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Master's Thesis
Academic Year 2020

Cybergait: Redesigning Human Gait Pattern by Intervening Human Sensorimotor System with Electrical Stimulation

Keio University
Graduate School of Media Design

Shuang Hao

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Shuang Hao

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Abstract of Master's Thesis of Academic Year 2020

Cybergait: Redesigning Human Gait Pattern by Intervening Human Sensorimotor System with Electrical Stimulation

Category: Science / Engineering

Summary

Technologies have changed the relationship between human and machine and the way they interact. However, there is always gap between human and machine that we can constantly recognize that "we are using a tool." To close the gap, we shifted from human-machine interaction to human-machine-integration. We introduced the human body as an input/output device to create seamless and effortless communication between human and machine.

Within this picture, we designed a system following the concept of human-machine integration and focusing on redesigning the human gait patterns. The system, named Cybergait, consists of a pressure sensing insole that monitors our movements and an ES toolkit that changes our gait pattern by intervening the human sensorimotor system with electrical stimulation.

In this paper, we described thoroughly the design, implementation and the validation of the pressure sensing insole and the ES toolkit. We provided a customized design for the user which effectively captures his gait data and changes his gait pattern. The experiment results proved that by applying electrical stimulation on one side of the foot, we are able to shift the pressure to the other side and hence changes the gait pattern.

Keywords:

Human Machine Integration, Human Augmentation, Gait Augmentation, Haptics, Electrical Stimulation, Wearable Sensing

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Chapter 1

Introduction

In this chapter, we will discuss about the evolving human-machine interaction and the idea of moving toward human-machine integration. We introduce our vision, which is designing a new human-machine experience that targets the augmentation of the human gait pattern. We state our research goal, explain the Cybergait approach and highlight our contributions.

1.1. The Gap Between Human and Machine

We live in a world where we are exposed to vast amount of information. The increased complexity in our life requires higher capability for information processing. As the human processing capacity becomes insufficient to handle the information overload, we start to outsource the workload to achieve better performance. For example, we use computers to do calculations so that we can get fast results; we rely on databases to store information so that we can optimize our memories for more prioritized matters.

It is clear to us now that we rely on machine not only on execution level but also in intellectual perspectives. To some extent, machine can be seen as an extension of the body, whether as an extension of the brain or of any other parts. However, machine has existed away from the body. The gap between the two is not defined by physical distance but by the way they interact.

One fundamental problem we notice is that interactions between human and machine almost always requires some sort of cognitive efforts. While machine can help us to process the information, store the data and produce the output, human cognitive effort is often needed for initializing the process, receiving the machine output, and further decision-making.

Furthermore, the current human-machine interaction are based on the communication via an interface. Whether it is the traditional “pushing buttons” type of interfaces, or the smart interfaces today (such as using voice control, gestural control, eye control, etc.), the fact that the communication between human and machine needs to be carried via an interface creates a fundamental barrier between the two.

Thus we wonder: How can we bring machine closer to us? Could machine understand our needs better? Could we communicate back and forth with machine in a more seamless way?

These questions drive us to find a better solution for the future of human-machine interaction.

1.2. Moving Toward Integration

As we think of establishing a closer relationship between human and machine, some proposed the idea of human-machine integration.

In the field of human augmentation, researchers have been exploring various possibilities to realize the human-machine integration. Among which, one popular direction in the recent years is to add devices as an extension of the body. For example, in MetaLimbs, Sasaki et al. added two robotic arms to the body as an extension to the human limbs [1]. In Arque, Nabeshima et al. attached an artificial biomimicry-inspired tail to the body to extend innate body functions [2].

While these researches proposed a scenario where machine becomes a part of our body, we see a different scenario where the interaction between human and machine shifts from an interface to the body itself. Up until now, we rely on the existence of interfaces because the communications with machine are built on visual and auditory feedbacks. Thus, to eliminate the interface, we need to think of a new way of interaction that can directly pass information to the body.

What comes to our attention is communicating through haptic feedback. In the consumer market, there are some devices, such as Apple Watch (Figure 1.1[1]), that embed haptic feedback to their user interfaces. When receiving a message, for example, user can sense the vibration on the arm and understand whether they received a message, a mail, or other types of notifications based on the vibration patterns. This proves that our body is capable of understanding different information passed through haptic feedbacks. However, with current devices, the information that can be delivered is very limited and serves mostly as a notification. Once users sensed the vibration, they would still need to look at the screen in order to check out what is going on.

Figure 1.1 User Interface of Apple Watch

In this research, we propose a scenario in which devices communicate directly with the human sensorimotor system through haptic feedbacks. Using haptics

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[1] https://www.indabaa.com/how-to-turn-off-apple-watch-notifications/

feedbacks, we aim to achieve effective and seamless communication between human and machine and shift the interaction toward an integration level.

1.3. A New Human-Machine Experience: Redesigning the Human Gait Pattern

One direction that we find interesting to apply the concept of human-machine integration is the redesign of the human gait pattern. As one of the most practiced activities in our daily life, walking requires very little thought. When we move from the desk to grab a cup of coffee in the kitchen, we don't consciously think that we are "walking" to from one place to another, moving our legs repeatedly and balancing ourselves in an upright postural. Rather, we focus on the purpose itself, which in this case is getting the cup of coffee. Similarly, when we decide to take a walk outside after dinner, the idea of "walking" might briefly appear when we decided to do so, but doesn't constantly stay in our mind while we are walking. Instead, our attention goes to somewhere else, such as to people that we encounter, to the neighbor's yard that recently got renovated, or even to the breeze on a hot summer night. It is argued by many that only in the face of injury or challenging situations (such as walking on a slippery surface) that we actually pay attention to the action of "walking" itself [3] [4].

While walking is a behavior that we do not actively think of, it creates challenges to the free control of our gait patterns, especially when we try to switch between different gait patterns. For example, when seeing fashion models walking down the runway, we may have tried to mimic their catwalk. However, we soon realize that even if we theoretically understand how we are supposed to step forward with the legs aligned in a straight line, our legs won't follow the same rule unless we pay full attention to the leg movements during the whole time. In the real life, this is highly unpractical as our attention can constantly get distracted to various things, such as the traffic, the environment, our smart phone, or any small matter that randomly pops up in our head.

As our body is incapable of taking full control over the gait patterns, we started to wonder: how could machine assist us in the human gait control? While we cannot pay full attention to our leg movements during the whole time, machine could substitute our role to inspect the movements and provide haptic feedback for gait changing.

1.4. Cybergait Approach

In this research, we propose a system, named Cybergait, that monitors our movements and changes our gait pattern by intervening the human sensorimotor system with electrical stimulation. It addresses the problems that we previously mentioned in the following aspects:

Seamless Human-Computer Integration

Cybergait shifts from human-machine interaction to human-machine integration by introducing the human body as an input/output device. The body gives command to the Cybergait through behavioral output that doesn't require any cognitive efforts. In return, Cybergait communicates with the body through sending haptic feedback, and the body can directly pass the sensory input to the brain to generate further behavioral output. It becomes an automatic loop that no operational effort is needed throughout the whole process. The system creates a more intimate and seamless relationship between human and machine that the users won't even feel that they are “using a tool”.

Real-time Gait Monitoring and Gait Pattern Changing

As human cognitive resources become insufficient for us to take full control our gait the whole time, Cybergait takes over the role to monitor our movements and provides haptic feedback to change the gait pattern. With the Pressure Sensing

Insole, we are able examine our gait from multiple aspects, including pressure distribution, contact areas, symmetry, speed and rhythm. These information contains valuable indicators of our health and how we look in front of others. Moreover, Cybergait uses electrical stimulation (ES) to provide haptic feedback that intervenes the human sensorimotor system. The ES feedback directly triggers gait pattern changes rather than serving just as a notification. The system is fully wearable and unnoticeable, as our vision is to embed everything inside the shoes. We believe that Cybergait will turn into a smart footwear that goes to the consumer market in the near future.

1.5. Research Goal

Our Research goal is to design and validate a feedback system that intervenes the human sensorimotor System and changes the walking behavior.

1.6. Contributions

This paper contributes to the fields of Human-Machine Integration and Human Augmentation as it introduces a novel human-machine experience that redesigns the human gait patterns. It explores with the concept of using the human body as an input/output device, eliminating the operational efforts when communicating with the machine. The system, named Cybergait, monitors and redesigns our gait pattern by intervening the human sensorimotor system with electrical stimulation.

In this paper, we explain the ideation process of Cybergait, including the background, concepts, methods and two application scenarios. We also walk through the design and implementation process for the Pressure Sensing Insole and ES Toolkit, providing a reference for others from both design and technical perspectives. Since different people have different foot shapes and different types of foot arch, we work with a 22-year-old healthy subject, who has a foot size of 26.5cm, and provide a customized solution for him.

With Cybergait, we managed to alter our user's gait pattern without the user noticing. By applying electrical stimulations on one side of the foot, we were able to shift the pressure to the other side and hence alters the gait pattern.

1.7. Thesis Outline

This thesis is structured as follows:

- Chapter 1 goes through the evolving human-machine interaction and the potential of using the human body as a new interface. We introduce a new human-machine experience: the augmentation of the human gait pattern. We explain the Cybergait approach, state the research goal and highlight our contributions.
- Chapter 2 examines some related work of this research. We first look at some previous work in the human augmentation field in general, and move on to our targeted area: human gait control. We investigate how the motor control system functions in our body and discuss the limitations of it. We then look into some common approaches for gait monitoring and compare different actuation mechanisms.
- Chapter 3 presents our concept, method and applications. Our concept comes from two directions, which is to design a more seamless interaction between human and machine, and also create a new human-machine experience that targets gait pattern augmentation. To realize these concepts, we ask ourselves two questions: How do we monitor the gait? How do we modify the gait? In this chapter, we walk through our answers for the two questions to give a fuller look of our system, and talk about some possible applications of the system.
- Chapter 4 is composed of 3 sections, which includes the Pressure Sensing Insole, the ES Toolkit and Discussion. We cover the design process and implementation details of the devices, as well as validation and discussion of the system.

- Chapter 5 concludes this paper by summarizing the important points mentioned. We also talk about several points that still remain unclear after the experiments, which can be continued by others who might be interested in this project.

Chapter 2

Literature Review

In this chapter, we examine some related work of this research. We first look at some previous work in the human augmentation field in general, and move on to our targeted area: human gait control. We investigate how the central nervous system rules our gait and discuss the limitations of it. We then look into some common approaches for gait monitoring and compare different actuation mechanisms.

2.1. Human Gait Control

Locomotion refers to the displacement of the subject's center of gravity (mass) from one location to another [5]. It includes various forms, such as walking, running, jumping, climbing, etc. Among which, walking is the most common form of locomotion that is practiced on a daily basis by a healthy subject. The complexity of walking is often neglected, as walking is one of the first skills that people have learned since an early age. Rather, the development of walking went through a long and 2-phase process, lasting at least 8 years of walking experiences, with the first phase devoted to "the learning of gait postural requirements", and the second phase devoted to "fine tuning of the gait." [6] [7] Along the process, multiple factors (other than diseases) can influence the gait development, including cognitive, social and cultural factors [8].

