation is not objective [31]. EEG can implicitly and objectively measure the emotional state of the user. Therefore, EEG is used to measure the emotional state of the user on the sender side.

8.2.2 Emotion Gesture Sets

Darwin divided nonverbal communication into facial expressions and body language [68]. Emotions are expressed through both facial expressions or through body language [80, 82, 90, 245, 277]. Emotional body language includes related body postures and movements. We

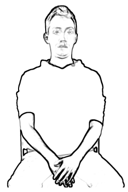
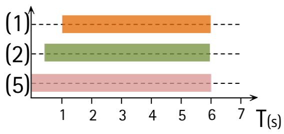
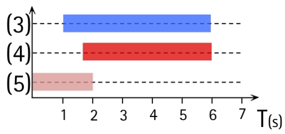
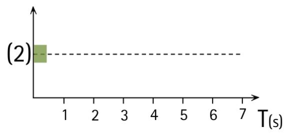
		Amusement	Anger	Sadness
Composed Gesture	**Movement**	Lift both hands (5), lower arms (2) and upper arms up (1)	Lift both hands slightly up (5) and claw the hands (3), then push the hands down (4)	Shortly both lower arms up (2)
	Gesture			
EMS Actuation	**Muscle**	Extensor digitorum muscle (5, pink), biceps brachii muscle (2, green), and deltoid muscle (1, orange)	Extensor digitorum muscle (5, pink), flexor digitorum superficialis muscle (3, blue), flexor digitorum profundus muscle (4, red)	Biceps brachii muscle (2, green)
	Timing			

Table 8.1: Linking emotions for composed gestures set: Elicited elementary movements with performed gestures, the muscles to actuate the movements and the action timing.

envision that emotion expressions can be copied on the receiver and used as actuated output. The haptic feedback needs to actuate the recipients to let them perform these expressions.

Therefore, based on a literature review, we composed two gesture sets to represent the following emotions: *anger*, *sadness*, and *amusement*. With these emotions we follow Russell's model of affect [282]. The basic emotions are placed near axes (misery, arousal and pleasure) of Russell's model. Sleepiness and neutral were used as baseline emotions.

In this work we do not actuate the face muscles to express emotional output as shown in this artwork [85]. Placing EMS electrodes to the face would be socially problematic and when they are integrated in textiles the user needs to wear a face mask. Furthermore applying EMS signals to the face is not recommend for safety reasons as discussed in Section 4.2.6. In this chapter we focus on body language to create the emotional output.

To create the first gesture set, we elicited elementary movements that are related to each emotion from the literature. Then we composed out of elementary movements one output gesture to express each emotion. We will call this *composed gesture* or *composed gesture set* since it is composed from natural movements that are described in the literature.

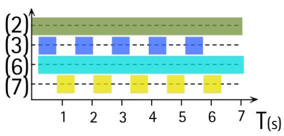
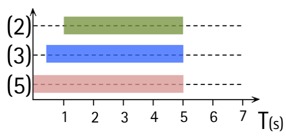
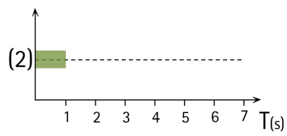
		Amusement	Anger	Sadness
American Sign Language Gesture	**Movement**	Lift the the lower arm up (2), claw the hand (3) then lift two finger up (7) and tow finger down (6)	Lift the hand up (5), then claw the hand (3) and lift lower the arm up (2)	Lift the lower arm up (2)
	Gesture			
EMS Actuation	**Muscle**	Biceps brachii muscle (2, green), flexor digitorum superficialis muscle (3, blue), flexor digitorum profundus muscle inside (6, cyan), extensor digitorum muscle inside (7, yellow)	biceps brachii muscle (2, green), flexor digitorum superficialis muscle (3, blue), extensor digitorum muscle (5, pink)	Biceps brachii muscle (2, green)
	Timing			

Table 8.2: Linking emotions for American Sign Language gestures set: Elicited elementary movements with performed gestures, the muscles to actuate the movements and the action timing.

In addition to composing a second gesture set, we analyzed how emotions are represented in the *American Sign Language*[21] (ASL). We picked as well for each emotion the corresponding gesture and elicited the elementary movements. In the following we consider for each emotion the two representative gestures.

Amusement Gesture

Amusement is usually expressed with open gestures that stretch and extend the limbs of the body [337]. Particular movements to express this emotion are opening the hands and keeping them high [118] while lifting both arms up [80]. The *composed gesture* for amusement is synchronous performed with both arms. First the hands are raised up then the lower arm and afterwards the upper arm. The hands and arms are kept up to the height of the head for a short while as illustrated in Table 8.1 on the left column.

[21] https://www.signingsavvy.com/sign/

The ALS gesture for amusement is to lift two fingers up and down in front of the face or chest. It is performed with one arm. As elementary movements these gestures consist of lifting the hand with the lower arm up while closing the hand to a fist, then holding this position and raising and releasing the index and middle finger (Table 8.2, left).

Anger Gesture

The gestures for the emotion anger are generally characterized as aggressive [65] and evoke a violent [48] posture. The fists are clenched while the body is held in an upright forward position. The fists are kept low or at the waist [118] and for a period of time the fists are shaking [337]. Hence, the composed gestures consist of making a fist with both hands and pushing them on the legs. Therefore the hand needs to be lifted up slightly, closed and pushed down on the legs (Table 8.1, middle).

In the ALS, the gesture looks like a clawed hand in front of the chest or the face. Therefore the hand needs to be lifted up with the lower arm and the finger tips closed while holding the hand palm open to make the claw gesture (Table 8.2, middle).

Sadness Gesture

Sadness is related to an introverted posture with lack of body tension [80, 337]. The intensity of the movements are low and they are performed rather slowly [337]. The hands are usually kept close to the body such as in into the pocket [65] or mostly folded in the lap [80]. The composed representative gesture for sadness is to lift both hands gently up and release them folded in the lap (Table 8.1, right).

The related gesture in the ASL, is to lift up the hand to the chest and let it slide down the body to the lap. The elementary movements are to lift the hand, release it in front of the upper body and let it slide down Table 8.2, right).

In contrast to the composed gesture the ASL gestures are performed only with one side of the body. They are more simple and generalized compared to the composed gestures.

8.2.3 Actuating the Gestures Sets

In a second step we extract from the elementary movements the related muscles that can be actuated with EMS (Sections 4.2.2 and 4.2.3). The toolkits were used to evaluate the reliability of the movements and the electrode placements, for example, lifting the arm up as discussed in Section 4.1. Then we designed the EMS gestures for each emotion, so the system can let the user perform the gestures corresponding to the emotions. The used muscles for the composed gesture set are shown in Table 8.1 and for the ASL gestures set in Table 8.2. The corresponding placement for all electrodes of both gestures set are presented in Figure 8.3. In total 12 muscles are used to create the specific gesture set to represent the three emotions. All postures start at the same position, with both hands lying on the upper leg.

Composed Gesture Set

The composed gestures set is composed of the elementary movements for amusement, anger and sadness (Table 8.1). Note the used numbers reflect to the placement in Figure 8.3.

The composed amusement takes overall 6 s. First the extensor digitorum muscles of both arms are actuated over the full time (5), then both biceps brachii muscle (2) after 0.5 s for 6.5 s followed by the deltoid muscles (1) after 1 s for 5 s. The digitorum muscles lift the hands up then the lower arms are lifted up with the biceps brachii muscle. To complete the gesture the deltoid muscles of both shoulders raise the arms higher.

The composed anger gesture takes as well 6 s and involves both sides in synchrony. The extensor digitorum muscles (5) are actuated from the beginning for 2 s, after 1 s, the digitorum superficialis muscles (3) were added for 5 s and finally the flexor digitorum profundus muscles (4) after 2 s for 4 s. The extensor digitorum muscles lift up shortly the hands to make space for the finger to clench one's fist on the upper legs. After that the digitorum superficialis muscles claw the hands to fists, finally the flexor digitorum profundus muscles push the hands down.

The composed sad gesture is with 0.5 s the shortest. The siceps brachii muscle (2) of both arms are activated (for 0.5 s) to lift the hands toward the chest and after the contraction they slide down to fold the hands in the lap.

ALS Gesture Set

The ALS gesture set also consists of three EMS-based gestures one for each emotion (Table 8.2 and Figure 8.3 for the placement).

The ASL amusement gesture takes in total 7.2 s. The biceps brachii muscle (2) is actuated from the beginning for the full 7.2 s, followed by the flexor digitorum profundus muscle (6) inwards, and the extensor digitorum muscle (7) inside with a delay of 0.25 s for 7.1 s. The extensor digitorum muscle (7) and flexor digitorum superficialis muscle (3) are alternatingly actuated for 0.4 s in total five times. The biceps lifts the arm up and as soon as the arm starts lifting, the flexor digitorum profundus muscle is actuated inside which closes the hand except for the index finger and middle finger. The extensor digitorum muscle (7) lifts the index and middle finger up and the flexor digitorum superficialis muscle (3) pushes the finger down again.

The ASL anger gesture takes 5 s. The biceps brachii muscle (2) is actuated over the whole time, then the extensor digitorum muscle (5) is actuated with a delay 0.3 s for 4.7 s, and the flexor digitorum superficialis muscle (3) with a delay of 0.5 s for 4.5 s. First, this lifts the lower arm up, followed by the hand, and it finally claws the fingers.

The ASL sad gesture only takes 1 s. The biceps is actuated for 1 s and pushes the lower arm up to the chest where it slides down the chest after the actuation.

The muscle position is user-dependent as discussed in Section 4.2.2, even small changes in position can result in a different movement. To achieve a realistic movement, each user needs to be calibrated individually with regard to the strength of the EMS signal and the position of the electrode (calibration process Section 4.2.4).

8.3 The Emotion Actuator Prototype

We created the *emotion actuator* system that senses emotion changes and creates embodied feedback gestures to investigate *embodied emotional feedback*. The system consists of two main components of an *EEG sensing* and an *EMS actuation* component. As soon as the sensing component recognizes a specific emotion, it sends this emotion to the actuation component. The actuation component lets the receiver perform EMS gestures that represent the related body language.

8.3.1 Sensing Component

To implicitly sense the emotional state of the user an off-the-shelf Emotiv EPOC[22] EEG device was used with 14 measuring and two reference saline-solution wet electrodes that are located above the different areas of the cortex. The EPOC was connected via WiFi to a PC that recorded EEG raw data, the affective and facial expression information. As features for the classifier we used the affective scores (excitement, engagement, and frustration) [7, 185, 207, 248] and facial expression information (smile, clench, and laugh) [10, 47] of the of EPOC device, which worked feasibly in literature to classify emotions[23].

[22] http://www.emotiv.com

[23] The sensing component is primarily developed by the Media Informatics Group

Additional to the EPOC build-in notch and noise filter we applied the Savitzky-Golay filter to further smooth the signal [287]. We chose a window size of 3 s and extracted the features for each window. We define a threshold for the facial expression (score smaller then > 0.3) to avoid false positives for smile, clench, and laugh. The 18-dimensional feature vector includes the minimum, maximum, mean, median, and standard deviation of the excitement, engagement, and frustration scores as well as the facial expression features. The defined feature vector was used with a random forest classifier with 100 trees to classify the selected videos form the database.

8.3.2 Actuating Component

To realize the actuating component, we used the toolkit as presented in Section 4.3. We used six instances of the control module and used the same amount of Breuer Sanitas SEM 43 [23] devices to generate the EMS signals to actuate the twelve muscles (Figure 8.3). The toolkit was connected to 24 self self-sticky electrodes 22 with a size of 40×40 mm and two (electrodes (3)) with a 40×80 mm that are placed over the muscles. As signal EMS parameters we used a pulse width of 100 μs, and the pulse frequency of 100 Hz. The toolkit was used to turn the signal on/off and to make fine-grained calibration of the intensity. The calibration of the maximal comfortable intensity was done with the Breuer EMS devices.

For composing the different gestures we deployed the Multiple Devices app (Section 4.4) on two Samsung Galaxy Tabs S (10.5) that connect to six control modules of the toolkit. The app controlled each muscle individually via a one-to-one mapping of button to muscle. In addition, the intensity of the EMS signal was controlled through a slider for each muscle. This individual activation and intensity adjustment enabled fine-grained calibration of each muscle. The app allowed a precise timing of the gestures. Finally we extended the app so that it is also able to *replay* complete gestures by consecutively actuating muscles using a predefined timing. After calibration, this can be used to replay gestures.

8.4 Detecting Emotions through EEG

We set up a user study to investigate if the defined classifier works with a reasonable accuracy. To detect the emotional state of the user the EEG data from the EPOC device were analyzed. To evoke the user's emotion we used visual and audiovisual stimuli [360]. We chose two videos for each emotion (anger, sadness, and amusement) and two neutral videos from an

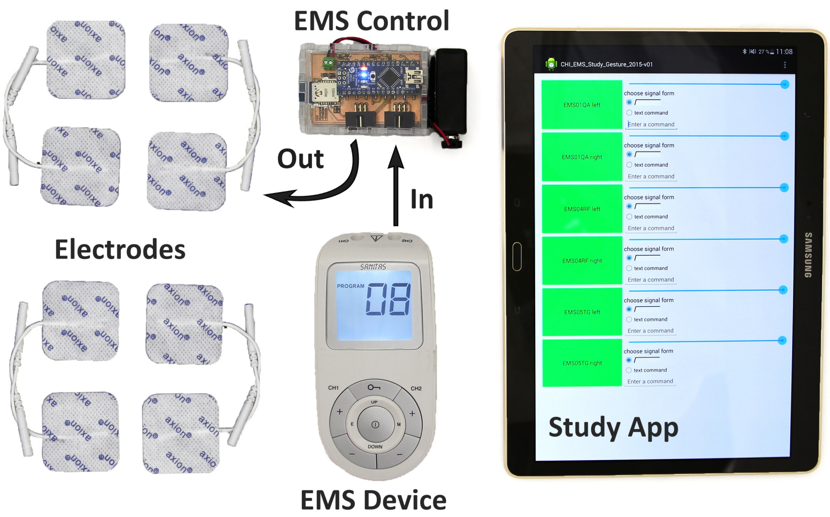


Figure 8.1: The toolkit configuration to control 12 muscle. Shown is one instance of the toolkit, that is connected to 6 modules and electrodes.

Figure 8.2: Snapshots of the different gestures performed in the second study. Each participant performed each of these six gestures.

existing database [288]. 364 participants ranked the videos from the database on 24 criteria. Each video had sound and duration of 2-4 minutes. The selected videos are shown in Table 8.3.

Emotion	Movie	Scene Description
Amusement	Benny & Joone	Benny plays the fool in a coffee shop.
	A Fish Called Wanda	The owners of the house found one of the characters naked.
Anger	Schindler's List	Concentration camp commander randomly shoots prisoners from his balcony.
	American History X	A neo-Nazi kills an African-American man, smashing his head on the curb.
Sadness	The Dead Poets Society	A schoolboy commits suicide.
	Philadelphia	Andrew describes to Joe the pain & passion felt by the opera character they are listening to.

Table 8.3: The movie snipes used in the study to evoke a certain emotion.

8.4.1 Study Design and Procedure

In this initial study the participants watched all movie snippets that are listed in Table 8.3 and the EEG data were collected. We measured how strongly the intended emotions were evoked through two questionnaires after each movie snippet. We invited ten participants (3 female) to take part on the study (M = 27, SD = 4.8 years) [24]. As participants arrived at the lab they were briefed about the study. We asked them to sign a consent form and fill out a demographics questionnaire. Then we equipped them with the EPOC device and ensured an optimal placement of the electrodes using the EPOC control panel. We placed the participants sitting in front of 30 inch screen and started by presenting a neutral video clip to establish a baseline. When the baseline was recorded the selected videos was shown in a random order. After each video clip the participants were asked to rank the three emotions (anger, sadness, and amusement) on a 7-point Likert they felt and for measuring the arousal and valence to fill in a 9-point Self-Assessment Manikin (SAM) scale [36].

8.4.2 Results

The video clips were labeled with the highest scored emotion from the self-assessment of all participants. In two case participants mixed up *angry* and *sad*. P10 ranked an *angry* movie as *sad* and P5 a *sad* movies as *angry*. In these cases we excluded the particular class from

[24] The EEG Study was primarily done by the Media Informatics Group

the evaluation. P5 related a sadness video ambiguously on both scoring systems, which were removed also from the dataset. With the defined feature vector we got classification accuracy using Weka[25] between 59.4% and 89.2%. The results are shown in Table 8.4. Due to the hairs of P2 the electrodes did not always have good contact to the skin during the study. This may explain the low classification accuracy of 59.4%. With this data set we got an overall accuracy of 72.6% with an *SD* of 9.5%.

Participant	Classes	Accuracy (%)
1	AM,REL,SAD,ANG	67.7
2	AM,REL,SAD,ANG	59.4
3	AM,REL,SAD,ANG	67.3
4	AM,REL,SAD,ANG	70.8
5	AM,REL,ANG	89.2
6	AM,REL,SAD,ANG	81.3
7	AM,REL,SAD,ANG	66.9
8	AM,REL,SAD,ANG	70.1
9	AM,REL,SAD,ANG	82.9
10	AM,REL,SAD	77.0

Table 8.4: Participant-dependent classification results using a Random Forest classifier.

8.5 Evaluating the Gesture Sets

We set up a second study to evaluate both gesture sets. We tested whether the elicited body movements fit the detected emotions, as judged by the participants. We compared the *composed gestures* to the *ASL gestures*. In addition, we collected user feedback in interviews. In particular we were interested if the actuated emotions gestures are easy to understand.

8.5.1 Study Design

A repeated-measures study design was used in which participants compare two gestures for each emotion. The independent variable was the gesture played via EMS, with these levels (see Table 8.1 and Table 8.2): composed amusement gesture, ASL amusement gesture, composed anger gesture, ASL anger gesture, composed sadness gesture, and ASL sadness gesture. We used a Latin squared order of gestures to prevent sequence effects. After experiencing a gesture, participants had to rate on a 7-point Likert scale how well they felt each gesture

[25] `http://www.cs.waikato.ac.nz/ml/weka/`

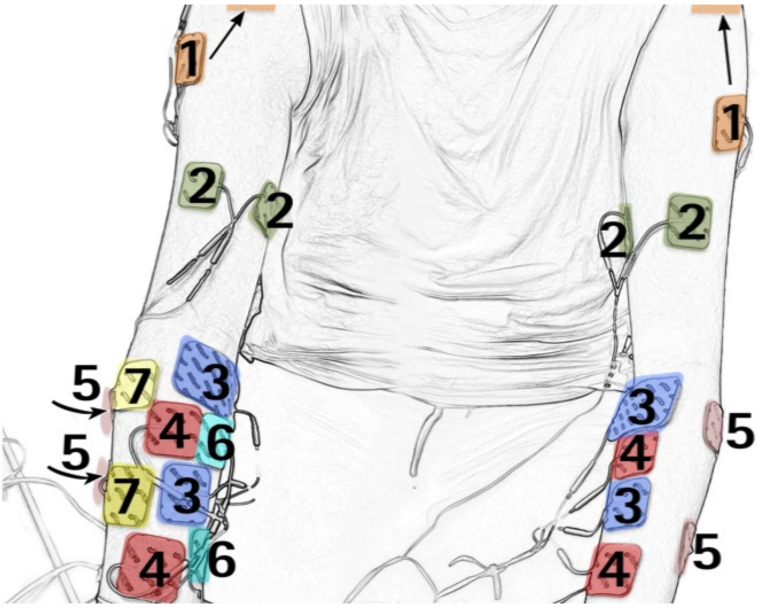


Figure 8.3: Placement of 12 electrode pairs to actuate muscles via EMS. The colors and numbers refer to the muscles of the gesture sets in Table 8.1 and Table 8.2

represented the three emotions amusement, anger, and sadness. In addition we collected interview responses for each gesture and after all gestures were performed.