In spite of the long development process, walking is an inherently complicated behavior that requires well coordination of whole-body joints and muscles. Bernstein described the complexity of this coordination in comparison with an orchestra: “As in orchestra, each instrument plays its individual score, so in the act of human walking each joint reproduces its own curve of movements and each center of gravity performs its sequence of accelerations, each muscle produces its melody of efforts, full with regularly changing but stable details. And in like manner, the whole of this ensemble acts in unison with a single and complete rhythm, fusing the whole enormous complexity into clear and harmonic simplicity. The consolidator and manager of this complex entity, the conductor and at the same time the composer of the analyzed score, is of course the central nervous system.” [9]

As Bernstein described, the central nervous system acts as the conductor in this complex coordination of joints and muscles. It regulates our gait through a combination of automatic and controlled processes. Thus, to augment the human gait patterns, it is necessary to look into the two processes to find out what we could possibly intervene. Here we will discuss the two processes in the control of human gait.

Automatic and Controlled Processes

In a psychology literature, Schneider and Shiffrin did a systematic review of the two processes and provided a definition for each term [10]. In their work, automatic process is defined with two properties that “the sequence of nodes (nearly) always becomes active in response to a particular input configuration” and that “the sequence is activated automatically without the necessity of active control or attention by the subject.” On the contrary, controlled process if defined as “temporary sequence of nodes activated under the control of, and through attention by, the subject.” The two processes result from two types of processing, whose characteristics are compared by Schneider et al. in a later work [11]. Here we summarize the characteristics of each processing method based on their work and discuss the limitations of each in the context of walking.

Automatic Processing

Automatic processing requires consistent training to develop. Once learned, it can react fast to the stimuli with very little effort, allowing it to operate in high workload situations. When it comes to walking, automatic processing enables our body to handle the complex multi-joint movements and respond to changes in the external environment (such as different road surfaces) without consuming much cognitive resources. Consequently, it free our mind for other things, such as paying attention to the traffic, environment and people that we encounter. However, automatic processing comes with the problem of low controllability. In terms of walking, automatic processing makes it difficult for us to freely control our gait pattern as it has become an automatic response of the body. On top of that, it takes three times longer to unlearn and relearn an automatic process than learning it from the beginning. While changing a gait pattern does not necessarily mean to unlearn and relearn the walking behavior completely, thinking of the years it costed to fine tune the gait makes us wonder how long it will take to truly adapt to a new gait pattern without thinking about the movements.

Controlled Processing

Compared with automatic processing, controlled processing allows us to acquire a skill quickly. For example, learning to skate on an icy surface can be accomplished after only a few trials. However, controlled processing is significantly slower than automatic processing, as it takes time to deliver the information to the brain, process the information, and pass it back to the joints and muscles for execution. The slow execution makes controlled processing not suitable to take in charge of walking as it is incapable of handling the complex coordination of whole-body joints and muscles in real time. Moreover, because controlled processing requires high effort to operate, it becomes strictly capacity limited and can respond to only a small number of stimuli at a time. For example, when walking a busy street, we can only pay attention to a few things. This is why often when people focus on their smart phones, they tend to ignore risks of falling down from a stage, running into other pedestrians, or get hit by a car. When it comes to gait pattern control, it becomes almost impossible to allocate our limited attention to the leg movements at all time.

2.2. Gait Monitoring

In his book “Biomechanics and Motor Control of Human Movement,” David Winter went through a thorough examination of the techniques used to measure, describe, analyze, and assess the human movement [12]. According to Winter, the term monitor is in conjunction with the term describe, and “to monitor means to note changes over time.” In order to monitor any change or improvement and validate the effectiveness of the gait changing attempt, accurate and reliable measurements must be taken, and thus we must understand first what to measure and how to measure. In this section, we will review from kinematic and kinetic perspectives based on Winter’s book and investigate the techniques used for each.

2.2.1 Kinematics

Kinematics refers to the description of the actual patterns, indicating the geometry of the movement rather than any internal or external force that causes the movement. It is concerned with linear and angular displacements, velocities and accelerations of the relative position from one limb to another, and from the body to the external space. The most basic assessment of kinematics are conducted through direct observation of the movement. By observing how the patient walks, for example, physical therapist can get a rough understanding the patient’s situation from his body tilt, leg movements, etc. However, as Winter indicated, direct observation challenges even the most experienced observers due to the extensive workload to document all details of the movements and the nearly impossible task to compare with previous measures [12]. Therefore, reliable techniques are needed to quantify the movements and provide data for further analysis.

One common approach to capture kinematic data in human gait analysis is through motion capturing systems. Different camera-based systems have been developed and used in motion capturing, allowing documentation of the movement at high frame rates. For example, Microsoft introduced Kinect (Figure 2.1) [1], a motion capturing device designed to track user's body movement for video gaming. Equipped with RGB cameras, infrared projectors and detectors, Kinect can capture 3 dimensional movements without using controllers or markers. It is not only used in video gaming, but also used by researchers for gait analysis. Pfister et al., for example, used Kinect to study sagittal plane hip and knee kinematics at three different velocities [13]; Gholami et al. used Kinect in clinical setting to quantify gait abnormalities in patients with multiple sclerosis [14]. It has been proved that imaging measurement techniques are widely used in studying the body kinematics and provide important reference in the analysis of human gait.

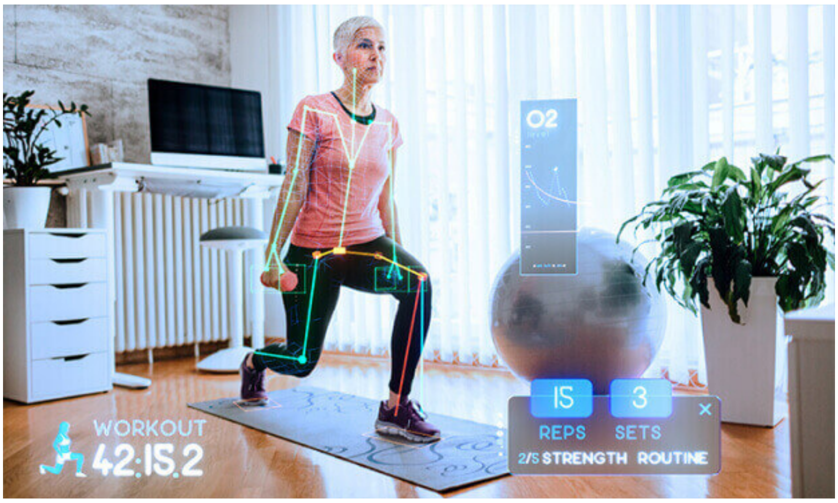

Figure 2.1 Microsoft Azure Kinect DK.

Another approach used to quantify kinematics data is through direct measurements, using techniques such as goniometers, accelerometers and inclinometers. For example, Chao used a modified triaxial goniometer to measure three-dimensional joint angular motion [15]. Kolber et al. used a goniometer and digital inclinometer to measure shoulder flexion, abduction, internal and external rotation and

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[1] https://azure.microsoft.com/en-in/services/kinect-dk/features

compared the intrarater reliability and concurrent validity between the two [16]. Lanningham-Foster et al. used an inclinometer-accelerometer system to measure body posture and movement in children [17]. Gafurov et al. placed an accelerometer in the user's trousers pocket for gait identification [18]. However, compare to the motion capturing approach, the use of direct measurements usually comes two major drawbacks: first, because of the way that sensors are mounted on the body, they can create limitations on the movement that influence the accuracy of the results; second, compare to camera-based systems, the direct measurement techniques focus on specific parts of the body, which greatly limits the information that can be extracted from the movements.

2.2.2 Kinetics

Kinetics refers to study of internal and external forces that cause the movement. As the names imply, internal forces come within the human body from muscle activity, ligaments, or the friction in the muscles and joints, whereas external forces come outside of the body from the external environment or objects. According to Winter, kinetic analysis plays a key role in the study of biomechanics as it provides crucial information for the cause of any movement, which allows us to get insight into "the mechanisms involved and into movement strategies and compensations of the neural system." [12] Since it is infeasible to directly measure forces within the human body, researches rely on alternative approaches to measure the forces directly.

The most common approach to measure kinetics is through the use of force platform, which consists of sensors embedded on the ground, measuring the ground reaction forces exerted by the body when subject stand, walk or run on them. The force platform technique has been widely used in measuring the steadiness and symmetry of gait and posture. Robinson et al., for example, used force platform variables to assess the effects of spinal manipulations on the gait symmetry of patients with sacroiliac dyskinesia [19]. Piirtola et al. used force platform measurements to assess the and predict falls among elderly populations [20]. While force platform is a useful tool to evaluate the overall balance, it does not provide information on each contact point of the foot. Moreover, force platforms are only for laboratory uses and are can not be used in daily measurements.

Due to the limitations of the force platform, alternative approaches have been developed to measure kinetic variables. Among which, in-shoe-based systems are one of the most popular techniques used in the recent years. Tekscan, for example, introduced a F-Scan System (shown in Figure 2.2) that uses insole-shape in-shoe sensors to capture the timing and pressure information for foot function and gait analysis[2]. The system provides quantifiable data of the full gait cycles and has been widely used in gait and postural analysis. However, there are also researchers who pointed out that wearing the F-Scan system alters gait characteristics during running and thus the data may not accurately reflect the real gait data in real-time setting [21]. Aside from commercial products, researchers have designed different in-shoe sensing systems for gait analysis purpose. Shu et al., for example, designed a in-shoe pressure measurement and analysis system based on a textile fabric sensor array [22]. Crea et al. designed a flexible insole with 64 pressure-sensitive elements to monitor the plantar pressure distribution [23]. These in-shoe pressure sensing systems are proved to be effective in capturing real-time gait data during walking.

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[2] https://www.tekscan.com/products-solutions/systems/f-scan-system

Figure 2.2 Tekscan F-Scan System.

Chapter 3

Cybergait Approach

Chapter 3 presents our concept, method and applications. Our concept comes from two directions, which is to design a more seamless interaction between human and machine, and also create a new human-machine experience that targets gait pattern augmentation. To realize these concepts, we asked ourselves two questions: How do we monitor the gait? How do we modify the gait? In this chapter, we walk through our answers for the two questions to give a fuller look of our system, and talk about some possible applications of the system.

3.1. Concept

To address to gap between human and machine and the challenge of human gait pattern control, we came up with a solution, Cybergait, with the following concept in mind:

3.1.1 Human Body as Input/ Output Device

We imagine that in the near future, human and machine could be seamlessly integrated. In particular, we see the interaction between human and machine move away from an interface. Instead, human body itself will serve as a new input/output device to communicate with the machine. The idea can be illustrated through Figure 3.1. Users no longer need to give command to the machine to initialize the process; instead, the body will serve as an indicator and send command directly to trigger the machine. In addition, when the machine delivers the output, the body will directly receive the signals and pass it on to the central nervous system to process. On a human-machine integration level, Cybergait closed the gap between human and machine by minimizing the demand for cognitive efforts to operate the system and by eliminating the interface for communication.

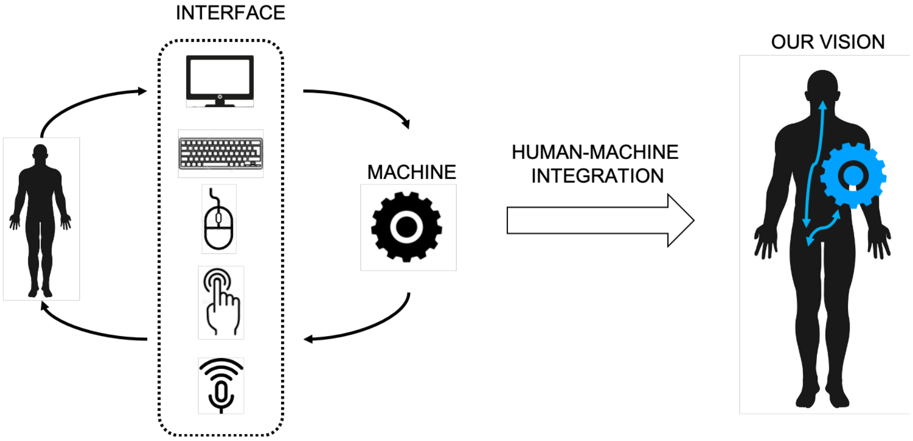

Figure 3.1 Our vision on human-machine integration.

3.1.2 Real-time Gait Monitoring and Gait Pattern Changing

While the human gait control won't allow us to freely switch our gait patterns, we want Cybergait to take part in the gait pattern control. We picture Cybergait to be a system that monitors and changes the gait pattern in real time. It enables us to gain control of our gait pattern without compromising extensive cognitive resources. It delivers haptic feedback to the body that directly influences in the signal flow in the gait control rather than serving as a passive notification. Moreover, we want the system to be wearable, intuitive and unnoticeable to the user that he/she won't feel any "invasion" of the machine to the body. We image that our concept of Cybergait will turn into a smart footwear in the near future.

3.2. Method

In order to design a system that monitors and regulates the gait pattern in real time, we identified two key questions to answer:

- How do we monitor the gait?
- How do we modify the gait?

In this section, we will walk-through our answers to the two questions.

3.2.1 How Do We Monitor the Gait?

Human gait involves a complex series of lower limbs movements. To analyze the gait, researchers look into various parameters of the movements, including joint positions, speed and rhythm, dynamic electromyography, and pressure distribution. While standard laboratories for gait analysis rely mostly on multi-camera motion capture systems, force platforms, and electromyographic devices, the unwearable characteristics and the complexity on operating these systems make them inapplicable for daily scenarios.

In this research, we monitor the gait through light-weight pressure sensors and embed them on shoe insoles to make the system fully wearable, effortless to operate, and applicable for continuous real-time monitoring. We focus on the measuring the foot pressure, which contains rich information of the movements including pressure distribution, contact areas, symmetry, speed and rhythm. These information are sufficient for us to understand the key parameters and identify the gait pattern efficiently in daily practices.

3.2.2 How Do We Modify The Gait?

Gait Changing Through Augmentation of Sensory Signals

Gait changing is often achieved through training and physical therapies. The process can be time and resources-consuming: professionals such as runway models or athletes take months or years of training and practices to achieve their ideal gaits, while patients with walking abnormalities can only take even longer. In recent years, researchers experiment with robot-assisted approaches for more effective gait changing. For example, Banala et al. used active leg exoskeleton (ALEX) and a force-field controller to assist in gait training of stroke survivors [24]. The robot-assisted approach may be effective for laboratories, but are difficult to operate and heavy to carry for daily practices.

In this research, we want to design an approach that is highly efficient, non-invasive, fully-wearable, and easy to operate. We started to rethink gait changing from its root: how gait is programmed in the central nervous system (CNS).

Our gait can be seen as an output from the CNS, which works as an information-processing system of the body. The CNS receives multi-sensory signals from different receptors of the body as the input, processes the information, and delivers different messages to the muscles and joints as the output. By modifying the signal input, we can theoretically change the output and achieve altered gaits.

In this research, we focus on the somatosensory (proprioceptive) signal, which informs the body about “objects in our external environment through touch (i.e., physical contact with skin) and about the position and movement of our body parts (proprioception) through the stimulation of muscle and joints.”[1] By augmenting the somatosensory (proprioceptive) signal through stimulation of targeted muscles, we assume that the body can detect and react to the stimuli and consequently triggers different gaits.

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[1] https://nba.uth.tmc.edu/neuroscience/m/s2/chapter02.html

Electrical Stimulation as Actuation Method

Somatosensation (proprioception) can be augmented through applying haptic feedback to the body. Researchers have experimented with vibrotactile feedback on the lower limbs in order to study its relevance on gait, posture and balancing. For example, Shull et al. applied vibration on the back, knee and foot of healthy subjects in gait retraining to reduce the knee adduction moment [25]. Kavounoudias et al. applied vibratory stimuli to applied to the forefoot areas and to the tendons of the tibialis anterior muscles of the subjects to induce whole-body tilts in human erect posture [26]. These researches all suggest the body's capability on detecting the somatosensory (proprioceptive) signals and reacting to the stimulus.

While vibrotactile feedback has been more commonly studied, there are few research on using electrotactile feedback to augment our somatosensation (proprioception) for postural/gait changing. Over the past decades, electrical stimulation has been used for standing and walking rehabilitation after serious injuries or diseases. This technique, commonly known as Functional Electrical Stimulation (FES), is used to "replace or assist a functional movement that is lost after injury to or diseases of the central nervous system." [27] In this research, we use electrical stimulation (ES) to provide haptic feedback on changing somatosensory (proprioceptive) signal input, which is fundamentally different from the traditional FES approach that artificially generate passive movements through electrical pulses.

3.3. Core Mechanism

As we walked through our answers to the two questions, we come up with a solution that falls under our concept in terms of functionality, efficiency and wearability. To summarize, we proposed a system that includes:

- Foot Pressure Sensing
- Electrical Stimulation Feedback

In every gait cycle, the pressure sensing insole monitors our movements and an ES toolkit changes our gait pattern by intervening the human sensorimotor system through electrical stimulation.

Cybergait uses electrical stimulation to modify the signal input of the body and stimulates the central nervous system to produce altered gait as output. The output from the body then serves directly as the input command of the system, eliminating the need to use cognitive resources for operations.

3.4. Application Scenarios

We picture 3 application scenarios for the system:

1. Use it to modify the body balance.
2. Use it to control our walking speed.
3. Use it to elevate how we look when we are walking.

Chapter 4

Implementation and Validation

Chapter 4 is composed of 3 sections, which includes the Pressure Sensing Insole, the EMS Toolkit and Discussion. We cover the design process and implementation details of the devices, as well as validation and discussion of the system.

4.1. System Mechanism

4.1.1 System Overview

Figure 4.1 shows the system overview of Cybergait, which consists two segments: sensing and actuation.

The sensing segment contains an FSR array (attached on an insole), a control unit, and software. When user step on the pressure sensing insole, the FSRs send out the pressure data to the microcontroller through a multiplexer. The microcontroller then uses Bluetooth to pass the data to Serial Port on Processing, where the data get processed and recorded. The sensing segment serves as the input of the system and receives signal output from the body. It captures the gait data, including pressure distribution, contact areas, symmetry, speed and rhythm.

The actuation segment contains an electrical signal generator, a signal control module, and software. From left to right on Figure 4.1, the signal generator sends out signal to the control module. The control module receives command

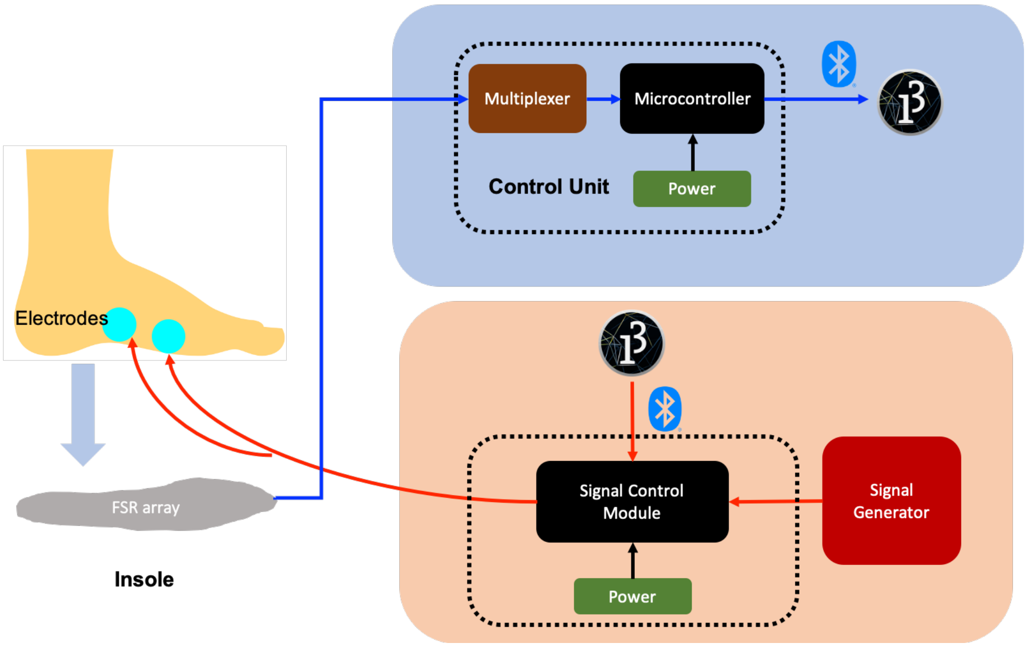


Figure 4.1 System Overview.

from Processing and send out regulated signals to the feet through electrodes. The actuation segment serves as the output of the system and sends out haptic feedback to to the body. It modifies our gait patterns by intervening the human sensorimotor system with electrical stimulation.

4.1.2 Sensing

For simplicity, the sensing segment will be referred as the Pressure Sensing Insole in this paper. The Pressure Sensing Insole consists of the following:

FSR Array

The FSR Array consists of 16 force sensing resistors (FSR), a force sensor that changes resistance based on the force applied. The resistance decreases as the force applied increases. Two types of FSRs were tested for comparison: MF01-N-221-A04 with Ø13mm, and FSR 402 with Ø18.28 mm. MF01-N-221-A04 was selected as it fits the best for the user's foot size. The Ø13mm MF01-N-221-A04 has an active area of Ø10.2mm, and a force sensitivity range from 10g to 1000g (0.1 N0.98 N).