8.5.2 Procedure

We recruited from our internal mailing list 8 participants aged between 20 to 28 years (4 females M = 22.4, SD = 2.7) and inverted them to our lab. First the participants were introduced to the purpose and the procedure of the study. After that the participants were ask to fill in a consent form and an initial demographic questionnaire. Then we introduced the EMS toolkit and tested whether the participant was comfortable with the sensation as described in Section 4.2.4. After the introduction we equipped the participant with electrodes (Figure 8.3) and calibrated the muscles for the intended movements. During the calibration process we actuated only sub sequences of gestures that needed to be tested together so that participants did not experience the whole gesture. In the study participants perceived each emotion gesture for the first time. The participant did not know the expected meaning of gestures or emotion. The whole calibration process took about 60 minutes.

When the gestures were calibrated, we let the participants perform each emotion gesture of both gesture sets in random order. We repeated the performance up to 4 times to ensure that participants got used to the actuation and experienced the movements of the gesture. After

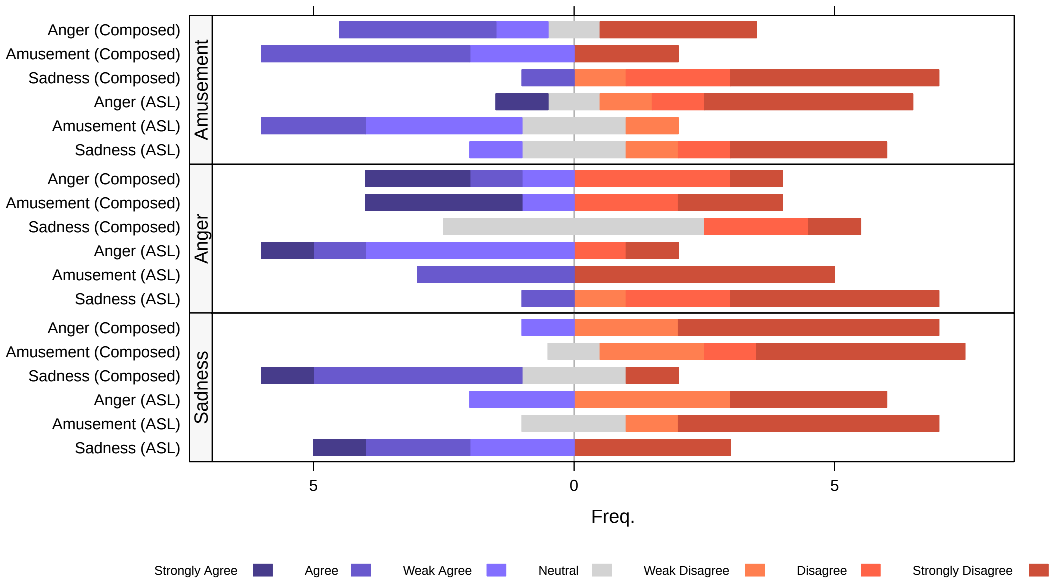


Figure 8.4: Rating of the composed and ASL emotions gesture sets for amusement, anger, and sadness, on a 5-point Likert scale.

the participants were familiar with the gesture we asked them to rank this gesture according to the degree of agreement to the statement "this gesture fits to the emotion [amusement, anger, sadness]" (1 = strongly disagree, 7 = strongly agree). In addition we interviewed the participants as to what they liked or disliked and which words they would use to describe each gesture. After rating all gestures we asked for further comments.

8.5.3 Results

Quantitative Results

The rankings from the participants showed agreement on the intended meaning of the gestures for the composed and ALS gesture sets as shown in Figure 8.4. In the user rankings, only the composed anger gesture was interpreted incorrectly as amusement (M = 3.5, Median Absolute Deviation (MAD) = 1.5) followed by anger (M = 4.5, MAD = 2). In contrast the ASL anger gesture was, as intended, the highest ranked as anger (M = 2.5 , MAD = 0.5) followed by amusement (M = 4.5, MAD = 2.5). Looking more closely at each gesture, we found that participants P7 and P8 misinterpreted the composed anger gesture of the composed gesture set as to represent that for amusement.

Qualitative Results

We were particularly interested in how the participants experienced the different gestures.

Amusement: The composed gesture was described by participants as exciting (P1, P6). P1 also said that he found the gesture somewhat hectic. Some participants mentioned that raising their hands very high made them feel kind of funny, but not very natural and not often used. This gesture is more used for cheering. In contrast, the ASL gesture that focused mainly on the actuation of the biceps and finger movements was also characterized as exciting (P6), with regard to the moving fingers and was considered to be much more natural (P8).

Anger: Subjective feedback suggests that both the composed as well as the ASL gesture were overall perceived as a good fit. P1 disliked the fact that the composed gesture felt cramped. P5 said that the composed gesture resembled shadow boxing. With regard to the ASL gesture, P1 and P7 said that the gesture created a kind of defensive, almost aggressive attitude, hence well reflecting the emotion. P3 stated that the gesture resembled dancing, since the arm rotates inwards.

Sadness: For the composed gesture, participants felt the gesture was defensive (P6), made them look puzzled (P8), and felt like waving at somebody (P8). P7 said that the ASL gesture made them feel thoughtful, thus nicely reflecting sadness. P8 felt the gesture could be confused with anger.

General feedback by the participants suggested that people did not actively interfere with the actuation and let the system control the movement. P3 mentioned that it was quite uncommon to be externally controlled, but soon got used to it. P7 mentioned that they felt the muscles, rather than the current. Only P2 felt that the actuation was artificial.

Emotion Gesture Set Selection

In summary, the qualitative feedback indicated that overall the gestures fit the emotions well – in particular the ASL gestures – even though there were some misinterpretations for both types of gestures. We believe that these mainly stem from the fact that people have different ways of expressing emotions. Apart from the qualitative feedback, an important criterion on which we based the decision for the final gesture set was the distinctiveness of a gesture. Thus, we looked at the maximum difference between the top and second rated emotion for the two gestures. Finally there was a tendency towards the ASL gesture set, that managed to represent each emotion correctly and the participants slightly favored it.

8.6 Prototype and Concept Exploration

A qualitative evaluation of the emotion actuator concept was conducted with groups of two users. In particular, we obtained information on the emotional state of one of the participants via EEG and then conveyed it through EMS actuation to the other participant. The purpose of the study was to understand how well our approach helped people to feel connected with the actuated output and in which situations they would like to use embodied emotional feedback.

To create a realistic scenario and to evaluate one directional actuated feedback, the two participants were given different tasks. Whereas on the sender side, participants watched the videos as in the sensing study, the receivers were asked to play a game on a 10.5 inch tablet computer as a distraction task. We chose a non-emotional, non-time critical game called "Find the Difference 38"[26] from the Google play store.

8.6.1 Apparatus

As with the end-to-end prototype, the sensing component (EEG) and the actuating components (EMS) were connected together. The EEG input side involved the Emotiv EPOC that was connected to a PC. It sent data to the PC, which computed the features and determined the emotional state of the sender. The state was then sent wirelessly to the EMS side. The notification on the emotional state of the sender was conveyed either through a standard text message on the Android tablet[27] on which the participant played the game or through actuated ASL gesture set as described above. Text notifications served as a simple baseline, as they are a common way of conveying emotional information. We chose short and easy-to-understand sentences. In particular, the messages stated "I am {angry | sad | amused}." In addition to the visual feedback the tablet computer vibrated twice when a notification was received.

In this study, we used the toolkit app with the replay function for ASL gesture set and with the timing of the gestures, the sequences and lengths of each actuation as summarized in Table 8.2. For creating the gestures that represent the different emotions we used the same EMS control modules and calibration process as Section 8.5.

[26] Find Difference 38 `https://play.google.com/store/apps/details?id=free.find.difference38`

[27] Android Notification `http://developer.android.com/guide/topics/ui/notifiers/notifications.html`

8.6.2 Study Design

The study followed a mixed design, in which the sender (EEG) and receiver (EMS) is a between-subjects variable (i.e., a participant was either a sender or a receiver) and the feedback channel (EMS vs. textual) is a within-subject variable (i.e., each recipient received both EMS and textual notifications). No quantitative data was gathered during the study but we focused on qualitative feedback provided by the participants. The goal was to gather a deeper understanding of how people felt connected and involved depending on the kind of feedback.

8.6.3 Procedure

For the study we recruited 8 participants (2 female, averge age 25.6, *SD* = 4.4 years) from a student mailing list and from our lab. Two of them were a married couple (P1, P2), two had been friends since childhood (P3, P4), two were colleagues (P5, P6), two did not know each other (P7, P8).

As participants arrived at the lab, they received an introduction on the purpose and the procedure of the study. Then they were divided randomly and assigned to one of the two groups – either the EEG group or the EMS group. Both were then led to separate rooms. People in the EEG group were equipped with the Emotiv EPOC and then shown the neutral movie for calibration. They got the same set of movie snippets (two per emotion) presented as in the initial study (Table 8.3). During each video, information on the respective emotional state was measured by the EEG device and directly sent to the other participant. Note that we checked each detected emotion before it was passed on to the receiver, because we could not guarantee that people responded to the movie snippets in the intended way or the emotion was correctly recognized. An unexpected emotion happened twice, when participants responded with *anger* to a *sad* video similar as in Section 8.4. Our approach ensured that the intended emotion was transmitted to the receiver. The participants were not informed about that and did not notice it. The videos were played in a counterbalanced order and took 2-3 minutes each. Both participants knew the condition and procedure of the other participant.

Participants assigned to the EMS group were first introduced to EMS (Section 4.2.4) and the muscles required to perform the gestures were calibrated (Table 8.2). We let the participants experience each gesture and told them about their meaning. We then handed the tablet to the participants and asked them to play the game. Furthermore, we explained to them that they would receive either a text notification on the tablet or would be actuated through EMS while playing the game. Participants were asked to verbally report the emotions they received.

After the people in the EEG group had watched all six movies, the emotions had been sent and feedback was performed and perceived, one researcher removed the EEG and EMS equipment. The participants were brought to the same room and a semi-structured interview was conducted with both participants together.

Introduction and calibration took around 45 minutes. The participants watched approximately 20 minutes of video or played the game. Six emotion responses were sent during that time.

8.6.4 Results

We clustered the statements and comments participants made during the interview according to different themes, which were discovered during the analysis process.

Emotion Reception

First we were interested in how intensive and immersive the gestures were experienced compared to the common text notifications. P4 stated that he found “emotions conveyed through motion much stronger than the textual emotions”. P4 added, though, that he was not sure whether this increased strength stems from the gestures or his surprise that the approach indeed works. P6 pointed out that “the electrical feedback is much more haptic” and added that it is “much more emotional if the body reacted compared to when you just look.” In addition he felt that more brain activity was involved. P2 stated that the actuated feedback “happens within the body and it somehow feels as if the emotion is inside the body.” P8 said that with “EMS you feel the emotion [...], the text message you can just neglect.” Asked about whether she felt connected to the other person, P8 answered “yes, somehow, yes.” P4 explained that in the case of the text message he was more involved in the game than connected to the other person. P4 pointed out that he could feel the anger and amusement from the actuated body language. Asked about what they liked and what they did not like P4 responded that “it [EMS] is more expressive, that is an advantage.” P6 said that “it [EMS] is much more immersive.”

Gesture Set

Participants said that it would have helped them to know the ASL. P4, P6, and P8 would have liked the gestures to differ more strongly from each other and that they could be more natural. “Apart from the fact that the gestures did not differ too much, they were quite nice” (P4) and argued that they were played too fast. We asked P8 whether she expected facial gestures to work better than the proposed gestures. P4 felt that they might not be diverse enough and added “smiling and opening my mouth could work.” When asked about how they liked the movement caused by EMS, P6 answered that it was “just normal – neither negative or positive.” Furthermore he said that it “was quite funny to see the arm alone go up without this being caused by the brain.” P4 was happy and surprised that it works so well. Furthermore, P4 said that despite being able to feel it without looking, he would have liked a notification to be “aware of that something is going to happen.” P4 also suggested that the gesture be repeated.

General Feedback

None of the participants felt pain and they got used to EMS after a short while. P6 mentioned that it just happened and the arm lifts up. P4 and P6 described the feeling as tickling. As limitations, the participants mentioned the long calibration and cables.

Sharing Emotions

We were interested to find out with whom people would like to share emotions through the presented system. There was agreement among participants, that they would mostly share this information with close friends, family, or partners. P3 stated that this would be appropriate for “friends and people I am close to.” P5 felt that his girlfriend “would be happy about that” and that his parents would be very interested in receiving this kind of information (“Parents! Oh parents are interested in that”). However, he also pointed out that it depends on the emotions themselves as well as on the granularity of the emotions.

We found a tendency that participants (P5, P6 and P7) would share negative emotions with close friends only, whereas it would be okay with them to share positive emotions with a wider audience.

Emotion Provisioning

A lot of the feedback focused on whether people would favor providing emotional feedback implicitly or explicitly. Participants had mixed views. On one hand, participants clearly liked to stay in control of what would be conveyed (P3: “I would like to stay in control of what I give away”), on the other hand, participants also stated that they think they would probably not share emotions unless this happened in an automated way. P5: “Feedback should be given implicitly.” He mentioned that he is lazy and finds it hard to talk about his feelings. He also added “I would never write, ‘Oh, hey sweetheart, I feel ...’ [...] But when I can engage my girlfriend with it, wonderful." Similarly, P3 emphasized that he also would not share such information in case he would need to do this explicitly.

Application Areas

Finally we asked the participants about application. They had a number of ideas for sharing emotions and expressing them with body language. P6 would like to apply the concept to *video calls* to enhance the experience. P5 said that he would like to share emotions he had during *sports* activities such as raising the hands. Some participants suggested using an emotional connection at *work* or in *lectures* to communicate cases in which they were overloaded or not being challenged enough (P5, P6, P7, P8).

P5 and P6 could imagine emotions as a *complementary communication channel* between them and their friends to implicitly share when they were bored. P7 mentioned that emotions could not only be transmitted to a remote person, but that it could also used for *self-reflecting* his own emotion. He said "one might benefit from knowing more about oneself." In line with this comment, P8 added that she would find it helpful to get to reflect on herself: "I often tend to be unfocused and am not aware of that. But the system could help me to get my focus back."

The participants saw also the potential of the approach in cases where two people do not speak the same language or where one person is handicapped (deaf and mute) (P4). P6 mentioned that he could imagine quite a number of places where this would be annoying: "it needs to be context aware. [...] I would not use it in a car."

8.7 Discussion

The presented system still requires a rather complex setup, but we envision that with advances in technology towards smaller and wearable devices, the approach will be applicable in everyday settings. The actuating components are already wearable and the electrodes could be integrated in clothes as discussed in Section 2.3.3. Electrodes grids could automatically calibrate the placements, which means reducing the time of a user individual calibration.

The focus was on building a working prototype to understand how people would implicitly share and perceive emotions in an immersive way through embodied emotional feedback. If a system for affective communication is to be integrated in everyday life, the amount and the moment of transmitting affective information is also relevant. It is probably annoying to be made aware of the affective state of the other person continuously, as mentioned by

P6. Hence, the emotional notification should have constraints to strong affective states or state changes, or be guarded by contextual factors. Future work can address such aspects of “affective notifications”. The body language of the remote person (sender) could be recoded with video or EMG and playback on the receiver when the sender enters an emotional stage. In this way the partners perceive a well-known gesture from the sender. The timing of the feedback needs to be investigated as well, for example if the feedback only occurs once, will be repeated or is continuous.

The presented studies investigate uni-directional communication of affective information. A real-life application, such as the affective communication of couples, makes a bi-directional exchange of affective information necessary. This would close the feedback loop. An important question for future work is how this feedback loop influences the emotional state of the connected persons: Does the received sadness result in sadness in the recipient, and when played back does it lead to a downwards spiral? Does the received amusement cheer a sad person up? Another important question is how and when the affective channel should be escalated to other forms of communication such as text or voice communication. Is the exchanged affective information a “ticket to talk” – a reason to start a conversation around the causes for the other person’s emotion? These questions require long-term studies with couples and more practical sensing and output technologies.

Affective information is privacy sensitive. There might be times in which somebody would not be willing to share their affective states even with their partner. Emotional information might be received by someone who is not the legitimate recipient. Social negotiation and security mechanisms are necessary to resolve these issues.

This chapter is motivated with connecting people who have a relationship intimate enough to exchange affective information. The information exchange in this scenario is one-to-one. However, it is also conceivable to extend the exchange of affective information towards larger groups in which the emotional state is transmitted anonymously. One scenario would be exchanging affective information about a sports team: The performance of the team would be reflected in the joint affective states of the fans of the team. Mechanisms to aggregate emotions would be necessary in such a many-to-many scenario. Another scenario was suggested by P5, namely to share the emotion when watching movies with other viewers and replay them while watching the movie.

There are also implications for other research areas. The quantified self-movements aim to make data about oneself visible in a new way. Instead of communicating affective states to another person, they could also be communicated to oneself to increase the awareness of, e.g., stressful states, and help in relaxation. The intuitive mapping and display of affective states is a crucial aspect to achieve this goal.

8.8 Conclusion

In this chapter we focused on fundamental aspects of communicating emotions and engagement between people remotely with embodied emotional feedback based on EMS gestures.

Emotions are sensed with an EEG system, classified as amused, angry, sad, or neutral, sent as notifications to the receiver, and played back using EMS to actuate the recipient's body. The presented studies have shown that EMS actuation can lead to an embodiment of emotional states, which contributes to an intuitive understanding, immersion, and empathy.

Two gesture sets of emotional body language were designed. The elementary movements to represent different affective states have been elicited from the literature. The output is based on natural movements related to emotions that are composed to gestures and sign language gestures (ASL). The ASL gesture set turned out to be more intuitive than the gesture set that is composed from the literature. One reason could be that we only considered gestures and body postures, but not facial expressions. Body language has personal, culture and environmental differences [90]. That could mean, that the ASL anger gesture is more general and reflects more strongly to anger. In future personalized emotional body language could be used and sent to a private partner.

In the end-to-end study participants wanted to share their emotions implicitly, but liked to stay in control about which emotion is shared and with whom. In particular they preferred more restrictive sharing for negative emotions than for positive emotions. Future implicit emotion sharing approaches should offer control over preselecting recipients based on the kind of emotion. Moreover, the context of the emotion is an important aspect of social acceptability. In addition, the situation and the context when receiving the actuated feedback need to be considered.

Open questions concern how to determine opportune moments of sending embodied emotional feedback, how much bi-directional emotional feedback influences the emotional states of the partners, and how and when the emotional feedback channel should be extended to other forms of communication.

The approach of embodied emotional feedback can also be generalized in sensing and receiving other feedback. The sender generates a kind of abstract notification i.e. an emotional state and the receiver displays this notification with her own body in case of an emotion with representative body language. The receiver becomes the output device for the sender. Similar remote concepts could support learning to use a tool over a distance, to learning sign language or other gestures instantly, to enhance video calls or sports. In this scenario the sender has an intention that could be sensed implicitly and the receiver displays the output by performing the specific movement. Also the actuated feedback or notification can reflect the particular state of a person, such as being stressed or unfocused. A person may not be aware of it and could be gently informed through an actuated feedback about this state. In this case the user can self-display her own state with her own body.