Control Unit

The control unit consists of a multiplexer, a microcontroller and a power supply. A multiplexer is a breakout board that sends multiple analog or digital input signals to a single output line. A 16-Channel Analog/Digital Multiplexer CD74HC4067 was used in this research, which allows us to work with the 16 FSRs using only 4 pins (S0-S3). The multiplexer was connected through pin S0-S3 to 4 digital pins on an ESP 32 microcontroller, which serves as slave device to a host MCU and transmit data in real-time via its Bluetooth function. A 3.7V Li-polymer battery was used to power the ESP 32, and multiplexer is powered by the ESP32 through VCC pin.

A printed circuit board (PCB) was designed to mount all components in the control unit, The schematics and PCB layout is illustrated in Figure 4.2.

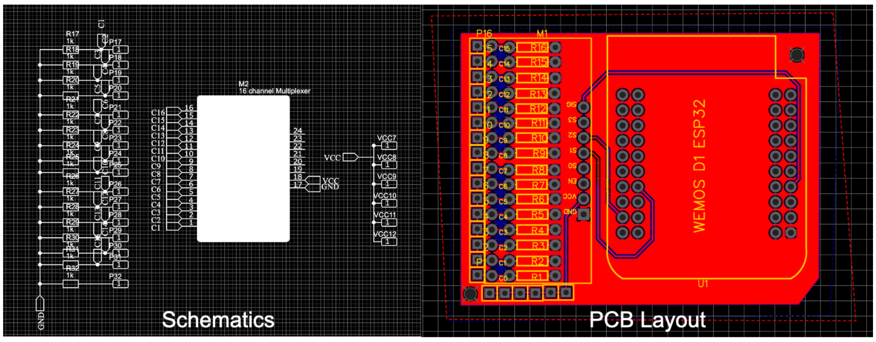


Figure 4.2 The schematics and PCB layout of the control unit.

Software

Processing is used to communicate with the control unit through Bluetooth connection. Delay time is set to 50 millisecond and thus data is collected at 20 data/second.

4.1.3 Actuation

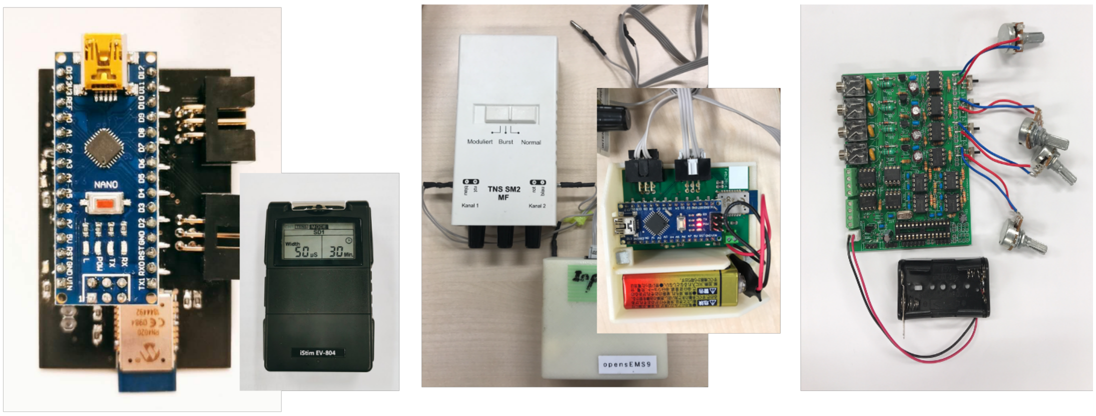
For simplicity, the actuation segment will be referred as Electrical Stimulation (ES) in this paper. It consists of the following:

Signal Generator

A signal generator is a device that sends out electrical signals with set properties of amplitude, frequency, and wave shape. Several ES signal generators were considered, including commercial models and devices that were developed for specific research purposes, such as the Multi-EMS [28]. For safety considerations, a medical-grade signal generator iSTEM EV-804 was selected to serve as the input. The device has both TENS and EMS modes. EMS mode was used in this research.

Signal Control Module

A signal control module is used to accurately and digitally set the properties of the electrical signals. In the HCI field, there are different versions of control modules developed for EMS related researches (shown in Figure 4.3), such as the Let Your Body Move Toolkit [29] and the OpenEMSStim [30]. These modules work as a signal amplifier and needs to be used together with a signal generator. There are also modules, such as the Multi-EMS [28], that not only offers independent controllable channels but also generate signals itself. However, because of safety concerns, the combination of a medical-grade signal generator and the control module from the Let Your Body Move Toolkit was selected for this study. To



LetYourBodyMove Control Module + iSTEM　openEMSstim　Multi-EMS

Figure 4.3 Three different control modules developed for ES related researches.

best fit the purpose, minor adjustments were made based on based on Pfeiffer's original design. The Arduino Nano was replaced by a ESP 32 to allow wireless and more stable communication with the computer. The schematics and PCB layout of the updated signal control module are illustrated in Figure 4.4.

Software

Processing is used to communicate with the control module through Bluetooth connection. Signal output can be adjusted via a graphical user interface (GUI) on Processing, which is illustrated on Figure 4.5. The top bar represents channel selection, which can be switched between "0" (channel 1) and "1" (channel 2). The next two bars represent intensity and signal length respectively, with each ranges from 0 to 255. When intensity is set at 75, for example, it means that the intensity of the signal output is at 29% of the input. From here, by clicking "send," a one-time ES signal can be delivered with the values set above. This is used in calibration of the ES. Once calibrated, repetition can be set with the bar below. The range was set from 0 to 50, but can be adjusted to any intended value. By clicking "Do Many," signals can be sent out at specified intensity, signal length, and repetition times through the selected channel.

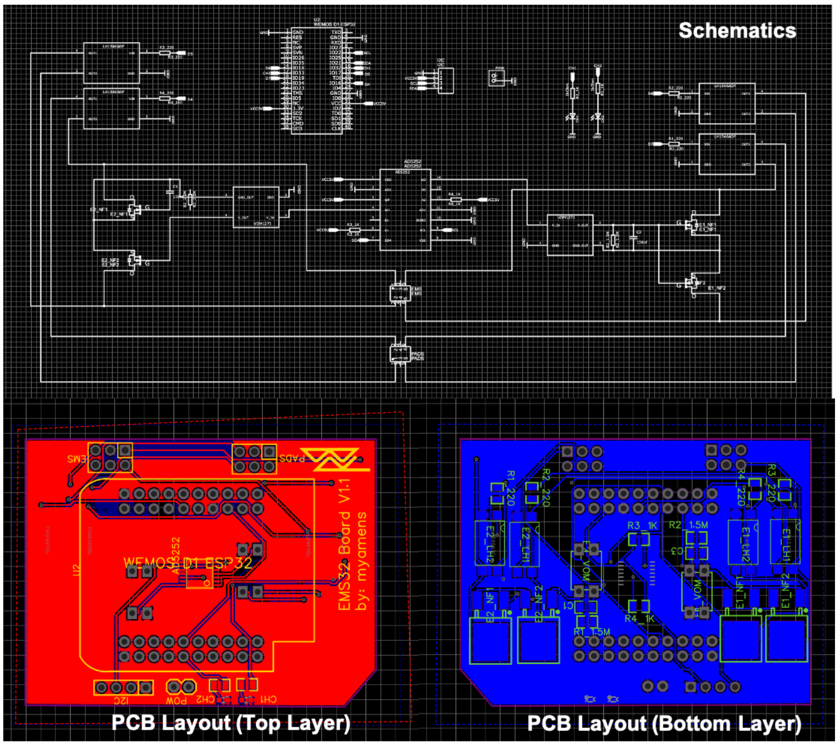
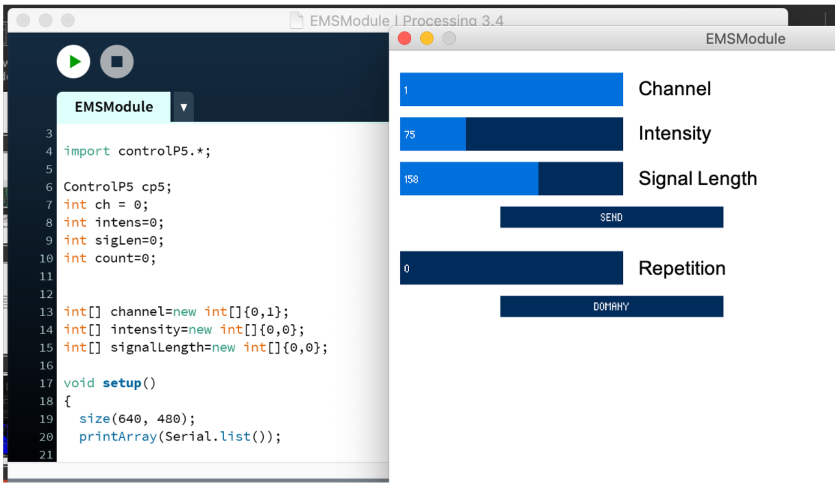


Figure 4.4 Schematics and PCB layout of ES control module.



```

import controlP5.*;

ControlP5 cp5;
int ch = 0;
int intens=0;
int sigLen=0;
int count=0;


int[] channel=new int[]{0,1};
int[] intensity=new int[]{0,0};
int[] signalLength=new int[]{0,0};

void setup()
{
  size(640, 480);
  printArray(Serial.list());

```

Figure 4.5 Graphical user interface (GUI) for ES signal output control.

4.1.4 Summary

Figure 4.6 demonstrates the final setups for the Pressure Sensing Insole and the Electrical Stimulation Toolkit. The design, implementation, and validation for the Pressure Sensing Insole, as well as the actuation design and validation for the overall system will be thoroughly explained in the following sections.

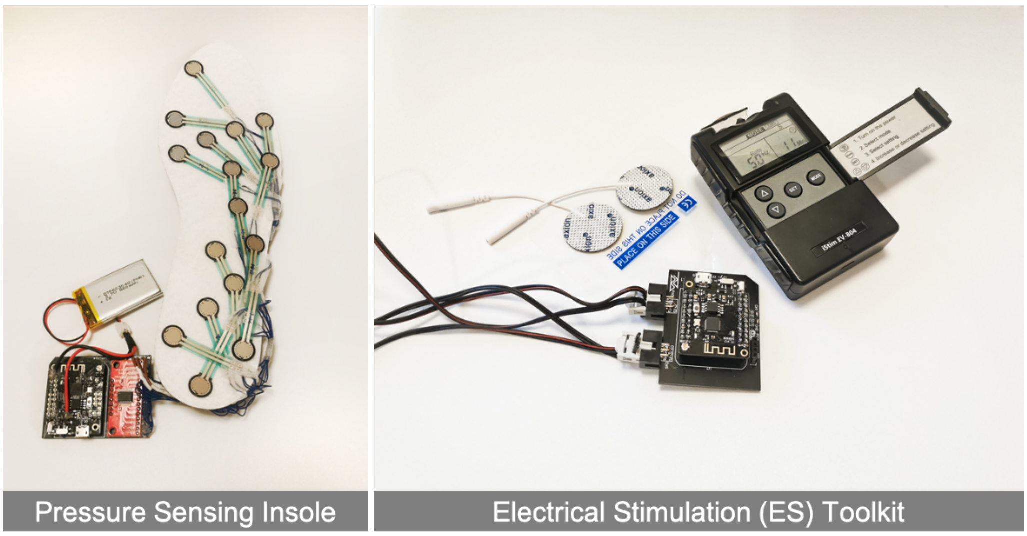


Figure 4.6 Final Setups for the Pressure Sensing Insole and the Electrical Stimulation Toolkit.

4.2. Pressure Sensing Insole

The Pressure Sensing Insole went through three versions of designs. The key differences between the three is the sensor placement design (shown in Figure 4.7). This section will walk through the design, implementation and validation process of the pressure sensing insole.

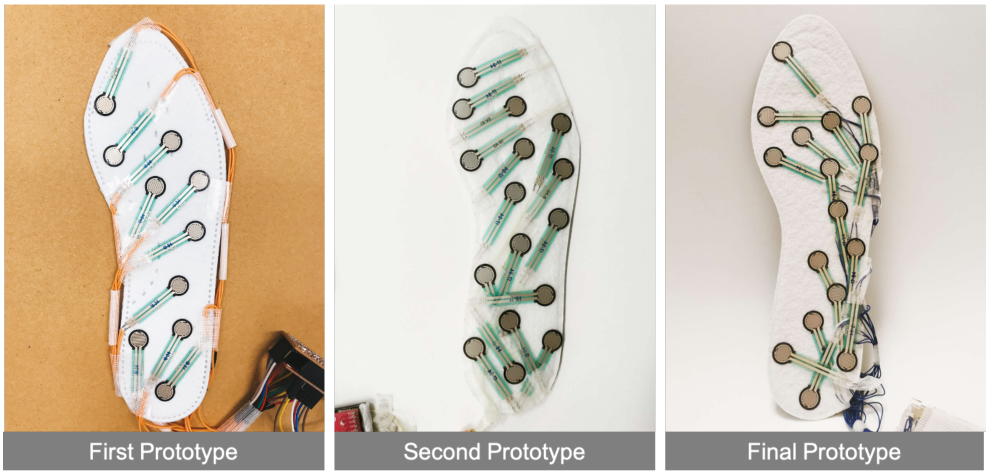


Figure 4.7 Three versions of design for the Pressure Sensing Insole.

4.2.1 First Prototype

Design and Implementation

The design and implementation process of the first prototype is shown in Figure 4.8. Footprint was collected from painting color on the user's feet and having him stand on a piece of white paper. Based on the footprint, 10 FSRs were placed on a soft cotton insole to cover the foot areas that are on contact with the ground. The FSRs were connected to the multiplexer through soft silicone wires, and components in the control unit were connected through jumper wires.

Initial Test

An initial test was conducted with the first prototype. The insole was placed inside a shoe and the controlling unit was attached on user's shoe with tape. The user was asked to walk in three types of foot placements, which includes inversion, normal and eversion. The three types of foot placements can be illustrated in Figure 4.9. In the inversion pattern, the user placed pressure mainly on the outer side of the feet. On the contrary, in the inversion pattern, the user placed pressure

Figure 4.8 Design and implementation process of the first prototype

mainly on the inner side of the feet.

Figure 4.9 Three types of foot placements: Inversion, Normal, Eversion.

Result and Evaluation

The user's pressure distribution during the gait can be seen through the real-time visualization on Processing. Key moments were manually selected from the screen recordings of the three gait patterns. On Figure 4.10, each circle represents an FSR on the same location of the pressure sensing insole. From white to red, the hue of the color indicates different values received by the FSR. The more pressure exerted on the FSR, the redder the circle will become.

Differences among the three gait patterns can be clearly seen from different activation levels of the FSRs, which proves that this setup can capture the user's foot

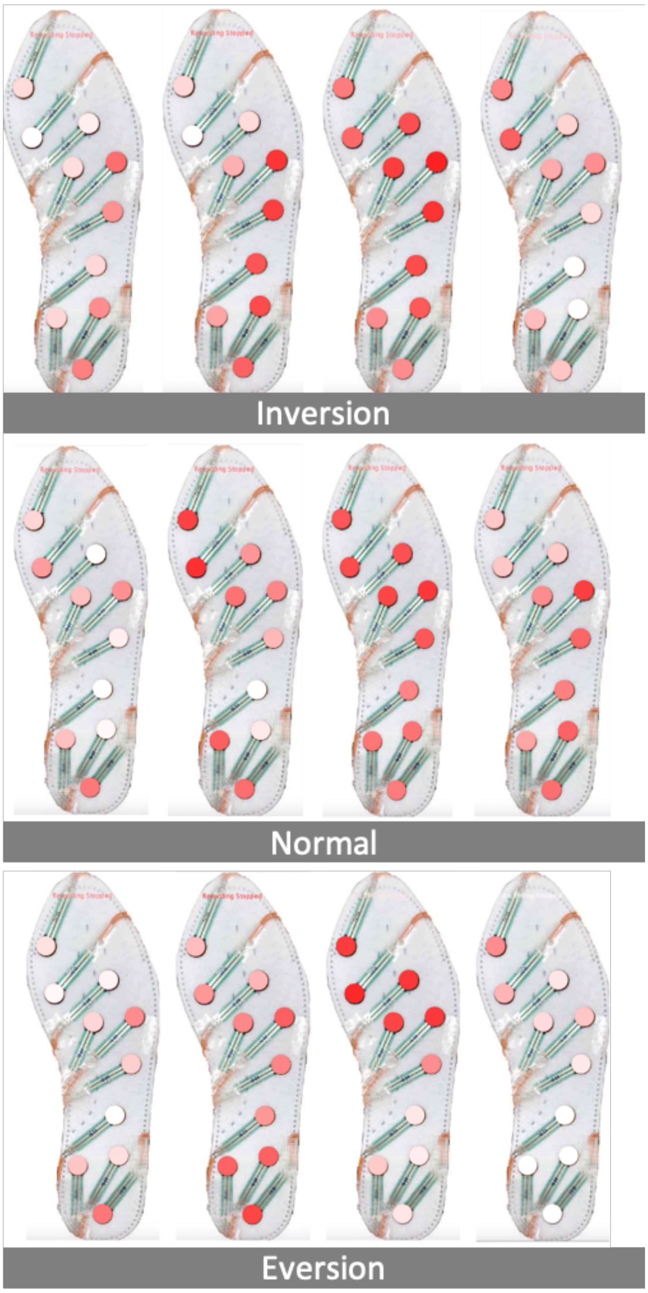


Figure 4.10 Generated images of the three foot placement patterns.

placement data and sends the data smoothly in real-time.

However, during the testing of this prototype, 2 key problems were identified: First, the footprint was collected with the user standing rather than walking on the paper. The pressure distribution could be different when he is walking, and there could be key areas that were not captured with the current sensor placement design. Second, the user reported that the setup is not very wearable as it created limitations while he was walking. The control unit also broke several times due to loose jumper wire connections.

4.2.2 Second Prototype

Design and Implementation

The second prototype was improved from 3 major aspects (shown in Figure 4.11): (1) Resolution was improved by using 16 FSRs in the second prototype. (3) Sensor placement was redesigned based on a new footprint collected by asking the user to complete one stance phase of gait ("begins when the foot first touches the ground and ends when the same foot leaves the ground" [1]) on a piece of white paper. (3) Wearability was greatly improved. The soft silicon wires that connect the 16 FSRs to the control unit is changed to a much thinner type, which has an outer diameter of 0.6mm, being only 1/3 of the previous one used. A layer of soft cotton insole was also added on top of the pressure sensing insole to prevent sweat and damage. A PCB was designed to mount all components in the control unit to make it more compact and more stable. The control unit is placed in a 3D printed box and attached on the side of the shoe with Velcro.

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[1] https://www.tekscan.com/blog/medical/gait-cycle-phases-parameters-evaluate-technology: :text=The%20stance%20phase%20of%20gait,foot%20touches%20the%20ground%20again

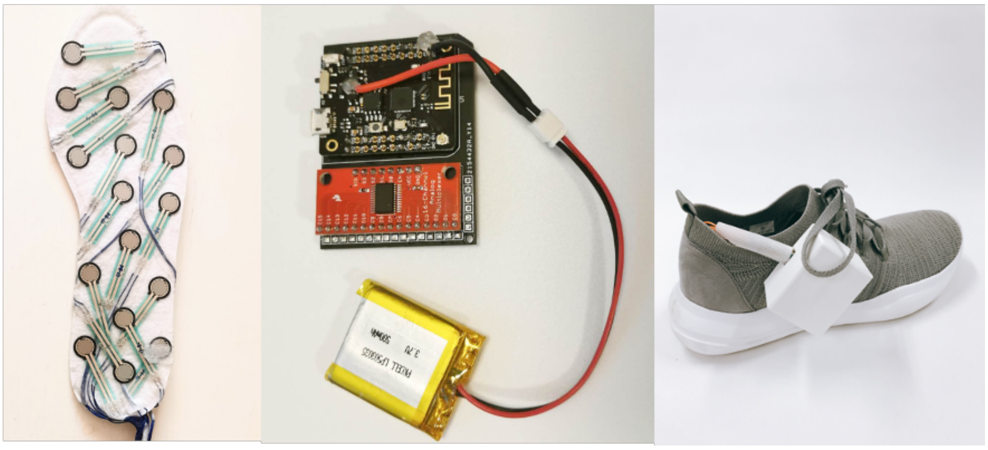

Figure 4.11 Major improvements made in the Second Prototype.

Testing and Evaluation

Same experiment procedure was conducted to test out the second prototype. Same as the previous time, key moments were manually selected from the screen recordings of the three gait patterns. Differences among the three gait patterns can be clearly seen from different activation levels of the FSRs. However, new issue was noticed as we attempted to analyze the data: As the FSRs were placed to simply cover the foot area that were in contact with the ground, there were no organized sensor groups to focus on specific areas of the feet, which created challenges for better understanding the data and identifying the gait pattern through data analyzation.

4.2.3 Final Prototype

Design and Implementation

The final prototype differs from the previous two versions mainly in the methodology used for the sensor placement design. Compare with the previous versions, in which the FSRs were randomly placed to cover the contact area, the final design separated the contact area into four regions and placed 4 sensors in each region.