Chapter 9

Conclusion

This thesis investigates ubiquitous haptic feedback in human-computer interaction (HCI) through electrical muscle stimulation (EMS). Based on Mark Weiser's vision [344], the concept of *ubiquitous haptic feedback* is introduced. To achieve this vision, haptic feedback technologies need to follow the trend of miniaturization and need a wide feedback range. We identified EMS to have the potential to follow this trend and to generate tactile and force feedback. However, EMS feedback is still in its infancy in the context of HCI as a feedback method. This work simplifies the use of EMS for HCI research. It contributes EMS feedback parameter settings that worked well in the context of HCI. To enable fast prototyping and to enable the integration into a ubiquitous infrastructure, an EMS toolkit consisting of hardware and software components was developed. The contributed toolkit can be used to explore the potential of ubiquitous haptic feedback through EMS and to consider different applications. This work shows how ubiquitous haptic feedback can extend interaction with virtual objects by simulating physical properties for *EMS*-based *free-hand interaction* and *EMS*-based *target selection*. It contributes the approach of *actuated navigation* that manipulates the user's movement in a real world scenario to solve a navigation task. Finally the concept of *embodied emotional feedback* is developed to connect communication partners in an immersive way. To investigate and evaluate this approach, several prototypes that use the toolkit were developed. The findings show the potential of ubiquitous haptic feedback and build a foundation for further research. We believe that this work has the potential to build a new community around EMS-based haptic feedback, as started with the workshops at World Haptics'15 [194] and CHI'16 [195].

9.1 Contributions

The concept of ubiquitous haptic feedback to extend human interaction with the real and the virtual world has been introduced. Certain criteria for feedback technologies to achieve ubiquitous haptic feedback have been discussed. It has been considered how EMS fits these criteria. Based on this we envisioned new interaction scenarios that use ubiquitous haptic feedback. Using EMS in such envisioned interaction scenarios presents new technological challenges and particular challenges for interaction designers. To face these challenges, we developed the “Let your Body Move” toolkit and prototyping processes for EMS-based haptic feedback. We believe that this reduces the entrance hurdle of using EMS in HCI. Furthermore, we looked more closely at specific aspects such as extending virtual objects with physical properties, augmented the user with haptic feedback to solve tasks and discovered new opportunities to support remote communication. This raised new research challenges and questions.

9.1.1 Enabling of EMS in HCI

As discussed in Section 2.1 the human sensory system is the interface between humans and their environment. During human evolution, different external sensors were developed that let us perceive and interact with our environment. The haptic sense gives important information about our environment. Haptic receptors are located across the body in the skin, tissues, tendons, joints, muscles, and organs. Simulating object properties or behaviors of our environment means to stimulate these human receptors as naturally as possible. Computers are miniaturized, integrated in our everyday life, and have become ubiquitous. Current haptic feedback technologies have difficulty in following this trend of miniaturization (Section 3.2). At the same time, EMS has a feedback range to simulate a large number of haptic sensors and the potential to miniaturize the technology. Hence, EMS feedback can be integrated in mobile devices and is wearable. For extended wearing periods, the electrodes can be integrated in textiles, and clothes (Section 2.3.3). The fact that feedback technology is attached to the user makes it always available. This concept was introduced as ubiquitous haptic feedback. We presented several scenarios where this feedback was successfully used to enhance the human experience when they interact with computers.

EMS has a longstanding history of application in medicine but is still in its infancy when used as haptic feedback in interactions. The initial effort to use EMS technology is quite high. Moreover, there are no standards for prototyping processes, user studies, user calibration, and the parameters that need to be reported.

RQ1: How to enable fast and easy prototyping with EMS as a haptic feedback technology?

In Section 4.2 we discussed the calibration of EMS for muscles, the use of EMS, safety aspects and which parameters should be reported to make user studies reproducible. Furthermore, it became clear that the entrance hurdle to use EMS is quite high. Apart from understanding EMS feedback specific parameters (Section 4.1) other researchers, who are new to using EMS haptic feedback, need to build hardware to run prototyping sessions and user studies. Therefore we introduced the *Let your Body Move* EMS prototyping toolkit, to reduce this entrance hurdle to using EMS haptic feedback technology. The toolkit enables fast prototyping, a simple integration in application scenarios and in new projects and the ability to run courses, tutorials, workshops, and user studies (Section 4.3).

A prototyping process to develop instances of the toolkit, to extend and to integrate it in other systems, and to run prototyping session has been presented in Section 4.3.2. In a first evaluation, we used the toolkit with one sample application in a workshop for a brainstorming and prototyping session. Furthermore, early instances of the toolkit were used to investigated EMS as haptic feedback from different perspectives (Chapters 5- 8).

9.1.2 Haptic Extensions of Virtual Objects

In the context of virtual and mixed-realities the users interact with virtual objects as well as with physical objects. In such interactions it might be obstructing or annoying to have the hand covered with haptic output devices. Furthermore, when interacting in public space or with large displays that are not reachable to the user, wearing a large haptic feedback device such as an exoskeleton, might be cumbersome. In this case, free-hand interaction [3, 18] becomes necessary, which requires a lightweight wearable feedback technology that does not cover the hands.

RQ2: Is EMS feedback suitable for simulating physical properties in free-hand interaction?

Physical objects have properties that are not directly visible, such as hardness or weight. These properties are often neglected in free-hand interaction. In Chapter 5 we present two studies to investigate the design of haptic feedback that reflected different types of interaction with different materials in free-hand interaction. It contributes the corresponding level between two feedback modalities (EMS and vibration) to compare these modalities. We found that the users prefer EMS feedback when interacting with different gestures (touch, grasp and punch) towards hard objects. The qualitative results indicate that EMS feedback could also be suitable to simulate cold and pointed object properties. Further the users were comfortable with the EMS feedback and got quickly used to it.

Likewise, vibration and EMS feedback can be used to support selection tasks of such virtual objects. Target section in a 3D environment has additional challenges related to the stereo viewing and occlusion of targets. Using haptic feedback could reduce the selection error and make the interaction more realistic.

RQ3: Is EMS a reasonable alternative to vibration feedback for 3D target selection in stereoscopic environments?

In a Fitts's Law experiment that was based on ISO 9241-9, we found that additional selection feedback (EMS, vibration and visual) significantly decreases the mean error rate (Chapter 6). For the throughput and average movement time, there was a trend for the haptic modalities (EMS and vibration) to be better than the non-feedback condition, but there was not such a significant improvement as for the additional visual feedback. However, the users ranked the haptic modalities as being reasonably realistic. In contrast to the vibration, EMS has a larger range of feedback spectrum. Again, the users got quickly used to the EMS feedback. Hence, EMS can be used as suitable alternative to vibration feedback in 3D hand target selection to reduce the selection errors. In future, it needs to be investigated if hand target selection in 3D gains from haptic feedback when the targets are very small and the visual feedback is completely occluded.

9.1.3 Haptic Real World Manipulation

In public space interacting with mobile devices often distracts users. In outdoor or navigation scenarios these distractions can lead to accidents. Haptic feedback has already been used to reduce the visual distraction for navigation, but the user still needs to interpret this navigation information and to map it to the real world. In Chapter 7 we introduced the approach of *actuated navigation* that directly manipulates the human locomotion system to bypass visual distraction, interpretation and mapping.

RQ4: Can EMS force feedback be used reliably to guide pedestrians?

For actuated navigation the user's locomotion system needs to be influenced to change the walking direction. The results of a lab study show that EMS force feedback manipulates the walking direction by around 16 degrees per metre. In the second study users were navigated along two routes in a public park with no navigation errors. The qualitative results were positive regarding this approach. The results indicate that participants would like to use such a navigation system. The user can focus more on the environment while "cruise controlled" walking through a park. Users had no ethical concerns with the system and stated that as long as they can overwrite the actuation and get back the control they do not see any issues in using such a system.

9.1.4 Haptic Notifications

Human body language expresses emotions in a natural way through physical expressions. In remote communication these physical expressions often get lost. Particularly in long-distance relations, sharing such emotions is not well supported.

RQ5: Can EMS actuated gestures communicate emotions over distance?

Embodied emotional feedback is an approach to support nonverbal communication with haptic notifications. Emotions are sensed implicitly on the sender side, transmitted to the receiver and expressed through actuated emotional gestures on the receiver side. The receiver's body becomes the output device through actuation, to express the emotion states of the sender. A prototype implementation of a one-direction end-to-end system is evaluated in three user studies to explore this approach. The first study considers emotion sensing through EEG on the sender side. In the second study two emotional gesture sets (ASL and composed gestures from literature) to express three emotions (amusement, anger and sadness) are compared. The user's limbs were actuated to perform the gestures automatically through their bodies. It turns out that the ASL gesture set represents the emotion better than the composed gesture set. In the third study the end-to-end system was tested with a user on the sender side and a user on the receiver side. The qualitative results show that users felt that the transmitted emotion gestures were "stronger", "more haptic", "much more emotional", and "more brain activity" was involved, compared to text notifications. The participants pointed out that they would stay in control of which emotions are sent to which user. Further, some participants stated that feedback can be annoying in a specific situation such as driving a car and needed to be overridable or switched off.

Ubiquitous haptic feedback is achievable through EMS and opens new possibilities of interaction and to support interaction. The presented explorations looked from different perspectives on EMS-based haptic feedback and show how EMS can be used in different interaction scenarios. There are still several fields and scenarios as envisioned in the concept that can be targeted using ubiquitous haptic feedback based on EMS.

9.2 Ethics

EMS is an immersive technology that applies current to the user's body, lets the body perform movements and physically manipulates the user's movements. This opens ethical questions such as potential risks, implanted devices and the remote control of individuals.

Applying current to the body has potential for medical risks to a set of users as discussed in Section 4.2.6. The users need to be informed about this risk. Moreover, users were not familiar with EMS before they took part in user studies (Section 4.2.4). In addition to the normal stress those users have in observed situations, connecting the user to cables and feeling the current during the calibration increases the stress level. It is important to introduce the users to the purpose of the study and to inform them fully about the procedure [44, 202].

The presented toolkit lowers the entrance hurdle to use EMS for HCI. Reducing the entrance hurdle does not mean it reduces the responsibility of researchers for users. Apart from following the ethics recommendations in HCI [220], researchers who are working with EMS need to understand the medical aspects such as current parameters, muscles and risks before applying EMS to users. Depending on the institution and on the country, an ethics board needs to be considered before running user studies. For this work, the local ethics board from the Leibniz University of Hannover or pd-net ethics process was consulted (Section 1.2.4).

In this work, we excluded implantations and implanted electrodes regarding potential safety and user acceptance problems. In medical research implants are commonly used such as for pacemakers [363], but also implanted electrodes to support stroke or facial paralysis patients with grasping or standing [268]. In HCI [138], implanted interfaces were also considered. How far such devices should go depends upon the application scenario and needs to be discussed generally in society.

The user's body is actuated to generate the haptic feedback. As discussed in Chapters 7 and 8 the users should easily take back the control, analogously to a cruise control while driving. In all user studies the current was kept at a comfortable level and the users were able to overwrite the contractions easily. Stronger muscle actuations need more effort to overwrite the actuation. Following the idea a bit further, it raises a new ethical question: Could users automatically be guided to the next shop or in a direction that they do not want to go? Physical manipulation then may become similar to mental manipulation, so the user should always stay in control over the system.

A topic that is not considered in this work is security. In contrast to traditional systems, such as driver assistance systems, hackers could take control over the body parts of a user. Therefore, depending on the application scenario, such actuation assistance systems need at least the same security standards as for vehicles.

9.3 Feedback Limitations

Beside the ethical questions, EMS has technical and physiological limitations and challenges that are not yet solved. In the future, some of the limitations can be overcome with new technologies and others are imposed by the physiological limitation of the human body.

9.3.1 Calibration

The calibration takes time and effort to find the right placement of the electrodes and the level of current to actuate the muscle. The calibration time increases with the number of actuated muscles (Chapter 8) and the complexity to calibrate each muscle (Chapter 7). Again, some muscles are overlaid by others or they are so tight together that a precise calibration is difficult. Electrode grids as used for EMG [5], which cover the skin could be used to auto calibrate muscles. Auto calibration could be integrated with EMG sensing [329]. In addition, textile electrodes could be in clothes and customized as discussed in Section 2.3.3. The position of the muscles then needs to be calibrated only once.

9.3.2 Exhausting the Muscles

EMS force feedback is limited in power and duration. In contrast to natural actuation, the muscles fatigue faster with EMS actuation. Depending on the muscle, the continuous actuation to hold a force is shorter [150], the muscles fatigue after a couple of repetitions [79] and the response is slower [162]. The approaches that are considered in this work use a limited contraction time and number of repetitions. In addition the time between each repetition was quite long. For example during the navigation task the user's legs were actuated only for a turn. Then the user had time to walk back to the starting point or to the next corner in the park. During that time the muscles had time to recover [162]. However, some scenarios might need longer actuation periods as feedback. Downey et al. [79] discusses how muscle fatigue can be reduced but there will be always a limit to the actuation time and repetition depending on the muscle's fitness.

9.3.3 Exact Control

There are EMS specific factors that influence the response time and strength of actuation such as the amount of current that crosses the muscle, the position where the current crosses and the fitness of the muscles. Using EMS for haptic feedback adds further external factors that influence the actuation. For example, surface electrodes are on the skin and shift differently than the underlying muscles. This shift between electrodes and muscles increases or decreases the current that crosses the muscles and allows them to contract more or less. Such shifts could be faced also with electrode grids that adopt the movements of the muscle under the skin. Furthermore the actuation strength is not linear with the applied current. Holding a limb in a specific height or position needs closed loop feedback that detects that position and adapts the actuation signal. For more complex gestures and to compensate differences, a proportional-integral-derivative (PID) system could be used to control the EMS signal as discussed in [158, 192].

9.3.4 User Acceptance

People who use EMS safely need to see a significant benefit and must be willing to wear electrodes, accept the side effect of feeling the current and the involved calibration effort. In our studies users got quickly used to the feeling of the current but with today's technology, there is always the tactile feeling as a side effect. Also, following the idea of ubiquitous haptic feedback, long-term usage needs to be further investigated. The qualitative feedback indicates that users are willing to wear such technology for enhancing interaction in virtual and mixed reality and for everyday scenarios. The main usability concerns that we found were the calibration time and the fact that users need the ability to overwrite the actuation with their own movements.

9.4 Open Issues and Future Work

This thesis investigated the use of EMS as a haptic feedback method and provides a basis for further investigation of ubiquitous haptic feedback. At the same time, it exposes new challenges that need to be solved in future work, as discussed in the previous section.

Different types of closed control loops should be considered to generate smooth movements, to hold limbs at specific positions or to perform gestures that are not pre-calibrated. Closed-loop systems have several internal and external factors that need to be taken into account. Internal factors include an adjustment of the muscle contraction if the muscle fatigues or the muscles are shifting away from the electrodes. External factors like voluntary or counter movements by the user or the weight that a user holds also need to be considered. When adjusting the shifting of muscles, electrode grids become necessary. Combining closed control loops with electrode grids could enable an automatic calibration of muscles. Single electrodes could be clustered to form larger electrodes that have the shapes of the muscles and cover them completely. The control loop can detect the movements to adjust the EMS signal and the electrode configuration.

Ubiquitous haptic feedback devices need to be worn for a long time and in everyday life. In future, long term studies need to investigate if textile electrodes and EMS feedback are suited for these tasks. For example, an EMS alarm clock that wakes up the user gently by moving the limbs would be worn throughout the night. Moreover, muscle fatigue effects should be considered for tasks that occur in quick succession.

There is relatively little work on making the EMS signal more comfortable [12, 32]. Maybe there are parameters that are better suited for generating force feedback, or multi electrodes could activate one muscle to reduce the tactile feeling. Finally, dry electrodes are easier to integrate in textiles, which might be increase the wearing comfort and the user's acceptance.

9.5 Concluding Remarks

Ubiquitous haptic feedback becomes possible through EMS. This thesis lays the foundation for ubiquitous haptic feedback based on EMS and takes first steps towards establishing EMS in the field of Human-Computer Interaction. It forms the basis for further investigations and for building a new community around EMS in this field. We introduced the concept of ubiquitous haptic feedback through EMS and reduced the entrance hurdles for other researchers to use EMS in the HCI context. We used the developed toolkit to investigate interaction concepts such as EMS-based free-hand interaction and target selection as well as actuated navigation and embodied emotional feedback. The results show the range of applications for EMS-based haptic feedback.

Bibliography

[1] G. D. Abowd, C. G. Atkeson, J. Hong, S. Long, R. Kooper, and M. Pinkerton. Cyberguide: A Mobile Context-aware Tour Guide. *Wireless Networks*, 3(5):421–433, 1997.

[2] M. Achibet, M. Marchal, F. Argelaguet, and A. Lecuyer. The Virtual Mitten: A novel interaction paradigm for visuo-haptic manipulation of objects using grip force. In *IEEE Symposium on 3D User Interfaces - 3DUI14*, pages 59–66. IEEE, 2014.

[3] R. Aigner, D. Wigdor, H. Benko, M. Haller, D. Lindbauer, A. Ion, S. Zhao, and J. Koh. Understanding mid-air hand gestures: A study of human preferences in usage of gesture types for hci. *Microsoft Research TechReport MSR-TR-2012-111*, 2012.

[4] T. Amemiya and H. Sugiyama. Haptic handheld wayfinder with pseudo-attraction force for pedestrians with visual impairments. In *Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility* Assets '09, pages 107–114. ACM Press, 2009.

[5] C. Amma, T. Krings, J. Böer, and T. Schultz. Advancing muscle-computer interfaces with high-density electromyography. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI'15*, pages 929–938, 2015.

[6] L. Angelini, M. Caon, D. Lalanne, O. Abou khaled, and E. Mugellini. Towards an anthropomorphic lamp for affective interaction. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* TEI'07, pages 661–666, ACM Press, 2015.

[7] V. H. Anh, M. N. Van, B. B. Ha, and T. H. Quyet. A real-time model based support vector machine for emotion recognition through eeg. In *International Conference on Control, Automation and Information Sciences*, pages 191–196, 2012.

[8] F. Argelaguet and C. Andujar. A survey of 3D object selection techniques for virtual environments. *Computers & Graphics*, 37(3):121–136, 2013.

[9] R. Arsenault and C. Ware. Eye-hand co-ordination with force feedback. *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI'00*, 2(1):408–414, 2000.

[10] P. Aspinall, P. Mavros, R. Coyne, and J. Roe. The urban brain: analysing outdoor physical activity with mobile eeg. *British Journal of Sports Medicine*, 2013.

[11] A. Badshah, S. Gupta, D. Morris, S. Patel, and D. Tan. Gyrotab: A handheld device that provides reactive torque feedback. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3153–3156, 2012.

[12] L. L. Baker, B. R. Bowman, and D. McNeal. Effects of waveform on comfort during neuromuscular electrical stimulation. *Clinical orthopaedics and related research*, (233):75–85, 1988.

[13] S. Balasubramanian, H. R. Wei, M. Perez, B. Shepard, E. Koeneman, J. Koeneman, and J. He. *Human Haptic Perception: Basics and Applications*. Birkhäuser Basel, 2008.

[14] K. Bark, E. Hyman, F. Tan, E. Cha, S. A. Jax, L. J. Buxbaum, and K. J. Kuchenbecker. Effects of vibrotactile feedback on human learning of arm motions. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 23(1):51–63, 2015.

[15] A. Barreto, J. Zhai, and M. Adjouadi. Non-intrusive physiological monitoring for automated stress detection in human-computer interaction. In M. Lew, N. Sebe, T. Huang, and E. Bakker, editors, *Human-Computer Interaction*, volume 4796 of *Lecture Notes in Computer Science*, pages 29–38, Springer Berlin Heidelberg, 2007.

[16] K. E. Barrett and W. F. Ganong. *Ganong's review of medical physiology*, volume 17. McGraw-Hill Education, 2010.

[17] O. Bau, I. Poupyrev, A. Israr, and C. Harrison. Teslatouch: Electrovibration for touch surfaces. In *Proceedings of the 23th Annual ACM Symposium on User Interface Software and Technology - UIST'10*, pages 283–292, 2010.

[18] P. Baudisch, M. Sinclair, and A. Wilson. Soap: How to make a mouse work in mid-air. In *CHI'07 Extended Abstracts on Human Factors in Computing Systems* CHI EA'07, pages 1935–1940, ACM Press, 2007.

[19] N. N. Bazarova, Y. H. Choi, V. Schwanda Sosik, D. Cosley, and J. Whitlock. Social sharing of emotions on facebook: Channel differences, satisfaction, and replies. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work and Social Computing* CSCW'15, pages 154–164, ACM Press, 2015.

[20] J.-M. Belda-Lois, S. M. del Horno, et al. Rehabilitation of gait after stroke: A review towards a top-down approach. *Jour. NeuEng. and Reha.*, 8(66), 2011.

[21] M. Benali-Khoudja, M. Hafez, and J.-M. Alexandre. Tactile interfaces: a state-of-the-art survey. *ISR 2004, 35th International Symposium on Robotics*, pages 23–26, 2004.

[22] P. J. Berkelman, R. L. Hollis, and D. Baraff. Interaction with a real time dynamic environment simulation using a magnetic levitation haptic interface device. In *Proceedings of IEEE International Conference on Robotics and Automatio* volume 4, pages 3261–3266 vol.4, 1999.

[23] Beurer. TENS+EMS DUO. `http://www.sanitas-online.de/web/_dokumente/GAs/therapie/752.907-0212_SEM43.pdf`. Accessed: 2016-02-04.

[24] D. Bhatia, G. Bansal, R. P. Tewari, and K. K. Shukla. State of art: Functional electrical stimulation (fes). *International Journal of Biomedical Engineering and Technology*, 5(1):77–99, 2011.

[25] D. Bial, D. Kern, F. Alt, and A. Schmidt. Enhancing outdoor navigation systems through vibrotactile feedback. *Proceedings of the 2011 annual conference extended abstracts on Human factors in computing systems - CHI EA'11*, page 1273, 2011.

[26] A. Bicchi, M. Buss, M. O. Ernst, and A. Peer. *The Sense of Touch and its Rendering: Introduction*, volume 45 of *Springer Tracts in Advanced Robotics*. Springer Berlin Heidelberg, 2008.

[27] Bioness. L300 Foot Drop System walk more naturally with speed, stability and confidence. `http://www.bioness.com/Products/L300_for_Foot_Drop.php`. Accessed: 2016-02-04.

[28] Bioness. NESS H200 regain more natural hand function - with wireless freedom. `http://www.bioness.com/Products/H200_for_Hand_Paralysis.php`. Accessed: 2016-02-04.

[29] J. Boritz and K. S. Booth. A study of interactive 3D point location in a computer simulated virtual environment. *Proceedings of the ACM symposium on Virtual reality software and technology - VRST'97*, pages 181–187, 1997.

[30] W. F. Boron and E. L. Boulpaep. *Medical Physiology: A Cellular and Molecular Approach*. ClinicalKey, Saunders Elsevier, 2012.

[31] D. O. Bos. EEG-based emotion recognition: The Influence of Visual and Auditory Stimuli. `http://hmi.ewi.utwente.nl/verslagen/capita-selecta/CS-Oude_Bos-Danny.pdf`, 2008. Accessed: 2016-01-03.

[32] B. R. Bowman and L. L. Baker. Effects of waveform parameters on comfort during transcutaneous neuromuscular electrical stimulation. *Annals of Biomedical Engineering*, 13(1):59–74, 1985.

[33] D. A. Bowman, D. B. Johnson, and L. F. Hodges. Testbed evaluation of virtual environment interaction techniques. In *Proceedings of the ACM symposium on Virtual reality software and technology - VRST'99*, pages 26–33, ACM Press, 1999.

[34] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev. *3D User Interfaces: Theory and Practice*. Addison-Wesley, 2004.

[35] R. M. Bracewell, A. S. Wimperis, and A. M. Wing. Brain Mechanisms of Haptic Perception. In A. Bicchi, M. Buss, M. O. Ernst, and A. Peer, editors, *The Sense of Touch and its Rendering*, chapter Brain Mech, pages 25–37, Springer, 2008.

[36] M. M. Bradley and P. J. Lang. Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, 25(1):49 – 59, 1994.

[37] A. Brant, K. Mandell, R. S. Rader, A. Walsh, E. deJuan Jr, and R. Greenberg. Voice command and control medical care system , 1999. US Patent 5,970,457.

[38] S. Brave and A. Dahley. intouch: A medium for haptic interpersonal communication. In *Extended Abstracts of the ACM CHI'97 Conference on Human Factors in Computing Systems - CHI'97*, pages 363–364. ACM Press, 1997.

[39] M. Brewing. *Miha bodytec: Möglichkeiten des Sprungkrafttrainings im Handballsport*. AV Akademikerverlag, Kiel, 2009.

[40] S. Brewster and L. M. Brown. Tactons: Structured tactile messages for non-visual information display. In *Proceedings of the Fifth Conference on Australasian User Interface* AUIC'04, pages 15–23, Australian Computer Society, 2004.

[41] S. Brewster, F. Chohan, and L. Brown. Tactile feedback for mobile interactions. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI'07*, page 159, ACM Press, 2007.

[42] G. Bruder, F. Steinicke, and W. Stuerzlinger. Touching the void revisited: Analyses of touch behavior on and above tabletop surfaces. *Human-Computer Interaction - INTERACT 2013*, pages 278–296, 2013.

[43] G. Bruder, F. Steinicke, and W. Sturzlinger. To touch or not to touch? comparing 2d touch and 3d mid-air interaction on stereoscopic tabletop surfaces. In *Proceedings of the 1st symposium on Spatial user interaction - SUI'13*, page 9, ACM Press, 2013.

[44] O. K. Burmeister. HCI professionalism: Ethical concerns in usability engineering. *CRPIT'00: Selected papers from the second Australian Institute conference on Computer ethics*, pages 11–17, 2000.

[45] C. Busso, Z. Deng, S. Yildirim, M. Bulut, C. M. Lee, A. Kazemzadeh, S. Lee, U. Neumann, and S. Narayanan. Analysis of emotion recognition using facial expressions, speech and multimodal information. In *Proceedings of the 6th International Conference on Multimodal Interfaces* ICMI'04, pages 205–211, ACM Press, 2004.

[46] J. T. Cacioppo, R. E. Petty, M. E. Losch, and H. S. Kim. Electromyographic activity over facial muscle regions can differentiate the valence and intensity of affective reactions. *Journal of personality and social psychology*, 50(2):260, 1986.

[47] V. Carofiglio and F. Abbattista. A rough bci-based assessment of user's emotions for interface adaptation: Application to a 3d-virtual-environment exploration task. In *International Workshop on Intelligent User Interfaces*, 2013.

[48] G. Castellano, L. Kessous, and G. Caridakis. Affect and emotion in human-computer interaction. chapter Emotion Recognition Through Multiple Modalities: Face, Body Gesture, Speech, pages 92–103, Springer-Verlag, 2008.

[49] S. K. Centofanti. *Application of Muscle/Nerve Stimulation in Health and Disease*, chapter Electrical, pages 69–116. Springer Netherlands, 2008.

[50] D. Cernea, P. S. Olech, A. Ebert, and A. Kerren. EEG-based measurement of subjective parameters in evaluations. In *Communications in Computer and Information Science* volume 174 CCIS, pages 279–283, 2011.

[51] G. Chanel, J. Kronegg, D. Grandjean, and T. Pun. Emotion assessment: Arousal evaluation using EEG's and peripheral physiological signals. *Lecture Notes in Computer Science*, 4105 LNCS:530–537, 2006.

[52] A. Chang, S. O'Modhrain, R. Jacob, E. Gunther, and H. Ishii. ComTouch: design of a vibrotactile communication device. *Proceedings of the 4th conference on Designing interactive systems: processes, practices, methods, and techniques*, pages 312–320, 2002.

[53] A. Chang, B. Resner, B. Koerner, X. Wang, and H. Ishii. Lumitouch: An emotional communication device. In *CHI'01 Extended Abstracts on Human Factors in Computing Systems* CHI EA'01, pages 313–314, ACM Press, 2001.

[54] L. D. Chen, Y. Papelis, G. Waston, and D. Solis. NADS at the University of IOWA: A tool for driving safety research. In *Proceedings of the 1st human-centered transportation simulation conference*, 2001.

[55] W.-C. Chien, S. Diefenbach, and M. Hassenzahl. The whisper pillow: A study of technology-mediated emotional expression in close relationships. In *Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces* DPPI'13, pages 51–59, ACM Press, 2013.

[56] K. Chun, B. Verplank, F. Barbagli, and K. Salisbury. Evaluating haptics and 3D stereo displays using Fitts' law. In *Proceedings. Second International Conference on Creating, Connecting and Collaborating through Computing* volume 2, pages 53–58. IEEE, 2004.

[57] K. Church, E. Hoggan, and N. Oliver. A study of mobile mood awareness and communication through and. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* NordiCHI'10, pages 128–137, ACM Press, 2010.

[58] J. A. Coan and J. J. Allen. Frontal {EEG} asymmetry as a moderator and mediator of emotion. *Biological Psychology*, 67(1-2):7 – 50, 2004. Frontal {EEG} Asymmetry, Emotion, and Psychopathology.

[59] T. R. Coles, D. Meglan, and N. W. John. The role of haptics in medical training simulators: A survey of the state of the art. *IEEE Transactions on Haptics*, 4(1):51–66, 2011.

[60] B. Corbett, T. Yamaguchi, and S. Liu. Influence of haptic feedback on a pointing task in a haptically enhanced 3D virtual environment. *Human-Computer Interaction. (HCII)*, (1954):561–567, 2013.

[61] A. Cosgun, E. A. Sisbot, and H. I. Christensen. Guidance for human navigation using a vibro-Tactile belt interface and robot-like motion planning. In *Proceedings - IEEE International Conference on Robotics and Automation*, pages 6350–6355, 2014.

[62] Y. Cui, J. Kangas, J. Holm, and G. Grassel. Front-camera video recordings as emotion responses to mobile photos shared within close-knit groups. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'13, pages 981–990, ACM Press, 2013.

[63] D. P. Currier and R. Mann. Muscular strength development by electrical stimulation in healthy individuals. *Physical Therapy*, 63(6):915–921, 1983.

[64] Cyber Glove Systems. Products CyberGrasp. `http://www.cyberglovesystems.com/cybergrasp/`. Accessed: 2016-08-07.

[65] N. Dael, M. Mortillaro, and K. R. Scherer. Emotion expression in body action and posture. *Emotion*, 12(5):1085–1101, 2012.

[66] M. Dainton and B. Aylor. Patterns of communication channel use in the maintenance of long distance relationships. *Communication Research Reports*, 19(2):118–129, 2002.

[67] N.-T. Dang. A survey and classification of 3D pointing techniques. In *2007 IEEE International Conference on Research, Innovation and Vision for the Future*, pages 71–80. IEEE, 2007.

[68] C. Darwin. The expression of the emotions in man and animals. *The American Journal of the Medical Sciences*, 232(4):477, 1872.

[69] M. Davies. DUTY explores sonic possibilities and human limits, harnessing the bodily convulsions produced by electrical impulses. `http://www.michaeladavies.net/duty.html`. Accessed: 2016-02-04.

[70] M. Davies. GAME ON players from the audience use joysticks to control the movement of two boxers. `http://www.michaeladavies.net/game_on.html`. Accessed: 2016-02-04.

[71] S. L. Delp, P. Loan, C. Basdogan, and J. M. Rosen. Surgical simulation: An emerging technology for training in emergency medicine. *Presence: Teleoperators and Virtual Environments*, 6(2):147–159, 1997.

[72] J. G. S. Demers, J. M. A. Boelen, and I. P. W. Sinclair. Freedom 6s force feedback hand controller. *1st IFAC Workshop on Space Robotics - SPRO'98*, 98(1):19–22, 1998.

[73] A. K. Dey and E. de Guzman. From awareness to connectedness: The design and deployment of presence displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'06, pages 899–908, ACM Press, 2006.

[74] R. A. Deyo, N. E. Walsh, D. C. Martin, L. S. Schoenfeld, and S. Ramamurthy. A Controlled Trial of Transcutaneous Electrical Nerve Stimulation (TENS) and Exercise for Chronic Low Back Pain. *The New England Journal of Medicine*, 322(23):1627–1634, 1990.

[75] S. P. DiMaio and S. E. Salcudean. Needle insertion modeling and simulation. *IEEE Transactions on Robotics and Automation*, 19(5):864–875, 2003.

[76] A. Dix, J. Finlay, G. D. Abowd, and R. Beale. Human-Computer Interaction. *Human-Computer Interaction*, Third:834, 2004.

[77] C. Dodge. The bed: A medium for intimate communication. In *CHI'97 Extended Abstracts on Human Factors in Computing Systems* CHI EA'97, pages 371–372, ACM Press, 1997.

[78] A. Dollar and H. Herr. Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art. *IEEE Transactions on Robotics*, 24(1):144–158, 2008.

[79] R. J. Downey, M. J. Bellman, H. Kawai, C. M. Gregory, and W. E. Dixon. Comparing the induced muscle fatigue between asynchronous and synchronous electrical stimulation in able-bodied and spinal cord injured populations. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 23(6):964–972, 2015.

[80] S. E. Duclos, J. D. Laird, E. Schneider, M. Sexter, L. Stern, and O. Van Lighten. Emotion-specific effects of facial expressions and postures on emotional experience. *Journal of Personality and Social Psychology*, 57(1):100–108, 1989.

[81] P. Ekman. An argument for basic emotions. *Cognition & emotion*, 6(3-4):169–200, 1992.

[82] P. Ekman and W. V. Friesen. Head and body cues in the judgment of emotion: A reformulation. *Perceptual and motor skills*, 24(3):711–724, 1967.

[83] A. El Saddik, M. Orozco, M. Eid, and J. Cha. *Haptics Technologies*. Springer Series on Touch and Haptic Systems, Springer, 2011.

[84] A. Elsenaar. ARTIFACIAL an art and research project that investigates the computer-controlled human face. `http://artifacial.org/`. Accessed: 2016-02-04.

[85] A. Elsenaar and R. Scha. Electric body manipulation as performance art: A historical perspective. *Leonardo Music Journal*, 12:17–28, 2002.

[86] D. England. Whole body interaction: An introduction. In *Whole Body Interaction*, pages 1–5, Springer, 2011.

[87] M. Enzweiler and D. M. Gavrila. Monocular pedestrian detection: Survey and experiments. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 31(12):2179–2195, 2009.

[88] J. B. F. V. Erp, H. a. H. C. V. Veen, C. Jansen, and T. Dobbins. Waypoint navigation with a vibrotactile waist belt. *ACM Transactions on Applied Perception*, 2(2):106–117, 2005.

[89] F. Farbiz, Z. H. Yu, C. Manders, and W. Ahmad. An electrical muscle stimulation haptic feedback for mixed reality tennis game. In *ACM Conference on Computer Graphics and Interactive Techniques - Posters* SIGGRAPH'07. ACM Press, 2007.

[90] J. Fast. *Body language*. Simon and Schuster, 1988.

[91] V. Fialka-Moser, G. Ebenbichler, and O. Gillert. *Elektrotherapie*. Pflaum Physiotherapie, Richard Pflaum Vlg GmbH, 2005.

[92] B. R. Fick and J. B. Makinson. Hardiman I prototype for machine augmentation of human strength and endurance: Final report. *General Electric Company, Schenectady, NY, GE Tech. Rep. S-71-1056*, 1971.

[93] A. Filipovic, H. Kleinöder, U. Dörmann, and J. Mester. Electromyostimulation–a systematic review of the influence of training regimens and stimulation parameters on effectiveness in electromyostimulation training of selected strength parameters. *Journal of strength and conditioning research / National Strength & Conditioning Association*, 25(11):3218–38, 2011.

[94] A. Filipovic, H. Kleinöder, U. Dörmann, and J. Mester. Electromyostimulation–a systematic review of the effects of different electromyostimulation methods on selected strength parameters in trained and elite athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association*, 26(9):2600–14, 2012.

[95] P. M. Fitts. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology.*, 47:381–391, 1954.

[96] R. C. Fitzpatrick, D. L. Wardman, and J. L. Taylor. Effects of galvanic vestibular stimulation during human walking. *The Journal of Physiology*, 517(3):931–939, 1999.

[97] A. Fong, Z. Ashktorab, and J. Froehlich. Bear-with-me: An embodied prototype to explore tangible two-way exchanges of emotional language. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems* CHI EA'13, pages 1011–1016, ACM Press, 2013.

[98] J. Forsslund, M. Yip, and E.-L. Sallnäs. Woodenhaptics: A starting kit for crafting force-reflecting spatial haptic devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction - TEI'15*, pages 133–140, 2015.

[99] J. Freeman, G. Watson, Y. Papelis, T. Lin, A. Tayyab, R. Romano, and J. Kuhl. The iowa driving simulator: An implementation and application overview. *SAE International Congress and Exposition*, 1995.

[100] M. Frey. CabBoots: Shoes with integrated guidance system. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* TEI'07, pages 245–246. ACM Press, 2007.

[101] A. Frisoli, F. Salsedo, M. Bergamasco, B. Rossi, and M. C. Carboncini. A force-feedback exoskeleton for upper-limb rehabilitation in virtual reality. *Applied Bionics and Biomechanics*, 6(2):115–126, 2009.

[102] M. Fukumoto and T. Sugimura. Active click: Tactile feedback for touch panels. In *CHI'01 Extended Abstracts on Human Factors in Computing Systems* CHI EA'01, pages 121–122, ACM Press, 2001.

[103] S. Fukushima and H. Kajimoto. Palm touch panel: providing touch sensation through the device. *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, pages 79–82, 2011.

[104] M. Funk, R. Boldt, B. Pfleging, M. Pfeiffer, N. Henze, and A. Schmidt. Representing indoor location of objects on wearable computers with head-mounted displays. *Proceedings of the 5th Augmented Human International Conference on - AH'14*, pages 1–4, 2014.

[105] I. Galiana and M. Ferre, editors. *Multi-finger Haptic Interaction*. Springer Series on Touch and Haptic Systems, Springer London, 2013.

[106] L. Galvani. De viribus electricitatis in motu muscularis commentarius. *De Bononiensi Scientiarum et Artium Instituto atque Academia Commentarii*, 7:363–418, 1791.

[107] G. Garcia-Molina, T. Tsoneva, and A. Nijholt. Emotional brain–computer interfaces. *International journal of autonomous and adaptive communications systems*, 6(1):9–25, 2013.

[108] Geomagic Solutions. The geomagic touch haptic device. `http://geomagic.com/en/products/phantom-omni/overview`. Accessed: 2016-08-07.

[109] M. Germani, M. Mengoni, and M. Peruzzini. Electro-tactile device for material texture simulation. *International Journal of Advanced Manufacturing Technology*, 68(9-12):2185–2203, 2013.

[110] D. Geronimo, A. M. Lopez, A. D. Sappa, and T. Graf. Survey of pedestrian detection for advanced driver assistance systems. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 32(7):1239–1258, 2010.

[111] O. Gerovichev, P. Marayong, and A. M. Okamura. The effect of visual and haptic feedback on manual and teleoperated needle insertion. In *MICCAI'02: Proceedings of the 5th International Conference on Medical Image Computing and Computer-Assisted Intervention-Part I*, pages 147–154, 2002.

[112] M. Gföhler. Technical rebuilding of movement function using functional electrical stimulation. In *Biomimetics – Materials, Structures and Processes*, pages 219–247, Springer, 2011.