Footprints were collected again by asking the user to complete one stance phase of gait on a piece of white paper. The process was repeated three times (on three different papers) with the user walking in three different patterns, which include inversion, normal and eversion. The footprints were further processed in Photoshop [2] and were combined to overlay each other on one single image. Based on the image generated (Figure 4.12), ABCD four areas were identified as the crucial areas for foot placement capturing. Four FSRs were evenly placed in each area, and in total 16 FSRs were used in this sensor placement design (Figure 4.13).

Figure 4.12 Three footprints collected (after image processing).

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[2] https://www.adobe.com/products/photoshop.html

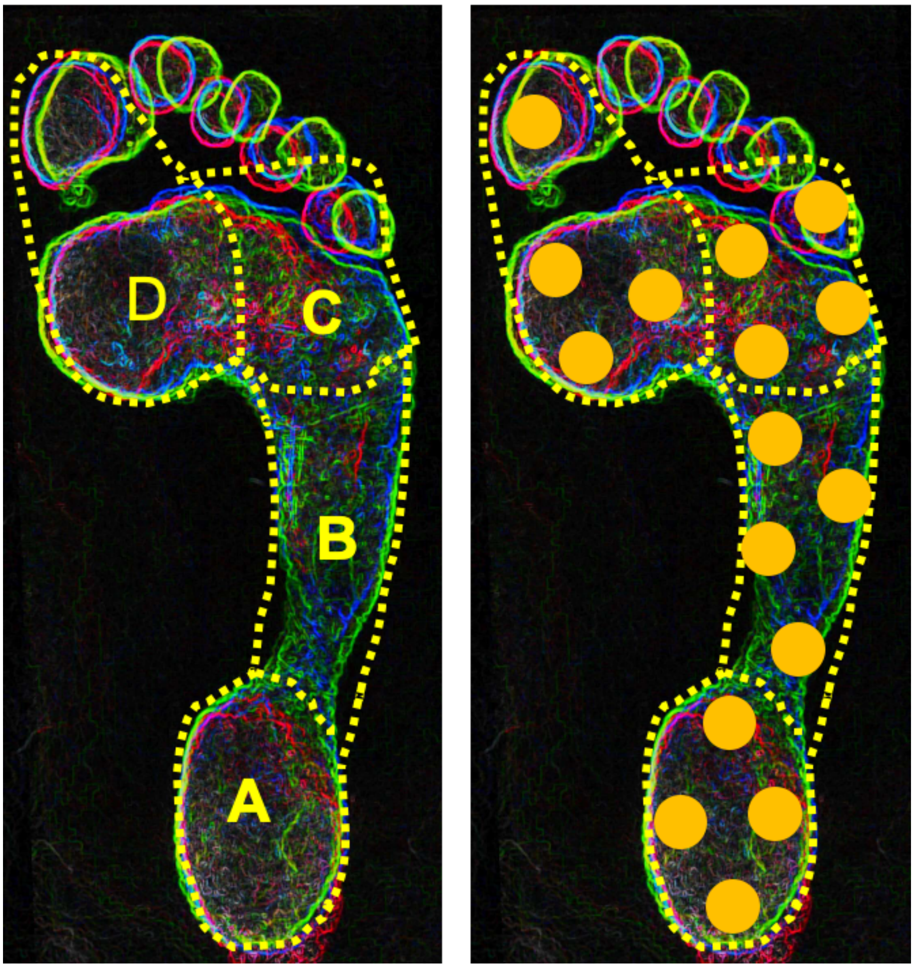

Figure 4.13 Sensor Placement Design.

4.2.4 Validation

Experiment Setup

Figure 4.14 demonstrates the wearable setup used in the validation of the final prototype. Pressure sensing insole was placed inside a shoe, and the control unit was attached to the user's ankle with an elastic band. It was confirmed with the user before taking any measurement that he didn't feel any restrictions and felt comfortable walking with the setup.

Figure 4.14 Wearable Setup for validation.

Experiment Procedure

The user was asked to walk within the same space three times with three different patterns, which includes normal, inversion and eversion. In all three times, data collection size was set to 1500 samples on Processing, meaning that the data recording will automatically stop after 1500 data are collected each time. The data was recorded at 20 samples/second , and each recording session took 75 seconds.

Result

Figure 4.15 illustrates the visualization of the three gait patterns. Differences can be clearly noticed in sensor activation among the three gait patterns.

Based on the data collected, four graphs were generated in order to to better understand the difference between three gait patterns (Figure 4.16). In the sine curve graphs, each graph demonstrates the change in total pressure experienced on the specific area over the 75 seconds. The three gait patterns are illustrated in three different colors. On each graph, the X axis indicates the time collapsed. As the data is collected at 20 samples/second, each unit on the X axis represents 0.05 second. The Y axis indicates the the total pressure applied on the specific area, which was calculated from sum of the 4 sensors in the area.

Figure 4.17 was further generated to demonstrate the average pressure exerted on each area in one gait cycle among the three gait patterns. Differences between three can be best in area D, C and B. Compare to the normal pattern, in the the inversion pattern, the pressure on area C and B is a lot higher than area D. While in the eversion pattern, the pressure on area D is a lot higher than area C and B.

Conclusion

This result proves that in order to identify the the three gait patterns, it is effective to place the sensors based on the ABCD four areas.

4.3. Electrical Stimulation

4.3.1 Actuation Design

Based on the validation of the pressure sensing insole, it can be identified that an inversion gait pattern is characterized by heightened pressure on area B, and low-

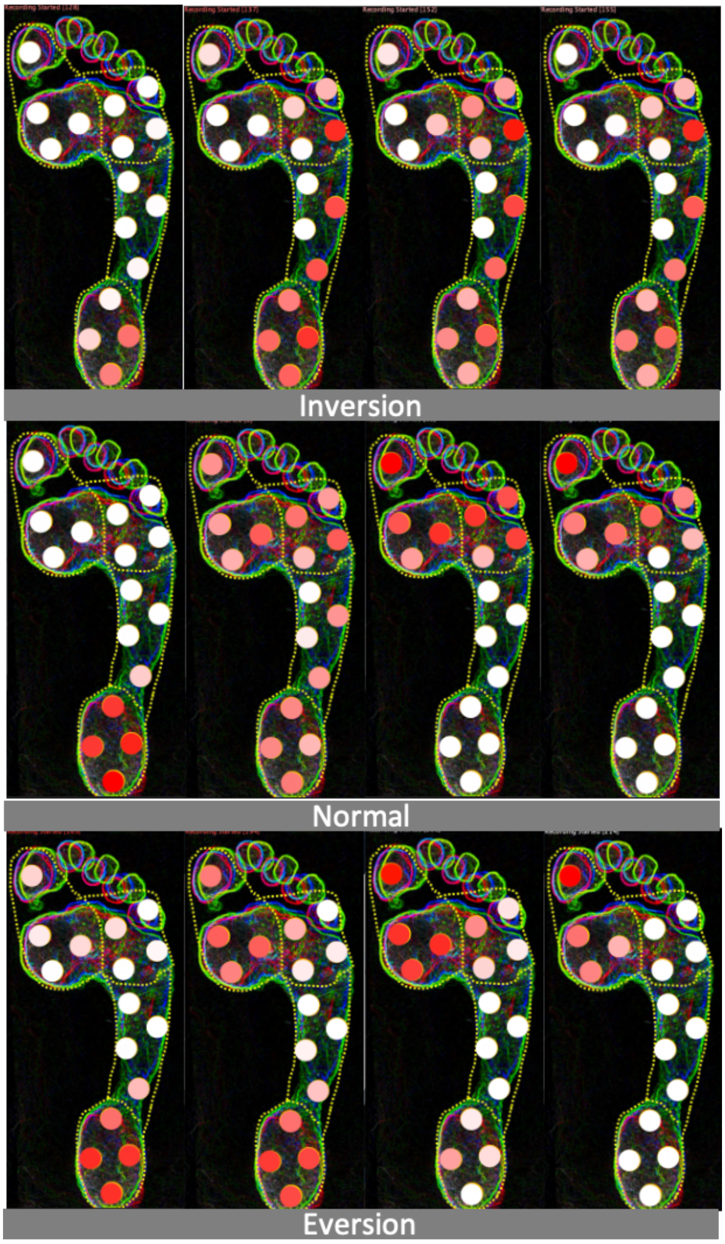

Figure 4.15 visualization of the three gait patterns.

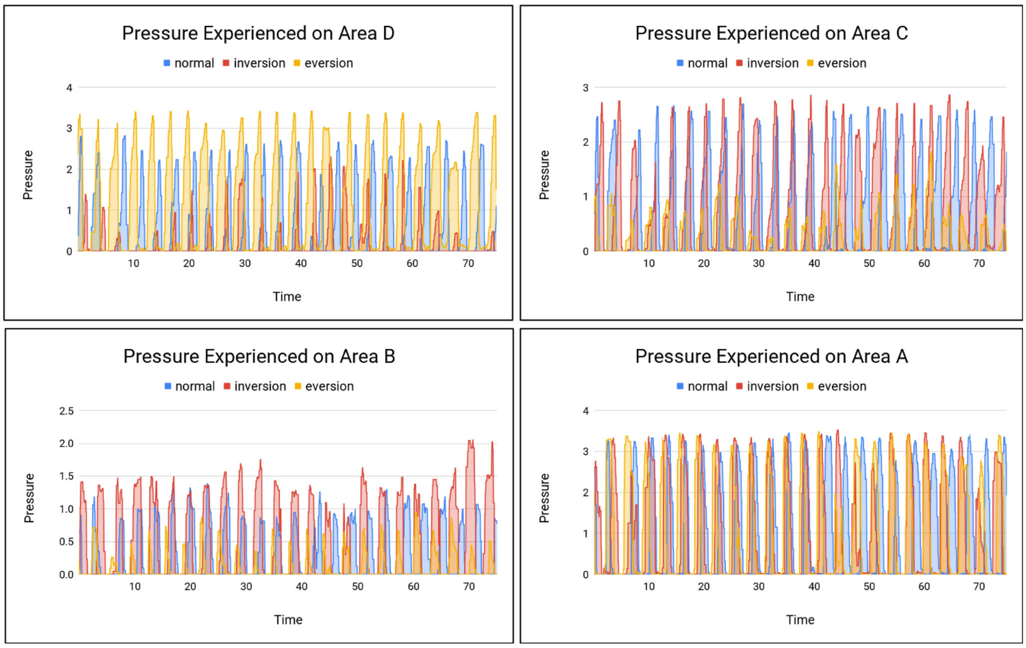

Figure 4.16 Sine curves of the total pressure on the corresponding area of the foot

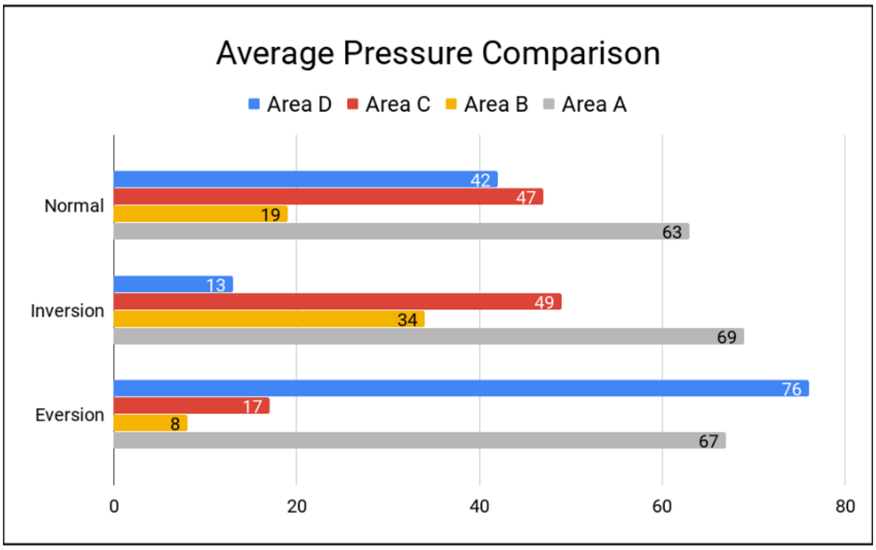

Figure 4.17 Average pressure exerted on each area in one gait cycle among the three gait patterns.

ered pressure on area D; on the contrary, an eversion gait pattern is characterized by heightened pressure on area D, and lowered pressure on area C and B. It can be further inferred that to modify the gait pattern means to change the pressure distributions among these three areas.