[113] J. J. Gibson. The senses considered as perceptual systems. *Journal of the British Society for Phenomenology*, 2(2):104–105, 1971.

[114] O. Gillert. *Elektrotherapie*. De Tijdstroom, 1984.

[115] D. Gooch and L. Watts. Yourgloves, hothands and hotmits: Devices to hold hands at a distance. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology* UIST'12, pages 157–166, ACM Press, 2012.

[116] S. Grange, F. Conti, P. Rouiller, P. Helmer, and C. Baur. Overview of the delta haptic device. In *Proceedings of EuroHaptics* volume 1, 2001.

[117] M. Grunwald, editor. *Human Haptic Perception: Basics and Applications*. Birkhaeuser Basel, 2008.

[118] H. Gunes and M. Piccardi. Bi-modal emotion recognition from expressive face and body gestures. *Journal of Network and Computer Applications*, 30(4):1334–1345, 2007.

[119] S. Gupta, D. Morris, S. N. Patel, and D. Tan. Airwave: Non-contact haptic feedback using air vortex rings. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing* UbiComp'13, pages 419–428. ACM Press, 2013.

[120] H2L. UnlimitedHand haptic game controller. http://unlimitedhand.com/. Accessed: 2016-02-04.

[121] S. Ha, L. Kim, S. Park, C. Jun, and H. Rho. Virtual prototyping enhanced by a haptic interface. *{CIRP} Annals - Manufacturing Technology*, 58(1):135–138, 2009.

[122] T. Hachisu and M. Fukumoto. Vacuumtouch: Attractive force feedback interface for haptic interactive surface using air suction. *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI'14*, pages 411–420, 2014.

[123] U. Hagn, M. Nickl, S. Jörg, G. Passig, T. Bahls, A. Nothhelfer, F. Hacker, L. Le-Tien, A. Albu-Schäffer, R. Konietschke, et al. The dlr miro: a versatile lightweight robot for surgical applications. *Industrial Robot: An International Journal*, 35(4):324–336, 2008.

[124] U. Hagn, T. Ortmaier, R. Konietschke, B. Kubler, U. Seibold, A. Tobergte, M. Nickl, S. Jorg, and G. Hirzinger. Telemanipulator for remote minimally invasive surgery. *Robotics Automation Magazine, IEEE*, 15(4):28–38, 2008.

[125] J. E. Hall. Guyton and Hall textbook of medical physiology. Elsevier Health Sciences, 2011.

[126] M. Halvey, G. Wilson, Y. Vazquez-Alvarez, S. Brewster, and S. Hughes. The effect of clothing on thermal feedback perception. *Proceedings of the 13th international conference on multimodal interfaces - ICMI'11*, page 217, 2011.

[127] Hang Zhang, S. Balasubramanian, Ruihua Wei, H. Austin, S. Buchanan, R. Herman, and Jiping He. RUPERT closed loop control design. In *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology* volume 2010, pages 3686–3689. IEEE, 2010.

[128] K. Hase and R. B. Stein. Turning strategies during human walking. *Journal of Neurophysiology*, 81:2914–2922, 1999.

[129] M. Hassenzahl, S. Heidecker, K. Eckoldt, S. Diefenbach, and U. Hillmann. All you need is love: Current strategies of mediating intimate relationships through technology. *ACM Transactions on Computer-Human Interaction*, 19(4):30:1–30:19 , 2012.

[130] C. Hasser and M. Daniels. Tactile feedback with adaptive controller for a force-reflecting haptic display. 1. Design. In *Proceedings of the 1996 Fifteenth Southern Biomedical Engineering Conference*, pages 526–529. IEEE, 1996.

[131] C. J. Hasser. Force-reflecting anthropomorphic hand masters. Technical report, DTIC Document, 1995.

[132] V. Hayward and J. M. Cruz-Hernandez. Tactile display device using distributed lateral skin stretch. *Proceedings of the haptic interfaces for virtual environment and teleoperator systems symposium*, pages 1309–1314, 2000.

[133] J. A. Healey and R. W. Picard. Detecting stress during real-world driving tasks using physiological sensors. *IEEE Transactions on Intelligent Transportation Systems*, 6(2):156–166, 2005.

[134] W. Heuten, N. Henze, S. Boll, and M. Pielot. Tactile wayfinder: A non-visual support system for wayfinding. In *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Extending Boundaries* NordiCHI'08, pages 172–181. ACM Press, 2008.

[135] C. Hick and J. Hartmann. *Intensivkurs Physiologie*. Elsevier, Urban & Fischer, 2006.

[136] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks. Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of vision*, 8(3):33.1–30, 2008.

[137] K. P. Hoffmann and R. Ruff. Flexible dry surface-electrodes for ecg long-term monitoring. In *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings*, pages 5739–5742, 2007.

[138] C. Holz, T. Grossman, G. Fitzmaurice, and A. Agur. Implanted user interfaces. *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI'12*, pages 503–512, 2012.

[139] K. Höök. Affective loop experiences — what are they? In *Proceedings of the 3rd International Conference on Persuasive Technology* PERSUASIVE'08, pages 1–12, Springer-Verlag, 2008.

[140] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda. Noncontact tactile display based on radiation pressure of airborne ultrasound. *IEEE Transactions on Haptics*, 3(3):155–165, 2010.

[141] K. Hoshino, M. Koge, T. Hachisu, R. Kodama, and H. Kajimoto. Jorro beat: Shower tactile stimulation device in the bathroom. In *Extended Abstracts of the ACM CHI'15 Conference on Human Factors in Computing Systems* volume 2, pages 1675–1680, 2015.

[142] S. Houben and N. Marquardt. Watchconnect: A toolkit for prototyping smartwatch-centric cross-device applications. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI'15*, pages 1247–1256, 2015.

[143] K. Huang, T. Starner, E. Do, G. Weiberg, D. Kohlsdorf, C. Ahlrichs, and R. Leibrandt. Mobile music touch: mobile tactile stimulation for passive learning. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI'10*, page 791, ACM Press, 2010.

[144] IFTech. ARAIG legion one kit. `https://araig.com/`. Accessed: 2016-02-04.

[145] Y. Imamura, H. Arakawa, S. Kamuro, K. Minamizawa, and S. Tachi. HAPMAP: Haptic walking navigation system with support by the sense of handrail. In *ACM Conference on Computer Graphics and Interactive Techniques SIGGRAPH'11 - Emerging Technologies*, 2011.

[146] International Organization for Standardization. *ISO 9241-9: Ergonomic requirements for office work with visual display terminals (VDTs) – Part 9: Requirements for non-keyboard input devices*. 2000.

[147] International Organization for Standardization. *ISO 9241-910: Ergonomics of human-system interaction – Part 910: Framework for tactile and haptic interaction*. 2011.

[148] K. Ito, T. Shioyama, and T. Kondo. Lower-limb joint torque and position controls by functional electrical stimulation (FES). *Complex Medical Engineering*, pages 239–249, 2007.

[149] R. Jacob, P. Mooney, and A. C. Winstanley. Guided by touch: tactile pedestrian navigation. In *Acta Psychologica* volume 124, pages 11–20. ACM, 2011.

[150] D. A. Jones, B. Bigland-Ritchie, and R. H. T. Edwards. Excitation frequency and muscle fatigue: Mechanical responses during voluntary and stimulated contractions. *Experimental Neurology*, 64(2):401–413, 1979.

[151] H. Kajimoto, M. Inami, N. Kawakami, and S. Tachi. SmartTouch - Augmentation of skin sensation with electrocutaneous display. In *Proceedings - 11th Symposium on*

Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS 2003, pages 40–46, 2003.

[152] H. Kajimoto, Y. Kanno, and S. Tachi. Forehead electro-tactile display for vision substitution. *Proceedings of EuroHaptics*, page 11, 2006.

[153] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi. Tactile feeling display using functional electrical stimulation. In *International Conference on Artificial Reality and Telexistence - ICAT'99*, page 133, 1999.

[154] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi. Electro-tactile display with tactile primary color approach. *Graduate School of Information and Technology, The University of Tokyo*, 2004.

[155] H. Kajimoto, N. Kawakami, S. Tachi, and M. Inami. Smarttouch: Electric skin to touch the untouchable. *IEEE Computer Graphics and Applications*, 24(1):36–42, 2004.

[156] H. Kajimoto, M. Suzuki, and Y. Kanno. HamsaTouch: Tactile vision substitution with smartphone and electro-tactile display. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems - CHI EA'14*, pages 1273–1278. ACM Press, 2014.

[157] S. Kammoun, C. Jouffrais, T. Guerreiro, H. Nicolau, and J. Jorge. Guiding blind people with haptic feedback. *Frontiers in Accessibility for Pervasive Computing - Pervasive'12*, 2012.

[158] O. B. Kaul, M. Pfeiffer, and M. Rohs. Follow the force: Steering the index finger towards targets using ems. In *Proceedings of the CHI'16 Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA'16*, pages 2526–2532, ACM Press, 2016.

[159] T. Kawabata, H. Satoh, and Y. Sankai. Working posture control of robot suit HAL for reducing structural stress. In *2009 IEEE International Conference on Robotics and Biomimetics, ROBIO'09*, pages 2013–2018, 2009.

[160] J. J. Kaye, M. K. Levitt, J. Nevins, J. Golden, and V. Schmidt. Communicating intimacy one bit at a time. In *CHI'05 Extended Abstracts on Human Factors in Computing Systems* CHI EA'05, pages 1529–1532, ACM Press, 2005.

[161] H. Kazerooni. The Berkeley Lower Extremity Exoskeleton Project. In *Springer Tracts in Advanced Robotics*, volume 21, pages 291–301, Springer, 2006.

[162] M. Kebaetse and S. Binder-Macleod. Strategies that improve human skeletal muscle performance during repetitive, non-isometric contractions. *Pflaegers Archiv - European Journal of Physiology*, 448(5):525–32, 2004.

[163] M. W. Keith, P. H. Peckham, G. B. Thrope, K. C. Stroh, B. Smith, J. R. Buckett, K. L. Kilgore, and J. W. Jatich. Implantable functional neuromuscular stimulation in the tetraplegic hand. *The Journal of hand surgery*, 14(3):524–530, 1989.

[164] H. Kern. Electrostimulation in sports and rehabilitation. *European Journal of Translational Myology*, 21(3-4):123, 2011.

[165] H. Kern. Functional electrical stimulation on paraplegic patients. *European Journal of Translational Myology*, 24(2), 2014.

[166] T. A. Kern. *Engineering Haptic Devices*. Springer Berlin Heidelberg, 2009.

[167] J. Kim, Y.-W. Park, and T.-J. Nam. Breathingframe: An inflatable frame for remote breath signal sharing. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* TEI'15, pages 109–112, ACM Press, 2015.

[168] J. Knutson and J. Chae. Functional electrical stimulation (FES) for upper limb function after stroke. In *Implantable Neuroprostheses for Restoring Function*, pages 307–329, Elsevier, 2015.

[169] H. Kobayashi, T. Aida, and T. Hashimoto. Muscle suit development and factory application. *International Journal of Automation Technology*, 3(6):709–715, 2009.

[170] Y. Kojima, Y. Hashimoto, S. Fukushima, and H. Kajimoto. Pull-Navi: A novel tactile navigation interface by pulling the ears. In *ACM Conference on Computer Graphics and Interactive Techniques - SIGGRAPH'09 - Emerging Technologies*, 2009.

[171] A. Kretz, R. Huber, and M. Fjeld. Force feedback slider (FFS): interactive device for learning system dynamics. In *Fifth IEEE International Conference on Advanced Learning Technologies - ICALT'05*, pages 457–458. IEEE, 2005.

[172] E. Kruijff, D. Schmalstieg, and S. Beckhaus. Using neuromuscular electrical stimulation for pseudo-haptic feedback. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology* VRST'06, pages 316–319, ACM Press, 2006.

[173] Y. Kurita, T. Ishikawa, and T. Tsuji. Stiffness display by muscle contraction via electric muscle stimulation. *IEEE Robotics and Automation Letters*, 1(2):1014–1019, 2016.

[174] J. D. Laird. The real role of facial response in the experience of emotion: A reply to Tourangeau and Ellsworth, and others. In *Journal of Personality and Social Psychology* volume 47, pages 909–917, American Psychological Association, 1984.

[175] M. Langheinrich, A. Schmidt, N. Davies, and R. José. A practical framework for ethics: The pd-net approach to supporting ethics compliance in public display studies. *Proceedings of the 2nd ACM International Symposium on Pervasive Displays - PerDis'13*, page 139, 2013.

[176] B. G. Lapatki. A thin, flexible multielectrode grid for high-density surface EMG. *Journal of Applied Physiology*, 96(1):327–336, 2003.

[177] J. Lazar, J. H. J. Feng, and H. Hochheiser. *Research methods in human-computer interaction*. John Wiley & Sons, 2010.

[178] D. Ledo, M. A. Nacenta, N. Marquardt, S. Boring, and S. Greenberg. The haptictouch toolkit: Enabling exploration of haptic interactions. In *Proceedings of the 6th International Conference on Tangible, Embedded and Embodied Interaction* TEI'12, pages 115–122, 2012.

[179] H. Lee, J. S. Kim, S. Choi, J. H. Jun, J. R. Park, A. H. Kim, H. B. Oh, H. S. Kim, and S. C. Chung. Mid-air tactile stimulation using laser-induced thermoelastic effects: The first study for indirect radiation. In *IEEE World Haptics Conference - WHC'15*, pages 374–380, 2015.

[180] V. Lehtinen, A. Oulasvirta, A. Salovaara, and P. Nurmi. Dynamic tactile guidance for visual search tasks. In *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology* UIST'12, page 445, ACM Press, 2012.

[181] I. Levin. Living apart together: A new family form. *Current Sociology*, pages 223–240, 2004.

[182] W. T. Liberson, H. J. Holmquest, D. Scot, and M. Dow. Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients. *Archives of physical medicine and rehabilitation*, 42:101–105, 1961.

[183] A. C. Liefbroer, A.-R. Poortman, and J. Seltzer. Why do intimate partners live apart? Evidence on LAT relationships across Europe. *Demographic Research*, 32(8):251–286, 2015.

[184] L. Liu, R. van Liere, C. Nieuwenhuizen, J.-B. J.-b. Martens, and R. V. Liere. Comparing aimed movements in the real world and in virtual reality. In *2009 IEEE Virtual Reality Conference*, pages 219–222. IEEE, 2009.

[185] Y. Liu, O. Sourina, and M. K. Nguyen. Real-time eeg-based human emotion recognition and visualization. In *International Conference on Cyberworlds (CW)*, pages 262–269, 2010.

[186] T. Lloyd, G. DE Domenico, G. R. Strauss, and K. Singer. A review of the use of electro-motor stimulation in human muscles. *The Australian journal of physiotherapy*, 32(1):18–30, 1986.

[187] H. S. Lo and S. Q. Xie. Exoskeleton robots for upper-limb rehabilitation: State of the art and future prospects. In *Medical Engineering and Physics* volume 34, pages 261–268, 2012.

[188] J. Löfhede, F. Seoane, and M. Thordstein. Textile electrodes for EEG recording–a pilot study. *Sensors*, 12(12):16907–19, 2012.

[189] P. Lopes and P. Baudisch. Muscle-propelled force feedback: Bringing force feedback to mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'13, pages 2577–2580. ACM Press, 2013.

[190] P. Lopes, L. Butzmann, and P. Baudisch. Muscle-propelled force feedback: Bringing force feedback to mobile devices using electrical stimulation. In *Proceedings of the 4th Augmented Human International Conference* AH'13, pages 231–232, ACM Press, 2013.

[191] P. Lopes, A. Ion, and P. Baudisch. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology - UIST'15*, pages 11–19. ACM Press, 2015.

[192] P. Lopes, A. Ion, W. Mueller, D. Hoffmann, P. Jonell, and P. Baudisch. Proprioceptive interaction. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI'15*, pages 939–948, ACM Press, 2015.

[193] P. Lopes, P. Jonell, and P. Baudisch. Affordance++: Allowing objects to communicate dynamic use. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI'15*, pages 2515–2524, 2015.

[194] P. Lopes, M. Pfeiffer, M. Rohs, and B. Baudisch. Let your body move: electrical muscle stimuli as haptics. *Proceedings of IEEE World Haptics*, 2015.

[195] P. Lopes, M. Pfeiffer, M. Rohs, and P. Baudisch. Hands-on introduction to interactive electrical muscle stimulation. In *Proceedings of the CHI'16 Conference Extended Abstracts on Human Factors in Computing Systems* CHI EA'16, pages 944–947, ACM Press, 2016.

[196] D. Lottridge, N. Masson, and W. Mackay. Sharing empty moments: Design for remote couples. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'09, pages 2329–2338, ACM Press, 2009.

[197] J. Luk, J. Pasquero, S. Little, K. MacLean, V. Levesque, and V. Hayward. A role for haptics in mobile interaction. In *Proceedings of the SIGCHI conference on Human Factors in computing systems - CHI'06*, page 171, ACM Press, 2006.

[198] G. Lyons, T. Sinkjaer, J. Burridge, and D. Wilcox. A review of portable FES-based neural orthoses for the correction of drop foot. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 10(4):260–279 , 2002.

[199] K. Lyytinen and Y. Yoo. Issues and challenges in ubiquitous computing. *Communications of the ACM*, 45(12):62–65, 2002.

[200] M. L. C. M. Carole Pistole, Amber Roberts. Attachment, relationship maintenance, and stress in long distance and geographically close romantic relationships. *Journal of Social and Personal Relationships*, 27(4):535–552 , 2010.

[201] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt. A survey on robotic devices for upper limb rehabilitation. *Journal of neuroengineering and rehabilitation*, 11(1):3, 2014.

[202] W. E. Mackay. Ethics, lies and videotape... In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 138–145, 1995.

[203] I. S. MacKenzie. Fitts' law as a research and design tool in Human-Computer Interaction. *Human-Computer Interaction*, 7(1):91–139, 1992.

[204] K. MaClean and J. Roderick. Smart tangible displays in the everyday world: a haptic door knob. In *IEEE International Conference on Advanced Intelligent Mechatronics - ASME'99*, pages 203–208. IEEE, 1999.

[205] T. Maeda, H. Ando, T. Amemiya, N. Nagaya, M. Sugimoto, and M. Inami. Shaking the world: Galvanic vestibular stimulation as a novel sensation interface. In *ACM Conference on Computer Graphics and Interactive Techniques - SIGGRAPH'05 - Emerging Technologies*, 2005.

[206] N. A. Maffiuletti, G. Cometti, I. G. Amiridis, A. Martin, M. Pousson, and J. C. Chatard. The effects of electromyostimulation training and basketball practice on muscle strength and jumping ability. *International Journal of Sports Medicine*, 21(6):437–443, 2000.

[207] E. Mampusti, J. Ng, J. Quinto, G. Teng, M. Suarez, and R. Trogo. Measuring academic affective states of students via brainwave signals. In *Third International Conference on Knowledge and Systems Engineering - KSE'11*, pages 226–231, 2011.

[208] S. D. o. E. Mann and C. E. at University of Toronto). Fluid Streams: Fountains that are keyboards with nozzle spray as keys that give rich tactile feedback and are more expressive and more fun than plastic keys. In *MULTIMEDIA'05: Proceedings of the 13th annual ACM international conference on Multimedia*, pages 181–190, 2005.

[209] J. Marescaux, J. Leroy, M. Gagner, F. Rubino, D. Mutter, M. Vix, S. E. Butner, and M. K. Smith. Transatlantic robot-assisted telesurgery. *Nature*, 413(6854):379–80, 2001.