We assume that to alternate the gait patterns, we need to mainly actuate the DCB areas to alter the pressure distribution. Three actuation designs (as shown in Figure 4.18) were created to verify this assumption:

1. Actuation Pattern 1

   Electrodes are placed vertically next to each other on the outer edge of area D. We assume that by applying ES feedback on the inner side of the feet, pressure will be shifted toward the outer side of the feet. We assume that by applying ES feedback on the inner side of the foot, pressure will be shifted toward the outer side of the foot.

2. Actuation Pattern 2

   Electrodes are placed vertically next to each other on the outer edge of area C. We assume that by applying ES feedback on the outer side of the foot, pressure will be shifted toward the inner side of the foot.

3. Actuation Pattern 3

   Electrodes are placed vertically next to each other on the outer edge of area B. We assume that by applying ES feedback on the outer side of the foot, pressure will be shifted toward the inner side of the foot.

4.3.2 Validation

Experiment Setup

Figure 4.19 shows the experiment setup for the ES device. Equipment used includes an iSTEM EV-804 signal generator, an ES control module, two electrodes , and a power bank for powering the control module.

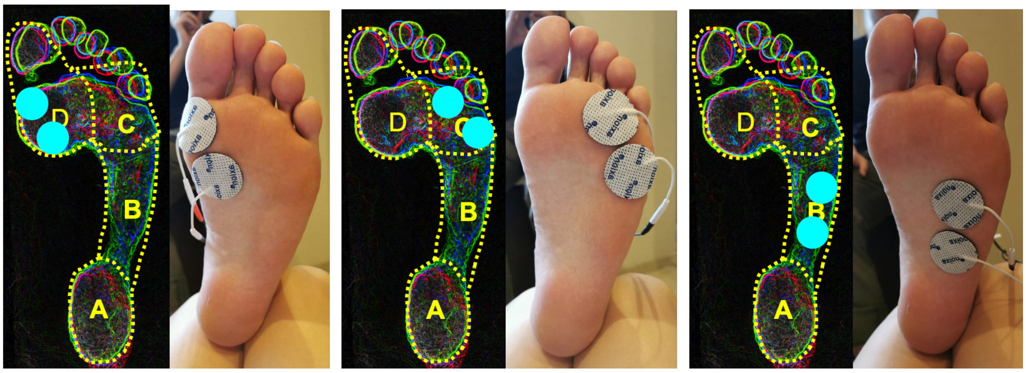

Figure 4.18 Design of three actuation patterns.

Figure 4.19 Experiment setup for the ES.

Other equipment used in the experiments includes a PC for remote signal control and data recording, a camera for capturing the process, tapes, and all equipment used in the pressure sensing insole setup.

On the iSTEM EV-805 signal generator, EMS mode was selected with pulse width at 50 microsecond and pulse repetition frequency at 50 hertz. The intensity was calibrated on the user's feet before the experiments and was determined to be set to level 6. On the GUI on processing, intensity was set at 100%, and signal length was set at 86%.

The ES Toolkit was attached on the user's waist. Cables were taped on the user's legs to prevent interfering with the movements. It was confirmed with the user before the experiment that he felt comfortable when walking with the setup and doesn't felt any constraint from the wires.

The user was instructed to wear the pressure sensing insole with the same experiment setup as before. To protect the electrodes and the pressure sensing insole, the user was asked to wear socks after electrodes were placed.

Experiment Procedure

Experiments were conducted for each actuation patterns to verify the assumption.

Electrodes were placed on area D, C and B respectively. In each experiment, the user was told to walk as he normally does within the same space twice, once with ES feedback applied and once without. The electrodes were attached on user's foot in both times. The user was not told what the ES feedback was for and was not aware the purpose of this study. In each time, the data recording was started at a random point while the user was walking, and was automatically stopped after 1500 data were collected.

Result

Two types of graphs were generated to validate the effectiveness of the three actuation patterns.

The sine curve graphs demonstrate the change in total pressure experienced on the specific area over the 75 seconds. The curves with ES feedback and without ES feedback are illustrated in red and blue respectively. On each graph, the X axis indicates the time collapsed. As data was collected at 20 data/second, each unit on the X axis represents 0.05 second. The Y axis indicates the total pressure per 0.05 second applied on the specific area, which was calculated from sum of the 4 sensors in the area.

The bar graphs illustrate the differences between the average peak values on each area before and after ES was applied. Peak values were identified from each stance phase over the 75 seconds on the specific area. On the graph, the X axis indicates the average peak value calculated.

1. Actuation pattern 1 (Figure 4.20)

   ES feedback was applied on area D. On the sine curves, pressure on area D decreased with ES. The pressure on area C and B slightly increased with ES. Area A doesn't show any visible difference.

   On the bar graph, the average peak value with ES shows a 15% decrease on area D, a 9% increase on area C, a 9% increase on area B, and a 1% decrease on area A.

   For each area, T-test was further conducted based on all peak values over the 75 seconds to check the significance of the changes. Area D shows ($P=.02$). Area C and B both show $P<.001$.

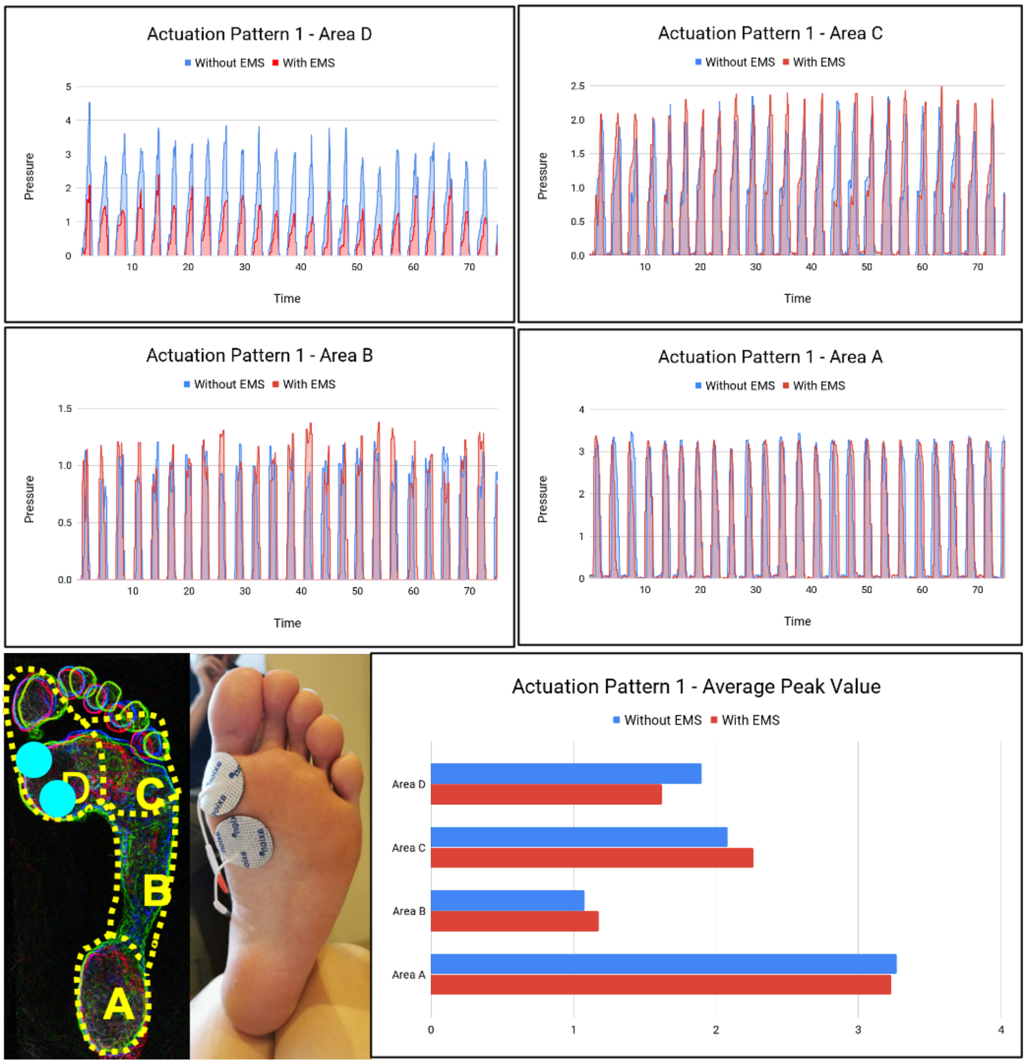

Figure 4.20 Actuation Pattern 1.