[210] P. Marshall, S. Payandeh, and J. Dill. A study on haptic rendering in a simulated surgical training environment. *2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 241–247, 2006.

[211] K. Masani and M. R. Popovic. Functional electrical stimulation in rehabilitation and neurorehabilitation. In *Springer Handbook of Medical Technology*, pages 877–896, Springer Berlin Heidelberg, 2011.

[212] T. H. Massie and J. K. Salisbury. The phantom haptic interface: A device for probing virtual objects. *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 295–300, 1994.

[213] V. Mateevitsi, B. Haggadone, J. Leigh, B. Kunzer, and R. Kenyon. Sensing the environment through SpiderSense. *Proceedings of Augmented Human 2013*, pages 51–57, 2013.

[214] M. Mauri, V. Magagnin, P. Cipresso, L. Mainardi, E. N. Brown, S. Cerutti, M. Villamira, and R. Barbieri. Psychophysiological signals associated with affective states. In

Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE, pages 3563–3566, 2010.

[215] T. McDaniel, S. Krishna, V. Balasubramanian, D. Colbry, and S. Panchanathan. Using a haptic belt to convey non-verbal communication cues during social interactions to individuals who are blind. In *HAVE 2008 - IEEE International Workshop on Haptic Audio Visual Environments and Games Proceedings*, pages 13–18, 2008.

[216] Merriam-Webster. Haptic. `www.merriam-webster.com/dictionary/haptic`. Accessed: 2016-02-04.

[217] Merriam-Webster. Kinesthesia. `http://www.merriam-webster.com/dictionary/kinesthesia`. Accessed: 2016-07-07.

[218] miha bodytec GmbH. miha bodytec optimum use and the highest comfort. `http://www.miha-bodytec.com/`. Accessed: 2016-08-07.

[219] Y. Miyazaki and T. Kamiya. Pedestrian navigation system for mobile phones using panoramic landscape images. In *International Symposium on Applications and the Internet - SAINT'06*, pages 7 pp.–108. IEEE, 2006.

[220] R. Molich, B. Laurel, C. Snyder, W. Quesenbery, and C. E. Wilson. Ethics in HCI. In *CHI'01 extended abstracts on Human factors in computer systems - CHI'01*, page 217, ACM Press, 2001.

[221] Y. Monnai, K. Hasegawa, M. Fujiwara, K. Yoshino, S. Inoue, and H. Shinoda. Haptomime: Mid-air haptic interaction with a floating virtual screen. *Annual ACM Symposium on User Interface Software and Technology - UIST'14*, pages 663–667, 2014.

[222] A. Morrison, A. Oulasvirta, P. Peltonen, et al. Like bees around the hive: A comparative study of a mobile augmented reality map. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'09, pages 1889–1898. ACM Press, 2009.

[223] M. C. Morrissey. Electromyostimulation from a clinical perspective. A review. *Sports Med*, 6(1):29–41, 1988.

[224] S. Nanayakkara, E. Taylor, L. Wyse, and S. H. Ong. An enhanced musical experience for the deaf: Design and evaluation of a music display and a haptic chair. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'09, pages 337–346, ACM Press, 2009.

[225] M. Nancel, J. Wagner, E. Pietriga, O. Chapuis, and W. Mackay. Mid-air pan-and-zoom on wall-sized displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'11, pages 177–186, ACM Press, 2011.

[226] J. L. Nasar and D. Troyer. Pedestrian injuries due to mobile phone use in public places. *Accident Analysis and Prevention*, 57:91–95, 2013.

[227] T. Nef, M. Mihelj, G. Kiefer, C. Perndl, R. Müller, and R. Riener. ARMin - Exoskeleton for arm therapy in stroke patients. In *IEEE 10th International Conference on Rehabilitation Robotics, ICORR'07*, pages 68–74, 2007.

[228] F. N. Newell, M. O. Ernst, B. S. Tjan, and H. H. Bülthoff. Viewpoint dependence in visual and haptic object recognition. *Psychological Science*, 12(1):37–42, 2001.

[229] D. Nie, X.-W. Wang, L.-C. Shi, and B.-L. Lu. Eeg-based emotion recognition during watching movies. In *5th International IEEE/EMBS Conference on Neural Engineering (NER)*, pages 667–670, 2011.

[230] K. Nieuwenhuizen, J.-b. Martens, L. Liu, and R. Van Liere. Insights from dividing 3d goal-directed movements into meaningful phases. *IEEE Computer Graphics and Applications*, 29:44–53, 2009.

[231] G. Nikolakis, D. Tzovaras, S. Moustakidis, and M. G. Strintzis. Cybergrasp and phantom integration: Enhanced haptic access for visually impaired users. In *9th Conference Speech and Computer*, 2004.

[232] J. Nishida and K. Suzuki. biosync: Synchronous kinesthetic experience among people. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA'16*, pages 3742–3745, ACM Press, 2016.

[233] J. Nishida, K. Takahashi, and K. Suzuki. A wearable stimulation device for sharing and augmenting kinesthetic feedback. In *Proceedings of the 6th Augmented Human International Conference on - AH'15*, pages 211–212, ACM Press, 2015.

[234] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Design issues of mobile haptic interfaces. *Journal of Robotic Systems*, 20(9):549–556, 2003.

[235] M. Obrist, S. A. Seah, and S. Subramanian. Talking about tactile experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'13, pages 1659–1668. ACM Press, 2013.

[236] A. M. Okamura. Haptic feedback in robot-assisted minimally invasive surgery. *Curr Opin Urol*, 19(1):102–107, 2009.

[237] A. M. Okamura, J. T. Dennerlein, and R. D. Howe. Vibration feedback models for virtual environments. In *Proceedings of IEEE International Conference on Robotics and Automation* volume 1, pages 674–679. IEEE, 1998.

[238] S. Olberding, M. Wessely, and J. Steimle. PrintScreen: Fabricating Highly Customizable Thin-film Touch-Displays. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology - UIST'14*, pages 281–290, ACM Press, 2014.

[239] T. Ooka and K. Fujita. Virtual object manipulation system with substitutive display of tangential force and slip by control of vibrotactile phantom sensation. In *Haptics Symposium, 2010 IEEE*, pages 215–218, 2010.

[240] Y.-W. Park, K.-M. Baek, and T.-J. Nam. The roles of touch during phone conversations: Long-distance couples' use of poke in their homes. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'13, pages 1679–1688, ACM Press, 2013.

[241] Y.-W. Park, C.-Y. Lim, and T.-J. Nam. Cheektouch: An affective interaction technique while speaking on the mobile phone. In *CHI'10 Extended Abstracts on Human Factors in Computing Systems* CHI EA'10, pages 3241–3246, ACM Press, 2010.

[242] T. Partala, M. Jokiniemi, and V. Surakka. Pupillary responses to emotionally provocative stimuli. In *Proceedings of the 2000 Symposium on Eye Tracking Research & Applications* ETRA'00, pages 123–129, ACM Press, 2000.

[243] A. Pavlovych and W. Stuerzlinger. The tradeoff between spatial jitter and latency in pointing tasks. *Proceedings of the 1st ACM SIGCHI symposium on Engineering interactive computing systems - EICS'09*, page 187, 2009.

[244] V. M. Pawar and A. Steed. Profiling the behaviour of 3D selection tasks on movement time when using natural haptic pointing gestures. *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology - VRST'09*, page 79, 2009.

[245] A. Pease. *Body language: how to read other thoughts by their gestures*. Sheldon Press, 1981.

[246] P. H. Peckham and J. S. Knutson. Functional electrical stimulation for neuromuscular applications. *Annual review of biomedical engineering*, 7:327–60, 2005.

[247] R. L. Peiris, O. N. N. Fernando, and A. D. Cheok. Flexible, non-emissive textile display. In *Ambient Intelligence Lecture Notes in Computer Science, Volume 7040/2011*, pages 167–171, Springer Berlin Heidelberg, 2011.

[248] M. Perakakis and A. Potamianos. Affective evaluation of a mobile multimodal dialogue system using brain signals. In *Spoken Language Technology Workshop (SLT), IEEE*, pages 43–48, 2012.

[249] A. Perttula, A. Koivisto, R. Mäkelä, M. Suominen, and J. Multisilta. Social navigation with the collective mobile mood monitoring system. In *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments* MindTrek'11, pages 117–124, ACM Press, 2011.

[250] K. H. Petra Fagerberg, Anna Stahl. Designing gestures for affective input: An analysis of shape, effort and valence. In *Proceedings of the 2nd International Conference on Mobile and Ubiquitous Multimedia* MUM'03 Mobile and Ubiquitous Multimedia, pages 57–65, Linköping University Electronic Press, 2003.

[251] E. A. Pfeiffer. Electrical stimulation of sensory nerves with skin electrodes for research, diagnosis, communication and behavioral conditioning: A survey. *Medical & Biological Engineering*, 6(6):637–651, 1968.

[252] M. Pfeiffer and T. Dünte. Let Your Body Move ToolKit - repository. `https://bitbucket.org/MaxPfeiffer/letyourbodymove`. Accessed: 2016-08-08.

[253] M. Pfeiffer, T. Dünte, S. Schneegass, F. Alt, and M. Rohs. Cruise control for pedestrians: Controlling walking direction using electrical muscle stimulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI'15*, pages 2505–2514, 2015.

[254] M. Pfeiffer, L. D. L. Phan, and M. Rohs. User - attached haptic feedback on touch displays via ems. *IEEE World Haptics - WIP*, 2015.

[255] M. Pfeiffer and M. Rohs. Haptic feedback for wearables and textiles based on electrical muscle stimulation. In *Handbook of Smart Textiles and Textile Electronics*, Springer HCI Series.

[256] M. Pfeiffer, S. Schneegass, and F. Alt. Supporting interaction in public space with electrical muscle stimulation. In *Proceedings of the 2013 ACM Conference on Pervasive and Ubiquitous Computing Adjunct Publication* UbiComp'13 Adjunct, pages 5–8, ACM Press, 2013.

[257] M. Pfeiffer, S. Schneegass, F. Alt, and M. Rohs. A design space for electrical muscle stimulation feedback for free-hand interaction. In *Workshop on Assistive Augmentation at CHI 2014*, 2014.

[258] M. Pfeiffer, S. Schneegass, F. Alt, and M. Rohs. Let me grab this: A comparison of ems and vibration for haptic feedback in free-hand interaction. In *Proceedings of the 5th Augmented Human International Conference on - AH'14*, pages 48:1–48:8, 2014.

[259] M. Pfeiffer and W. Stuerzlinger. 3d virtual hand selection with ems and vibration feedback. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA'15*, pages 1361–1366, ACM Press, 2015.

[260] R. W. Picard and R. Picard. *Affective computing*, volume 252. MIT Press Cambridge, 1997.

[261] M. Pielot, B. Poppinga, and S. Boll. PocketNavigator: Vibro-tactile waypoint navigation for everyday mobile devices. *Proceedings of the 12th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI'10*, pages 423–426, 2010.

[262] M. Pielot, B. Poppinga, W. Heuten, and S. Boll. Pocketnavigator : Studying tactile navigation systems. *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI'12*, pages 3131–3139, 2012.

[263] H. Pohl, D. Becke, E. Wagner, M. Schrapel, and M. Rohs. Wrist Compression Feedback by Pneumatic Actuation. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA'15*, pages 315–318, ACM Press, 2015.

[264] H. Pohl and R. Murray-Smith. Focused and casual interactions: Allowing users to vary their level of engagement. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'13, pages 2223–2232. ACM Press, 2013.

[265] I. M. Pohl and L. Loke. Touch toolkit: A method to convey touch-based design knowledge and skills. In *Proceedings of the Eight International Conference on Tangible, Embedded, and Embodied Interaction - TEI'14*, pages 251–258, 2013.

[266] T. Pola and J. Vanhala. Textile electrodes in ecg measurement. In *3rd International Conference on Intelligent Sensors, Sensor Networks and Information - ISSNIP'7*, pages 635–639, 2007.

[267] J. L. Pons. *Wearable Robots: Biomechatronic Exoskeletons*. John Wiley & Sons, Ltd , 2008.

[268] M. R. Popovic, A. Curt, T. Keller, and V. Dietz. Functional electrical stimulation for grasping and walking: Indications and limitations. *Spinal Cord*, 39(8):403–412, 2001.

[269] J. P. Porcari, K. P. MCLEAN, C. Foster, T. Kernozek, B. Crenshaw, and C. SWENSON. Effects of electrical muscle stimulation on body composition, muscle strength, and physical appearance. *The Journal of Strength & Conditioning Research*, 16(2):165–172, 2002.

[270] I. Poupyrev, T. Ichikawa, S. Weghorst, and M. Billinghurst. Egocentric object manipulation in virtual environments: Empirical evaluation of interaction techniques. *Computer Graphics Forum*, 17(3):41–52, 1998.

[271] A. Prochazka, M. Gauthier, M. Wieler, and Z. Kenwell. The Prochazka1997: An electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia. *Archives of Physical Medicine and Rehabilitation*, 78(6):608–614, 1997.

[272] Promedics Healthcare. Prorelax TENS+EMS DUO http://www.prorelax.com/. Accessed: 2016-08-07.

[273] D. Prutchi and M. Norris. *Design and development of medical electronic instrumentation: a practical perspective of the design, construction, and test of medical devices*. John Wiley & Sons, 2005.

[274] M. Ptito, S. M. Moesgaard, A. Gjedde, and R. Kupers. Cross-modal plasticity revealed by electrotactile stimulation of the tongue in the congenitally blind. *Brain*, 128(3):606–614, 2005.

[275] J. P. Reilly. *Applied Bioelectricity: from Electrical Stimulation to Electropathology*, volume 20. Springer, 2009.

[276] H. Richter, F. Manke, and M. Seror. Liquitouch: Liquid as a medium for versatile tactile feedback on touch surfaces. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction* TEI'13, pages 315–318, ACM Press, 2013.

[277] J. Riskind and C. Gotay. Physical posture: Could it have regulatory or feedback effects on motivation and emotion? *Motivation and Emotion*, 6(3):273–298, 1982.

[278] D. C. Rodger, A. J. Fong, W. Li, H. Ameri, A. K. Ahuja, C. Gutierrez, I. Lavrov, H. Zhong, P. R. Menon, E. Meng, J. W. Burdick, R. R. Roy, V. R. Edgerton, J. D. Weiland, M. S. Humayun, and Y. C. Tai. Flexible parylene-based multielectrode array technology for high-density neural stimulation and recording. *Sensors and Actuators, B: Chemical*, 132(2):449–460, 2008.

[279] J. Rodriguez and A. Shahrokni. One-dimensional force feedback slider: Digital platform. In *IEEE VR 2007 Workshop on Mixed Reality User Interfaces: Specification, Authoring, Adaptation*, pages 47–51, 2007.

[280] C. Rotsch, S. Hanus, D. Schwabe, H. Oschatz, A. Neudeck, and U. Möhring. Intelligent textiles and trends. In *Springer Handbook of Medical Technology*, pages 1321–1336, Springer, 2011.

[281] S. Rümelin, E. Rukzio, and R. Hardy. Naviradar: A novel tactile information display for pedestrian navigation. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology - UIST'11*, pages 293–302. ACM Press, 2011.

[282] J. A. Russell. A circumplex model of affect. *Journal of Personality and Social Psychology*, 39(6):1161–1178, 1980.

[283] J. J. Sacco, J. Botten, F. Macbeth, A. Bagust, and P. Clark. The average body surface area of adult cancer patients in the uk: A multicentre retrospective study. *PLoS ONE*, 5(1):e8933, 2010.

[284] A. Sahami, P. Holleis, A. Schmidt, and J. Häkkilä. Rich tactile output on mobile devices. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* volume 5355 LNCS, pages 210–221, 2008.

[285] B. Saket, C. Prasojo, Y. Huang, and S. Zhao. Designing an effective vibration-based notification interface for mobile phones. *Proceedings of the 2013 conference on Computer supported cooperative work - CSCW'13*, page 149, 2013.

[286] Y. Sankai. Leading edge of cybernics: Robot suit HAL. In *2006 SICE-ICASE International Joint Conference*, 2006.

[287] A. Savitzky and M. J. Golay. Smoothing and differentiation of data by simplified least squares procedures. *Analytical chemistry*, 36(8):1627–1639, 1964.

[288] A. Schaefer, F. Nils, X. Sanchez, and P. Philippot. Assessing the effectiveness of a large database of emotion-eliciting films: A new tool for emotion researchers. *Cognition and Emotion*, 24(7):1153–1172, 2010.

[289] T. Schlömer, B. Poppinga, N. Henze, and S. Boll. Gesture recognition with a Wii controller. In *Proceedings of the 2nd International Conference on Tangible and Embedded Interaction* TEI'08, pages 11–14, ACM Press, 2008.

[290] A. Schmidt. Ubiquitous computing: Are we there yet? *Computer*, 43(2):95–97, 2010.

[291] J. J. Scott and R. Gray. A comparison of tactile, visual, and auditory warnings for rear-end collision prevention in simulated driving. *Human factors*, 50(2):264–275, 2008.

[292] W. Seager and D. S. Fraser. Comparing physical, automatic and manual map rotation for pedestrian navigation. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI'07*, pages 767–776. ACM Press, 2007.

[293] Y. Sekiguchi, K. Hirota, and M. Hirose. The design and implementation of ubiquitous haptic device. In *Proceedings - 1st Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems; World Haptics Conference, WHC 2005*, pages 527–528, 2005.

[294] Y. Shi, N. Ruiz, R. Taib, E. Choi, and F. Chen. Galvanic skin response (gsr) as an index of cognitive load. In *CHI'07 Extended Abstracts on Human Factors in Computing Systems* CHI EA'07, pages 2651–2656, ACM Press, 2007.

[295] K. a. Sluka and D. Walsh. Transcutaneous electrical nerve stimulation: basic science mechanisms and clinical effectiveness. *The journal of pain : official journal of the American Pain Society*, 4(3):109–121, 2003.

[296] G. Smith, W. Stuerzlinger, T. Salzman, B. Watson, and J. Buchanan. 3d scene manipulation with 2d devices and constraints. In *Graphics interface* volume 1, pages 135–142, 2001.

[297] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr. AIREAL: Interactive tactile experiences in free air. *ACM Trans. Graph.*, 32(4):134:1–134:10 , 2013.

[298] M. A. Srinivasan and R. H. Lamotte. Tactual discrimination of softness. *Journal of Neurophysiology*, 73(1):88–101, 1995.

[299] Statistisches-Bundesamt. Statistik der schwerbehinderten Menschen. Technical report, Statistisches Bundesamt, 2013.

[300] E. Steinbach, S. Hirche, J. Kammerl, I. Vittorias, and R. Chaudhari. Haptic data compression and communication. *Signal Processing Magazine, IEEE*, 28(1):87–96, 2011.

[301] F. Steinicke, G. Bruder, L. Kohli, J. Jerald, and K. Hinrichs. Taxonomy and implementation of redirection techniques for ubiquitous passive haptic feedback. In *2008 International Conference on Cyberworlds*, pages 217–223. IEEE, 2008.

[302] Stelarc. Ping Body an internet actuated & uploaded performance. http://www.stelarc.va.com.au/pingbody/index.html,http://www.medienkunstnetz.de/works/ping-body/. Accessed: 2016-11-11.

[303] R. J. Stone. Haptic feedback: A brief history from telepresence to virtual reality. In *Haptic Human-Computer Interaction*, pages 1–16, Springer, 2001.

[304] M. Stoppa and A. Chiolerio. Wearable electronics and smart textiles: A critical review. *Sensors (Switzerland)*, 14(7):11957–11992, 2014.

[305] P. Strojnik, A. Kralj, and I. Ursic. Programmed six-channel electrical stimulator for complex stimulation of leg muscles during walking. *IEEE Transactions on Biomedical Engineering*, BME-26(2):112–116, 1979.

[306] P. Ström, L. Hedman, L. Särnå, A. Kjellin, T. Wredmark, and L. Felländer-Tsai. Early exposure to haptic feedback enhances performance in surgical simulator training: a prospective randomized crossover study in surgical residents. *Surgical endoscopy and other interventional techniques*, 20(9):1383–1388, 2006.

[307] W. Stuerzlinger. Considerations for targets in 3D pointing experiments. *Surfaces for Interaction with Stereoscopic 3D - ISIS3D*, 2013.

[308] B. Sumner, C. Mancuso, and R. Paradiso. Performances evaluation of textile electrodes for EMG remote measurements. *Proceedings of Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*, 2013:6510–3, 2013.

[309] P. Sundström, A. Ståhl, and K. Höök. In situ informants exploring an emotional mobile messaging system in their everyday practice. *International Journal of Human-Computer Studies*, 65(4):388–403 , 2007.

[310] C. Swindells, K. E. MacLean, K. S. Booth, and M. J. Meitner. Exploring affective design for physical controls. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI'07*, page 933, ACM Press, 2007.

[311] C. Swindells, A. Unden, and T. Sang. TorqueBAR: An ungrounded haptic feedback device. In *Proceedings of the 5th international conference on Multimodal interfaces - ICMI'03*, page 52, ACM Press, 2003.

[312] K. Takahashi. Remarks on emotion recognition from biopotential signals. In *Proceedings of the 2nd International Conference on Autonomous Robots and Agents*, pages 186–191, 2004.

[313] Y. Takeuchi. Gilded Gait: Reshaping the urban experience with augmented footsteps. In *Proceedings of the 23th Annual ACM Symposium on User Interface Software and Technology - UIST'10*, pages 185–188. ACM Press, 2010.

[314] E. Tamaki, T. Miyaki, and J. Rekimoto. Possessedhand: A hand gesture manipulation system using electrical stimuli. In *Proceedings of the 1st Augmented Human International Conference* AH'10, pages 2:1–2:5, ACM Press, 2010.

[315] E. Tamaki, T. Miyaki, and J. Rekimoto. Possessedhand: Techniques for controlling human hands using electrical muscles stimuli. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* CHI'11, pages 543–552, ACM Press, 2011.

[316] Y. Tanaka, K. Yuka, Y. Fukui, J. Yamashita, and N. Nakamura. Mobile torque display and haptic characteristics of human palm. In *International Conference on Artificial Reality and Telexistence - ICAT'01*, pages 115–120, 2001.

[317] R. H. Taylor, A. Menciassi, G. Fichtinger, and P. Dario. *Medical Robotics and Computer-Integrated Surgery*, chapter Medical Ro, pages 1199–1222. Springer Berlin Heidelberg, 2008.

[318] R. J. Teather, A. Pavlovych, W. Stuerzlinger, and I. S. MacKenzie. Effects of tracking technology, latency, and spatial jitter on object movement. *2009 IEEE Symposium on 3D User Interfaces*, pages 43–50, 2009.

[319] R. J. Teather and W. Stuerzlinger. Pointing at 3D targets in a stereo head-tracked virtual environment. In *IEEE Symposium on 3D User Interfaces - 3DUI'11*, pages 87–94. IEEE, 2011.

[320] R. J. Teather and W. Stuerzlinger. Pointing at 3d target projections with one-eyed and stereo cursors. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI'13*, page 159, 2013.

[321] R. J. Teather and W. Stuerzlinger. Visual aids in 3D point selection experiments. In *Proceedings of the 2nd ACM symposium on Spatial user interaction - SUI'14*, pages 127–136, ACM Press, 2014.

[322] Tesla Studios. Teslasuit virtual reality suit. `http://www.teslastudios.co.uk/teslasuit`. Accessed: 2016-02-04.

[323] N. Tsagarakis, D. Caldwell, and G. Medrano-Cerda. A 7 DOF pneumatic muscle actuator (pMA) powered exoskeleton. In *8th IEEE International Workshop on Robot and Human Interaction. RO-MAN'99*, pages 327–333. IEEE, 1999.

[324] D. Tsetserukou and A. Neviarouskaya. World's first wearable humanoid robot that augments our emotions. In *Proceedings of the 1st Augmented Human International Conference* AH'10, pages 8:1–8:10, ACM Press, 2010.

[325] K. Tsukada and M. Yasumura. Activebelt: Belt-type wearable tactile display for directional navigation. In *Ubiquitous Computing*, volume 3205, pages 384–399, Springer, 2004.

[326] K. Tsukada and M. Yasumura. Activebelt: Belt-type wearable tactile display for directional navigation. In *Proceedings of the 2004 ACM international joint conference on pervasive and ubiquitous computing*, UbiComp'04, pages 384–399, Springer, 2004.

[327] M. Ueberle, N. Mock, and M. Buss. VISHARD10, a novel hyper-redundant haptic interface. In *Proceedings of 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems - HAPTICS'04*, pages 58–65, 2004.

[328] D. Valkov, F. Steinicke, G. Bruder, and K. Hinrichs. 2d touching of 3d stereoscopic objects. *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI'11*, page 1353, 2011.

[329] M. Valtin, T. Schauer, C. Behling, M. Daniel, and M. Weber. Combined stimulation and measurement system for array electrodes. In *BIODEVICES*, pages 345–349, 2012.

[330] A. van Boxtel. Skin resistance during square-wave electrical pulses of 1 to 10 mA. *Medical & biological engineering & computing*, (6):679–87, 1977.

[331] R. Q. Van der Linde, P. Lammertse, E. Frederiksen, and B. Ruiter. The hapticmaster, a new high-performance haptic interface. In *Proceedings of EuroHaptics*, pages 1–5, 2002.

[332] J. B. F. van Erp, K.-U. Kyung, S. Kassner, J. Carter, S. Brewster, G. Weber, and I. Andrew. Setting the standards for haptic and tactile interactions: ISO's work. In *Haptics: Generating and Perceiving Tangible Sensations*, pages 353–358, Springer, 2010.

[333] D. W. F. van Krevelen and R. Poelman. A Survey of Augmented Reality Technologies, Applications and Limitations. *The International Journal of Virtual Reality*, 9(2):1–20, 2010.

[334] D. Vogel and R. Balakrishnan. Occlusion-aware interfaces. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI'10*, page 263, ACM Press, 2010.

[335] S. A. Wall and W. S. Harwin. Quantification of the effects of haptic feedback during motor skills tasks in a simulated environment. In *Proceedings of Second PHANToM users research symposium*, 2000.

[336] S. A. Wall, K. Paynter, A. M. Shillito, M. Wright, S. Scali, J. Clerk, and M. Building. The effect of haptic feedback and stereo graphics in a 3d target acquisition task. *Proceedings of EuroHaptics*, pages 23–29, 2002.

[337] H. G. Wallbott. Bodily expression of emotion. *European Journal of Social Psychology*, 28(6):879–896, 1998.

[338] D. Wang, J. Xiao, and Y. Zhang. *Haptic Rendering for Simulation of Fine Manipulation*. Springer Berlin Heidelberg, 2014.

[339] A. R. Ward and N. Shkuratova. Russian electrical stimulation: the early experiments. *Physical therapy*, 82(10):1019–1030, 2002.

[340] R. Watanabe, T. Hachisu, M. Sato, S. Fukushima, H. Kajimoto, N. Saito, and Y. Mori. Development of roller-type itch-relief device employing alternating hot and cold stimuli. In *Proceedings of the 4th Augmented Human International Conference* AH'13, pages 43–46, ACM Press, 2013.

[341] D. Watson, L. A. Clark, and A. Tellegen. Development and Validation of Brief Measures of Positive and Negative Affect. *The PANAS Scales*, 54:1063–1070, 1988.

[342] Wearable Life Science. Antelope Suit the new era of fitness. `http://www.antelope.club/`. Accessed: 2016-02-04.

[343] E. H. Weber. *Die Lehre vom Tastsinne und Gemeingefühle auf Versuche gegründet*. Friedrich Vieweg und Sohn, 1 edition, 1851.

[344] M. Weiser. The computer for the 21st century. *Scientific american*, 265(3):94–104, 1991.

[345] M. Weiss, C. Wacharamanotham, S. Voelker, and J. Borchers. Fingerflux: Near-surface haptic feedback on tabletops. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology - UIST'11*, page 615, ACM Press, 2011.

[346] J. Werner, R. Wettach, and E. Hornecker. United-pulse: Feeling your partner's pulse. In *Proceedings of the 10th International Conference on Human-Computer Interaction with Mobile Devices and Services* MobileHCI'08, pages 535–538, ACM Press, 2008.

[347] R. Wettach, C. Behrens, A. Danielsson, and T. Ness. A thermal information display for mobile applications. In *Proceedings of the 9th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI'07*, pages 182–185, 2007.

[348] M. J. Willis and C. M. Jones. Emotishare: Emotion sharing on mobile devices. In *Proceedings of the 26th Annual BCS Interaction Specialist Group Conference on People and Computers* BCS-HCI'12, pages 292–297, British Computer Society, 2012.

[349] G. Wilson, S. a. Brewster, M. Halvey, and S. a. Hughes. Thermal icons: Evaluating structured thermal feedback for mobile interaction. *Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI'12*, pages 309–312, 2012.

[350] G. Wilson, M. Halvey, S. Brewster, and S. Hughes. Some like it hot: Thermal feedback for mobile devices. *Proceedings of the SIGCHI conference on Human Factors in Computing Systems - CHI'11*, pages 2555–2564, 2011.

[351] J. Wilson, B. N. Walker, J. Lindsay, C. Cambias, and F. Dellaert. Swan: System for wearable audio navigation. In *11th IEEE International Symposium on Wearable Computers*, pages 91–98, 2007.

[352] C. Winkler, J. Seifert, D. Dobbelstein, and E. Rukzio. Pervasive Information through Constant Personal Projection : The Ambient Mobile Pervasive Display (AMP-D).

Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pages 4117–4126, 2014.

[353] K. Wolf and T. Bäder. Illusion of surface changes induced by tactile and visual touch feedback. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA'15*, pages 1355–1360, ACM Press, 2015.

[354] XBody Hungary Kft. XBody Hungary Kft exclusive manufacturer of xbody newave ems devices! `http://www.xbodyworld.com/`. Accessed: 2016-02-04.

[355] K. Yamamoto, K. Hyodo, M. Ishii, and T. Matsuo. Development of power assisting suit for assisting nurse labor., 2001.

[356] N. Yannier, A. Israr, J. F. Lehman, and R. L. Klatzky. Feelsleeve: Haptic feedback to enhance early reading. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI'15*, pages 1015–1024, 2015.

[357] H. Yano, M. Yoshie, and H. Iwata. Development of a non-grounded haptic interface using the gyro effect. In *Proceedings - 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS 2003*, pages 32–39, 2003.

[358] K. Yatani, D. Gergle, and K. Truong. Investigating effects of visual and tactile feedback on spatial coordination in collaborative handheld systems. *Proceedings of the ACM Conference on Computer Supported Cooperative Work - CSCW'12*, page 661, 2012.

[359] K. Yatani and K. N. Truong. Semfeel: A user interface with semantic tactile feedback for mobile touch-screen devices. *System*, pages 111–120, 2009.

[360] Z. Zeng, M. Pantic, G. I. Roisman, and T. S. Huang. A survey of affect recognition methods: Audio, visual, and spontaneous expressions. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 31(1):39–58, 2009.

[361] D. Zhang, T. H. Guan, F. Widjaja, and W. T. Ang. Functional electrical stimulation in rehabilitation engineering: A survey. In *Proceedings of the 1st International Convention on Rehabilitation Engineering & Assistive Technology: In Conjunction with 1st Tan Tock Seng Hospital Neurorehabilitation Meeting* i-CREATe'07, pages 221–226, ACM Press, 2007.

[362] K. Zilles and B. N. Tillmann. *Anatomie*. Springer-Lehrbuch, Springer Berlin Heidelberg, 2010.

[363] P. M. Zoll, H. A. Frank, and A. J. Linenthal. Implantable cardiac pacemakers. *Annals of the New York Academy of Sciences*, 111(3):1068–1074, 1964.

Appendix

Appendix I Study Forms

Studien-Nr.: ___________

Überblick über die Studie: Haptische Feedback-Methoden

Bitte lesen Sie diesen Überblick sorgfältig durch. Bitte fragen Sie nach, wenn etwas unklar sein sollte. Dieser Überblick dient dazu, Ihnen das Experiment vorzustellen und Sie auf Ihre Rechte als freiwilliger Versuchsteilnehmer hinzuweisen.

Vielen Dank, dass Sie an dieser Studie teilnehmen. Wir erheben Daten von mehreren Teilnehmern. Diese Daten helfen uns, interaktive Systeme zu evaluieren und zu verbessern. Es geht um die Evaluierung des Systems und nicht um Ihr individuelles Abschneiden im Experiment. Die Daten werden in der Regel gemittelt und der Trend aller Daten ist für unsere Forschung von Interesse.

In dieser Studie untersuchen wir, inwiefern zielgerichtete Bewegungen, wie sie beim Drücken von Tasten auf einem Tastenfeld auftreten, mit Hilfe von haptischem Feedback unterstützt werden können. Das haptische Feedback wird dabei von einem Vibrationsmotor oder von einem Massagegerät erzeugt. Das Massagegerät gibt durch Haftelektroden elektrische Signale an die Muskulatur, um diese zu aktivieren.

Die Studie besteht aus mehreren Teilen. Zunächst werden Sie gebeten, einen Fragebogen auszufüllen, in dem u.a. Alter, Geschlecht und Computerkenntnisse erfragt werden. Im zweiten Teil wird das EMS-Gerät kalibriert und Sie werden einige Probedurchgänge absolvieren können. Im Hauptteil werden Sie gebeten, eine Reihe von Interaktionsaufgaben zu lösen. Ihre Aktivität (Eingaben, Handbewegungen) wird von einem Computer aufgezeichnet und vom Experimentator beobachtet. Darüber hinaus wird das Experiment – wenn Sie einverstanden sind – mit einer Videokamera aufgezeichnet. Nachdem Sie die Aufgaben erledigt haben, werden Sie gebeten, einen kurzen Fragebogen über den Test auszufüllen.

Die Studie wird insgesamt ca. 60 Minuten dauern.

Sie haben das Recht die Teilnahme an diesem Versuch jederzeit und ohne Angabe von Gründen abzubrechen. Machen Sie insbesondere bei Unwohlsein von diesem Recht Gebrauch.

Bitte lesen Sie nun sorgfältig die Einverständniserklärung und die dort beschriebenen Hinweise.

Studien-Nr.: ___________

Einverständniserklärung zur Studie: Haptische Feedback-Methoden

Diese Studie wird am Fachgebiet Mensch-Computer-Interaktion der Leibniz Universität Hannover durchgeführt. Der Experimentator ist Max Pfeiffer.

Ich habe den Überblick über die Studie gelesen und verstanden. Ich nehme freiwillig und ohne Vergütung an dieser Studie teil. Ich habe das Recht die Teilnahme jederzeit und ohne Angabe von Gründen abzubrechen.

Wichtig! Unter den folgenden Umständen darf ich **nicht** an der Studie teilnehmen:

- Bei Schädigung sensorischer Nerven oder überempfindlicher Haut
- Bei jeglichen Herzerkrankungen / Herzschrittmachern
- Bei vermuteter oder diagnostizierter Epilepsie oder Diabetes
- Während der Menstruation oder der Schwangerschaft
- Nach kürzlich erfolgter Operation
- Bei einer Tendenz zur Blutung, z.B. nach akuten Verletzungen oder Frakturen
- Bei einer Krebserkrankung

[ ] Keiner dieser Punkte trifft auf mich zu.

[ ] Mindestens einer der Punkte trifft auf mich zu.

Ich wurde darüber informiert, dass während der Studie Daten aufgezeichnet, elektronisch gespeichert und zur Auswertung der Studie herangezogen werden. Die aufgezeichneten Daten werden ausschließlich für die wissenschaftliche Nutzung anonymisiert ausgewertet. Damit bin ich

[ ] einverstanden.

[ ] nicht einverstanden.

Ich habe momentan keine körperlichen Beschwerden oder Schmerzen. Dies

[ ] trifft zu.

[ ] trifft nicht zu.

Ich habe die oben genannten Risiken zur Kenntnis genommen und fühle mich gesundheitlich in der Lage, an der Studie teilzunehmen.

Vorname: ______________________ Nachname: ______________________

Ort, Datum ______________________ Unterschrift: ______________________

Email: ______________________ Telefon: ______________________

Studien-Nr.: ___________

Einverständniserklärung zu Foto-, Video- und Audioaufnahmen

Durch Unterzeichnung dieser Einverständniserklärung zu Foto-, Video- und Audioaufnahmen gebe ich dem Fachgebiet Mensch-Computer-Interaktion der Leibniz Universität Hannover die Erlaubnis, Foto-, Video- und Audioaufnahmen von mir, die während meiner Studienteilnahme angefertigt worden sind, zu nutzen. Diese Erlaubnis gebe ich freiwillig.

Für dieses Einverständnis erhalte ich weder jetzt noch in der Zukunft eine Vergütung. Die Aufnahmen dürfen ausschließlich zu wissenschaftlichen Zwecken und nicht zu kommerziellen Zwecken verwendet werden.

Die Aufnahmen dürfen intern im Rahmen der Analyse des Experiments ausgewertet werden. Die ausgewerteten Beobachtungen werden nur anonymisiert veröffentlicht. Damit bin ich

[ ] einverstanden.

[ ] nicht einverstanden.

Die Aufnahmen dürfen als Ganzes oder in Teilen zusammen mit anderen Aufnahmen im wissenschaftlichen Kontext (z.B. auf Konferenzen, in der universitären Lehre oder Online) gezeigt werden. Damit bin ich

[ ] einverstanden.

[ ] nicht einverstanden.

Vorname: ________________________ Nachname: ________________________

Ort, Datum ________________________ Unterschrift: ________________________

Teilnehmer-Nr.: ___________ Studien-Nr.: ___________

Allgemeine Angaben

A.1 Datum: _______________ Uhrzeit: _______________

A.2 Geschlecht: [ ] weiblich [ ] männlich [ ] andere

A.3 Alter: _______________

A.4 Seit wann sind Sie heute wach? _______________

A.5 Wie lange haben Sie letzte Nacht geschlafen? _______________

A.6 Haben Sie Erfahrungen mit 3D-Technologien, wie z.B. 3D-Kinofilme oder 3D-Computerspiele?

[ ] ja
[ ] nein

Wenn ja, welche? ____

A.7 Haben Sie Erfahrungen mit haptischen Ausgabetechnologien?

[ ] ja
[ ] nein

Wenn ja, welche? ____

A.8 Haben Sie Erfahrungen mit elektrischer Muskelstimulation (EMS)?

[ ] ja
[ ] nein

Wenn ja, welche? ____

Bitte schalten Sie jetzt Ihr Handy aus. Bitte fragen Sie, wenn etwas unklar ist oder sonst noch etwas ist. Vielen Dank!

Studien-Nr.: ___________

Instruktionen zur Studie: Haptische Feedback-Methoden

In diesem Versuch geht es darum, virtuelle Kugeln so präzise und schnell wie möglich auszuwählen. Die Kugeln werden mit einem 3D-Projektor auf die Wand vor Ihnen projiziert. Sie stehen an einer markierten Stelle vor der Wand und tragen eine Shutterbrille für den 3D-Effekt. Außerdem werden EMS-Elektroden am Arm befestigt, mit denen haptisches Feedback erzeugt wird, so dass Sie spüren können, wenn Sie nach einer virtuellen Kugel greifen oder diese berühren. Am Zeigefinger der dominanten Hand (rechte Hand bei Rechtshändern) wird ein Marker zur Positionserkennung und ein kleiner Vibrationsmotor befestigt. In der anderen Hand halten Sie einen Knopf.

Der Zeigefinger der dominanten Hand soll von der zuletzt ausgewählten Kugel zur nächsten Kugel geführt werden. Die nächste Kugel wird farblich gekennzeichnet. Wenn Sie die Kugel erreicht haben, bestätigen Sie dies mit einem Klick auf den in der anderen Hand gehaltenen Knopf. Die Kugeln schweben vor Ihnen und sind in einem Kreis angeordnet.

Wenn „Pause" eingeblendet, haben Sie Zeit, sich kurz zu entspannen, etwas zu trinken und sich hinzusetzen. Sie können auch nach jedem vollendeten Kreis eine zusätzliche Pause einlegen. Um die Messungen der Position nicht zu beeinträchtigen, sprechen Sie bitte während der Durchgänge nicht. Fragen können Sie jederzeit zwischen den Durchgängen stellen.

Die Ziele werden in unterschiedlichen, Entfernungen, Größen und Abständen angezeigt. Sie sollten während der Ausführung möglichst entspannt auf der für Sie markierten Stelle stehen. Je nach Situation wird beim Berühren einer Kugel unterschiedliches Feedback ausgelöst, nämlich: EMS-Feedback, Vibrations-Feedback, Einfärbung oder kein Feedback.

Teilnehmer-Nr.: ___________ Studien-Nr.: ___________

Abschlussfragebogen

Bitte kreuzen Sie die passende Position an.

B.1 Wie gut konnten Sie die verschiedenen Formen von haptischem Feedback (EMS und Vibration) unterscheiden?

Sehr gut Sehr schlecht

0 0 0 0 0

B.2 Wie realistisch fanden Sie das EMS-Feedback?

Sehr realistisch Sehr unrealistisch

0 0 0 0 0

B.3 Wie realistisch fanden Sie das Vibrations-Feedback?

Sehr realistisch Sehr unrealistisch

0 0 0 0 0

B.4 Wie realistisch fanden Sie das visuelle Feedback?

Sehr realistisch Sehr unrealistisch

0 0 0 0 0

B.5 Wie intensiv haben Sie das Feedback empfunden?

Vibration:

Sehr intensiv Gar nicht intensiv

0 0 0 0 0

EMS:

Sehr intensiv Gar nicht intensiv

0 0 0 0 0

B.6 Haben Sie das EMS-Feedback bezüglich Ihrer Bewegung als verzögert wahrgenommen?

Nicht verzögert Stark verzögert

0 0 0 0 0

B.7 Haben Sie das Vibrations-Feedback bezüglich Ihrer Bewegung als verzögert wahrgenommen?

Nicht verzögert Stark verzögert

0 0 0 0 0

B.8 Haben Sie das visuelle Feedback bezüglich Ihrer Bewegung als verzögert wahrgenommen?

Nicht verzögert Stark verzögert

0 0 0 0 0

B.9 Wie passend fanden Sie die Feedbackposition am Unterarm für das EMS-Feedback bei der Interaktion mit den virtuellen Objekten?

Sehr passend Gar nicht passend

0 0 0 0 0

B.10 Wie passend fanden Sie die Feedbackposition am Finger für das Vibrations-Feedback bei der Interaktion mit den virtuellen Objekten?

Sehr passend Gar nicht passend

0 0 0 0 0

B.11 Wie passend fanden Sie das visuelle Feedback bei der Interaktion mit den virtuellen Objekten?

Sehr passend Gar nicht passend

0 0 0 0 0

B.12 Als wie angenehm bzw. unangenehm haben Sie das EMS-Feedback empfunden?

Sehr angenehm Sehr unangenehm

0 0 0 0 0

B.13 Als wie angenehm bzw. unangenehm haben Sie das Vibrations-Feedback empfunden?

Sehr angenehm Sehr unangenehm

0 0 0 0 0

B.14 Welche haptische Feedback-Methode würden Sie vorziehen?

EMS-Feedback viel besser	EMS-Feedback besser	Gleich gut	Vibrations-Feedback besser	Vibrations-Feedback viel besser
0	0	0	0	0

B.15 Bitte bewerten Sie die folgenden Aussagen:

	Trifft völlig zu				Trifft gar nicht zu
Ich habe mich an das EMS-Feedback nach einigen Versuchen gewöhnt.	0	0	0	0	0
Ich konnte das EMS-Feedback auf das Objekt beziehen.	0	0	0	0	0
Ich kann mir vorstellen EMS-Feedback regelmäßig zu verwenden.	0	0	0	0	0
Ich habe das EMS-Feedback zu stark gespürt.	0	0	0	0	0

B.16 Können Sie sich vorstellen ein solches System im Alltag zu verwenden?

[ ] ja [ ] nein

Falls ja: In welchem Kontext könnten Sie sich vorstellen, dass Sie selbst oder jemand anders ein solches System verwendet?

B.17 Haben Sie weitere Anmerkungen oder Anregungen?

Vielen Dank für die Teilnahme an der Studie! :-)

Appendix II Curriculum Vitae

Personal information

First name / Surname	Max Pfeiffer, M.Sc.
Address	Herwarthstr. 59, 45138 Essen, Germany
Telephone	+ 49 (0) 201 75922354
Mobile	+49 (0) 179 1428492
Email	maxpfeiffer.hci@gmail.com
Nationality	German
Date of birth	10/05/1981
Gender	Male
Personal status	Married

Postdoctoral

Dates	Since 08/2016
Title of qualification	**Post-Doc in Geoinformatics and Human-Computer Interaction**
Name and type of organization	Situated Computing and Interaction Lab at University of Münster, Germany Prof. Dr. Christian Kray

Doctor of Philosophy

Dates	10/2012 – 10/2016
Title of qualification	**PhD (Dr. rer. nat.) in Human-Computer Interaction** **Title of thesis:** Ubiquitous Haptic Feedback in Human-Computer Interaction through Electrical Muscle Stimulation
Name and type of organization	Human-Computer Interaction group of the Leibniz University Hannover, Germany **Doctoral thesis supervisor:** Prof. Dr. Michael Rohs and Albrecht Schmidt
Dates	07/2010 – 08/2012
Title of qualification	**Research Assistant in Software Engineering, esp. Mobile Applications**
Name and type of organization	paluno - The Ruhr Institute for Software Technology at the University of Duisburg-Essen, Germany Prof. Dr. Volker Gruhn

School and Studies

Dates	10/2007 – 03/2010
Title of qualification awarded	**Master of Science in Applied Informatics – Software Engineering** **Title of thesis:** Multi-Touch Steering Wheel Interaction with Rotatable Displays in Vehicles
Name and type of organization	Pervasive Computing and User Interface Engineering Group, University of Duisburg-Essen, Germany Prof. Dr. Albrecht Schmidt
Dates	10/2002 – 09/2007
Title of qualification awarded	**Bachelor of Science in Systems Engineering – Network Engineering** **Title of thesis:** Random and Permutation Method in Use with Parameters of UWB, Bluetooth, and WLAN
Name and type of organization	Institute of Digital Signal Processing, University of Duisburg-Essen, Germany Prof. Dr. Han Vinck
Dates	09/2003 – 07/2004
Title of qualification awarded	**Study Abroad Program**
Principal subjects	Software Engineering
Name and type of organization	School of Computer Science, University of Newcastle upon Tyne, UK
Dates	08/1998 – 07/2001
Title of qualification awarded	State-examined assistant in information engineering and the entrance qualification for studies at a university of applied sciences (Fachabitur)
Principal subjects	Electronics, information and telecommunication engineering
Name and type of organization	Heinz-Nixdorf-Berufskolleg, Essen, Germany
Dates	08/1992 – 07/1998
Title of qualification awarded	Testimony / Certificate of Advanced Technical College Entrance Qualification (Fachoberschulreife)
Name of school	Gustav-Heinemann-Gesamtschule, Essen, Germany
Dates	08/1988 – 07/1992
Title of qualification awarded	Primary School
Name of school	Kantschule, Essen, Germany

Compulsory Community Service

Dates	09/2001 – 07/2002
Name and address of employer	Community Church Centre Essen - Katernberg Nord, Germany

Work experience

Dates	Since 08/2016
Occupation or position held	**Post-Doc Research Assistant**
Name and address of employer	Situated Computing and Interaction Lab at University of Münster, Germany
Type of business or sector	Research / teaching
Dates	09/2012 – 07/2016
Occupation or position held	**Research Assistant**
Name and address of employer	Human-Computer Interaction group of the Leibniz University Hannover, Germany
Type of business or sector	Research / teaching
Dates	07/2010 – 08/2012
Occupation or position held	**Research Assistant**
Name and address of employer	paluno - The Ruhr Institute for Software Technology at the University of Duisburg-Essen, Germany
Type of business or sector	Business projects / research projects / teaching
Dates	09/2007 – 03/2010
Occupation or position held	**Student Research Assistant**
Name and address of employer	Pervasive Computing and User Interface Engineering Group, University of Duisburg-Essen, Prof. Dr. Albrecht Schmidt
Type of business or sector	Research / teaching
Dates	09/2009 – 10/2009
Occupation or position held	**Internship**
Name and address of employer	Department of Computer and Information Sciences, University of Strathclyde, Prof. Dr. Eva Hornecker and Prof. Maria Fox
Type of business or sector	Research
Dates	12/2006 – 08/2007
Occupation or position held	**Student Research Assistant**
Name and address of employer	Institut für Experimentelle Mathematik und Technik der Rechnernetze, University of Duisburg-Essen, Prof. Dr.-Ing. Rathgeb
Type of business or sector	Research / teaching
Dates	06/2007 – 08/2007
Occupation or position held	**Freelance**
Name and address of employer	Lopavent GmbH, Berlin, Germany
Type of business or sector	Event management

Dates	09/2001 – 07/2002
Occupation or position held	**Junior Systems Administrator / Part time work**
Name and address of employer	microbuss software GmbH, Essen, Germany
Type of business or sector	Software Engineering

Teaching Experience

Dates	2012 – 2015
Title of course	**Human-Computer Interaction 1**
Occupational skills	Organization and execution of exercises, lecturing in place of the professor, employment and management of tutors
Type of exam	Bachelor course with written exam
Dates	2013 – 2015
Title of course	**Mobile Interaction**
Occupational skills	Leading and organization of exercises, lecturing in place of the professor, employing and managing tutors
Type of exam	Master course with written exam
Dates	2013 – 2015
Title of qualification	**Current Topics in Human–Computer Interaction**
Occupational skills	Preparing research topics for lessons, introducing methods and prototyping technologies, supervising groups of students
Type of exam	Master lab course with final presentation
Dates	2013 – 2015
Title of qualification	**Physical Computing Lab**
Occupational skills	Teaching user center design methods and 101 electronics, introducing methods and prototyping technologies, supervising groups of students
Type of exam	Bachelor lab course with final presentation
Dates	2013 – 2015
Title of qualification	**Proseminar Mensch-Computer-Interaktion**
Occupational skills	Prepared research topics for lessons and supervised students
Type of exam	Bachelor seminar with final presentation and composition of the topics and discussion
Dates	2012 – 2013
Title of qualification	**Programmieren 1**
Occupational skills	Leading and organizing exercises, lecturing in place of the professor, employing and managing of tutors
Type of exam	Practical exam

Dates	2012
Title of qualification	**iOS programming in Objective C**
Occupational skills	Conceiving of lecture materials and notes for the students and establishing practical exercises
Type of exam	Advanced vocational training with written exam

Dates	2011 – 2012
Title of qualification	**Hauptseminar (Angewandte Informatik / Software Systems Engeneering)**
Occupational skills	Preparing research topics for lessons and supervising students
Type of exam	Bachelor seminar with final presentation, composition of the topics and discussion

Dates	2011
Title of qualification	**Java Web developing with JSF**
Occupational skills	Conceiving lecture materials and notes for the students and establishing practical exercises
Type of exam	Advanced vocational training with written exam

Supervised Theses

Dates	2016
Title of thesis	A Self-Calibrating Wearable Electrode Grid for Controlling Hand Gestures via EMS
Name of student	Tim Dünte (Master)

Dates	2016
Title of thesis	Konzeption und Implementierung eines Systems zur Hindernisvermeidung bei Fußgängernavigation mit Electrical Muscle Stimulation
Name of student	Sven Lilge (Master)

Dates	2015
Title of thesis	Automatic Pedestrian Navigation using Differential GPS and Electrical Muscle Stimulation
Name of student	Peter Denis (Master)

Dates	2015
Title of thesis	Dynamic Textures with EMS-based Haptic Feedback for Interactive Surfaces and Mobile Devices
Name of student	Eike Karsten Schlicht (Bachelor)

Dates	2015
Title of thesis	Haptic Feedback of Grabbing and Moving Diverse 3D Objects
Name of Student	Wei Chen (Bachelor)

Dates	2015
Title of thesis	Haptic Feedback in 3D Interaction – Simulating Object Properties Using EMS

Name of Student	Martin Buntrock (Bachelor)
Dates	2015
Title of thesis	Using Biofeedback for Estimating User Workload in Lab Studies
Name of Student	Björn Fiedler (Bachelor)
Dates	2015
Title of thesis	Haptic Feedback for Mobile Augmented Reality Interactions with Physical Objects
Name of Student	Oliver Beren Kaul (Master)
Dates	2015
Title of thesis	Simulating Textures with EMS-based Haptic Feedback for Interactive Surfaces
Name of Student	Le Duy Linh Phan (Bachelor)
Dates	2014
Title of thesis	Simulating Haptic Feedback for 3D Interaction: Distinguishing Different Sizes of Virtual Objects Using EMS
Name of Student	Gill Engel (Bachelor)
Dates	2014
Title of thesis	Design and Implementation of a Wearable Prototype for EMS-based Pedestrian Navigation
Name of Student	Tim Dünte (Bachelor)
Dates	2012
Title of thesis	Modellbasierte Echtzeituberwachung von Geschäftsprozessen - Erweiterung der BPMN um modellbasierte Echtzeitaspekte zur Überwachung und prototypische Implementierung auf der Microsoft Surface Platform
Name of Student	Felix Föcker (Bachelor)

Appendix III Selected Press Responses

Online	**Cruise Control for Pedestrians: Controlling Walking Direction using Electrical Muscle Stimulation**
Date	02/04/2015
Title of the article	Human cruise control app steers people on their way
Magazine / author	New Scientist / Hal Hodson
Date	12/04/2015
Title of the article	'Human Sat Nav' guides tourists through streets by controlling leg muscles
Magazine / author	The Telegraph / Sarah Knapton
Date	13/04/2015
Title of the article	Human cruise control zaps legs to send you in the right direction
Magazine / author	CNET / Leslie Katz
Date	13/04/2015
Title of the article	'Human Sat Nav' zaps people's legs with electrodes to guide them through streets
Magazine / author	Belfast Telegraph
Date	13/04/2015
Title of the article	Leg Electrodes Turn Humans Into Sat Navs
Magazine / author	SkyNews
Date	13/04/2015
Title of the article	Инженеры научились дистанционно направлять пешеходов по нужному маршруту
Magazine / author	lenta.ru - Russia
Date	14/04/2015
Title of the article	Researchers Use Electrodes for “Human Cruise Control”
Magazine / author	MIT Technology Review / Rachel Metz
Date	14/04/2015
Title of the article	Navigation für Fußgänger: Elektrische Muskelstimulation als Richtungsgeber
Magazine / author	Heise Online / Axel Kannenberg
Date	14/04/2015
Title of the article	Autopilot für Fußgänger: Forscher steuern Menschen via App
Magazine / author	Deutsche Wissenschaft Nachrichten

Date	14/04/2015
Title of the article	Pedestrian 'cruise control' uses electric shocks to steer you home
Magazine / author	Mirror / Jeff Parsons
Date	14/04/2015
Title of the article	Creepy 'Sat Nav' Device Steers People With Tiny Jolts Of Electricity
Magazine / author	The Huffington Post / Jacqueline Howard also in The Huffington Post Korea
Date	15/04/2015
Title of the article	'Human Cruise Control' Uses Electrodes to Steer People in the Right Direction
Magazine / author	Big think / Natalie Shoemaker
Date	15/04/2015
Title of the article	Navigationshilfe: Fußgänger-Navi per Elektroschock
Magazine / author	MensHealth / Swantje Kamp
Date	16/04/2015
Title of the article	Remote Control Humans Are Here
Magazine / author	Discovery News / Eric Niiler
Date	20/04/2015
Title of the article	Scientists Are Using Electrodes to Remote-Control People
Magazine / author	Wired US / Nick Stockton also in Wired UK and Wired DE
Date	21/04/2015
Title of the article	Fernsteuerung für Fußgänger
Magazine / author	Heise Online / Rachel Metz
Date	21/04/2015
Title of the article	So steuert man einen Menschen mit einem Smartphone
Magazine / author	Galileo / Florian Aich
Date	22/04/2015
Title of the article	Σύστημα τηλεχειρισμού ανθρώπων δοκιμάζεται στη Γερμανία
Magazine / author	in.gr – Greek
Date	18/06/2015
Title of the article	ドイツで開発「人体ナビゲート」
Magazine / author	EpochTimes.jp

Printed

Date	06/2015
Title of the article	Ein Lenker für die Füsse
Magazine / author	GEO / Tilman Botzenhardt

	Date	06/2015
	Title of the article	Des jambes à direction assistée
	Magazine / author	Le monde des sciences / Clémentine Vignon
	Date	07/2015
	Title of the article	Hommes téléguidés, ça marche
	Magazine / author	Science & Vie Junior / Philippe Fontaine
Radio		
	Date	08/07/2015
	Title of the article	Ein Autopilot für Fußgänger
	Magazine / author	Deutschlandfunk / Friederike Maier
	Date	27/04/2015
	Title of the article	News program
	Magazine / author	La Fm / Denise Michelsen - Colombia
	Date	30/04/2015
	Title of the article	The Moncrieff Show
	Magazine / author	newtalk / Claire Collins – Ireland
Television		
	Date	15/06/2015
	Title of the article	Wenn das Handy jeden Schritt steuert
	Magazine / author	NDR - Hallo Niedersachsen / Henning Orth
	Date	03/10/2015
	Title of the article	Being controlled by electric shocks
	Magazine / author	BBC Click / Nick Kwek
Online		**Gestural interaction on the Steering Wheel: Reducing the Visual Demand**
	Date	04/06/2011
	Title of the article	Gestensteuerung im Auto: Her mit dem Wisch
	Magazine / author	Spiegel Online/ Tom Grünweg
	Date	06/06/2011
	Title of the article	Touch-screen steering wheel keeps drivers focused on the road
	Magazine / author	PhysOrg.com / Deborah Braconnier
	Date	06/06/2011
	Title of the article	Touch-Screen Steering Wheel Keeps Eyes on Road
	Magazine / author	Discovery News

Date	06/2011
Title of the article	German Researcher Working on Multi-touch Gestures Steering Wheel
Magazine / Author	SOFTSAILOR.COM
Date	13/06/2011
Title of the article	Researchers Working On Touch Screen Steering Wheel
Magazine / author	PistonHeads/ Riggers
Date	14/06/2011
Title of the article	New Touchscreen Steering Wheel May Reduce Driver Distractions
Magazine / author	ExtremeTech/ Bill Howard
Date	14/06/2011
Title of the article	Touchscreen-Lenkrad: Wischen wechselt Radiosender
Magazine / author	Online Focus / SP-X also in n-tv auto.de

Printed

Date	09/06/2011
Title of the article	Smooth ride: Now, steer car with a touch
Magazine / author	The Times of India