2. Actuation pattern 2 (Figure 4.21)

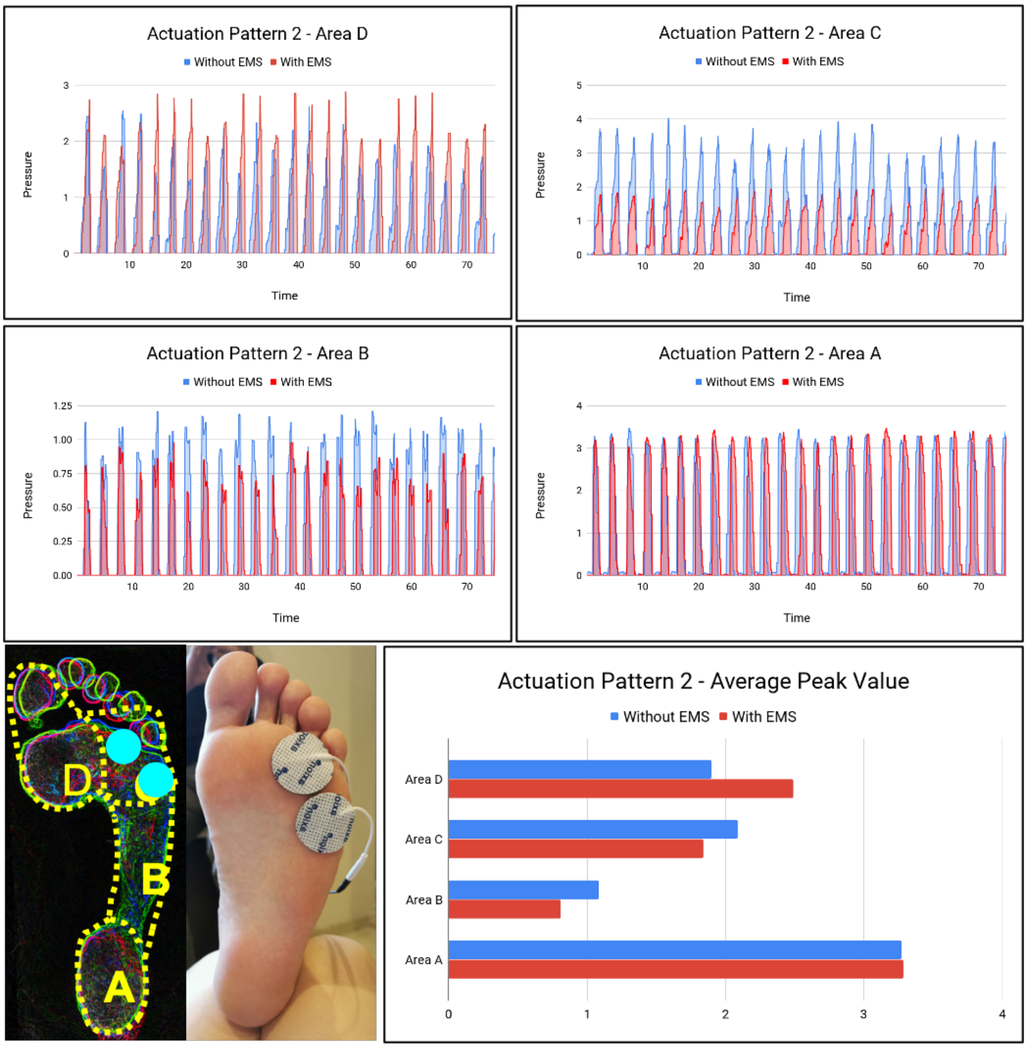

Figure 4.21 Actuation Pattern 2.

ES feedback was applied on area C. On the sine curves, pressure on area D increased with ES. The pressure on area C and B decreased with ES. Area A doesn't show any visible difference.

On the bar graph, the average peak value with ES shows a 31% increase on area D, a 12% decrease on area C, a 25% decrease on area B, and a 0.4% increase on area A.

For each area, T-test was further conducted based on all peak values over the 75 seconds to check the significance of the changes. For all three area, P<.001.

3. Actuation pattern 3 (Figure 4.22)

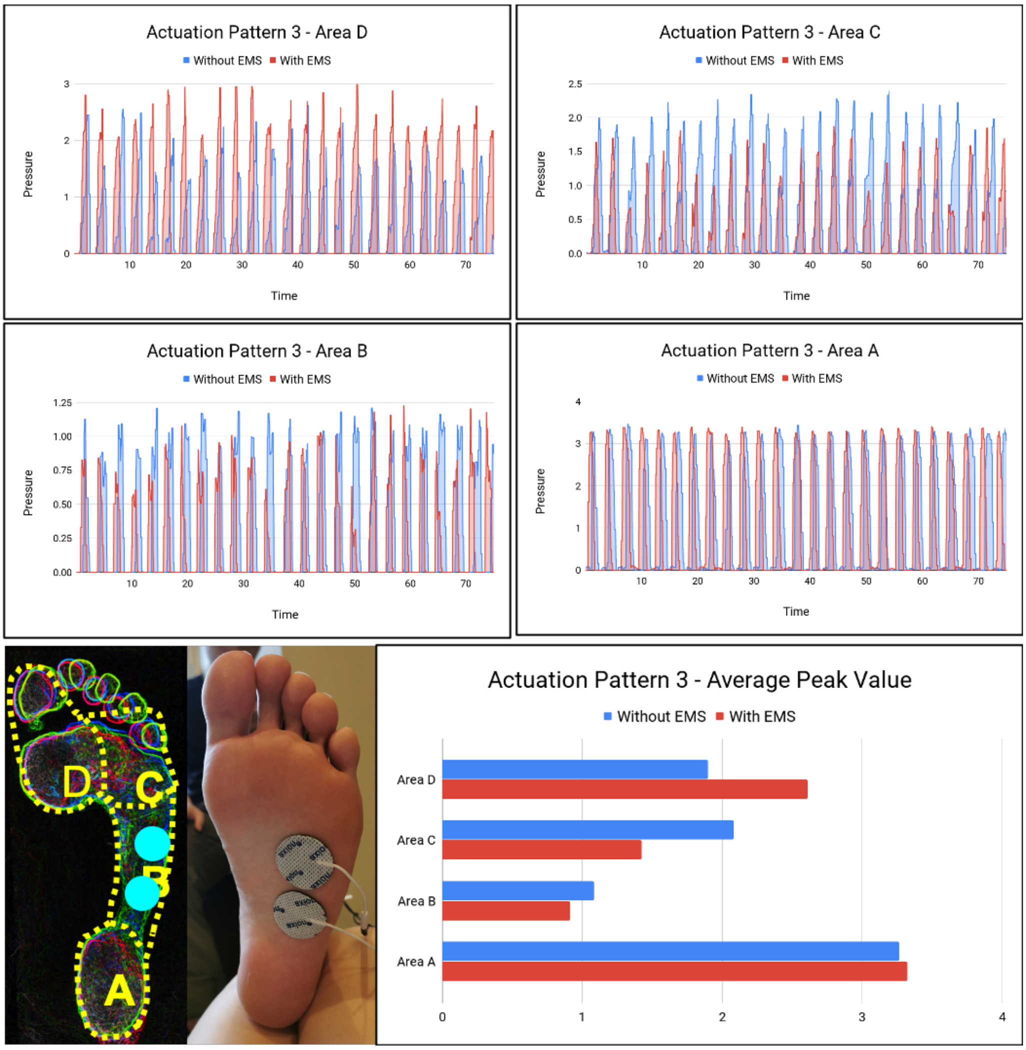

Figure 4.22 Actuation Pattern 3.

ES feedback was applied on area B. On the sine curves, pressure on area D increased with ES. The pressure on area C and B decreased with ES. Area A doesn't show any visible difference.

On the bar graph, the average peak value with ES shows a 38% increase on area D, a 31% decrease on area C, a 15% decrease on area B, and a 2% increase on area A.

For each area, T-test was further conducted based on all peak values over the 75 seconds to check the significance of the changes. For all three area, $P<.001$.

Conclusion

The results proved our assumption that area D, C, B are the key areas for actuation in order to alternate the gait patterns. By applying ES feedback on the outer side of the foot (either area C or B), pressure will be shifted toward the inner side of the foot to achieve an eversion pattern. On the contrary, by applying ES feedback on the inner side of the foot (area D), pressure will be shifted toward the outer side of the foot to achieve an inversion pattern.

Chapter 5

Conclusion

5.1. Conclusion

Technologies have changed the relationship between human and machine and the way they interact. While the interaction has became easier and smoother, the demand for operational effort still remains. To some extent, there is always gap between human and machine that we can constantly recognize that "we are using a tool." The gap between the two is not defined by physical distance but by the way they interact.

To tackle this problem, we discussed the concept of human-machine integration and proposed a scenario where we shifted the interface from the machine to the human body. Our goal is to close the gap between human and machine by introducing our body as an input/output device and minimizing the demand for operational efforts. Within this picture, we designed a system following the concept of human-machine integration and focusing on redesigning the human gait patterns. The system, named Cybergait, monitors our movements and changes our gait pattern by intervening the human sensorimotor system with electrical stimulation.

In this paper, we walked through the ideation process of Cybergait, including the background, concept, methods and application scenarios. The system, as we explained in Chapter 3, consists of a pressure sensing insole that monitors our movements and an ES toolkit that changes our gait pattern by intervening the human sensorimotor system with electrical stimulation. The system falls under our concept in terms of functionality, efficiency and wearability.

In Chapter 4, we described thoroughly the design, implementation and the validation of the system. As we understand that the core of human-machine integration should focus on designing for human rather than for the machine, we worked closely with our user throughout the process and listened carefully to his insights and feedbacks. We provided a customized design for the user which effectively captures his gait data and changes his gait pattern. The experiment results proved that by applying electrical stimulations on one side of the foot, we are able to shift the pressure to the other side and hence changes the gait pattern.

5.2. Limitations and Future Work

Real-Time Gait Evaluation

Cybergait is a system that monitors the gait and changes the gait through electrical stimulation. It answers the question of “how to monitor the gait?” as well as “how to modify the gait?” However, to help people truly gain better control of their gait patterns, an additional question remain to be answered, which is: how to regulate the gait? While the Pressure Sensing Insole enables us to observe and keep a record of our gait data, it does not provide any further reference or evaluation on the performance itself. Therefore, a real-time gait evaluation system must exist to analyze the gait data and trigger the haptic feedback for gait changing. In this research, ES feedback was triggered through manual activation via a graphical user interface on Processing. For future work, we aim to make Cybergait a closed-loop system that regulates the gait on itself. Our plan is to use a machine learning algorithm to identify each foot placement, compare with a preset “ideal” data, and triggers the feedback.

Actuation Design

In the experiments, we managed to alter the foot placement by just actuating one area per time. Although current actuation design allows us to switch to an inversion or an eversion pattern, it does not allow precise control over the gait changing. The relationship between the change in foot placement data and the properties (such as amplitude, frequency, and wave shape) set for the electrical stimulation need to be systematically examined in a future study to allow controllable adjustments.

Electrical Stimulation Setup

For safety considerations, we used a medical-grade signal generator and a modified control module based on the LetYourBodyMove Toolkit for the electrical stimulation. However, 2 major problems are identified to be improved in a future work: First, the actuation setup is big and requires to be mounted separately from the shoes. This conflicts which our intention of turning Cybergait into a smart footwear in the near future. The setup needs to be redesigned and improved to a much smaller size. Second, the current control module only allows 2 independent channels. To allow free control of the actuation patterns, the setup should be improved to provide multiple independent channels.

Reason Behind the Gait Pattern Change

In the experiments, the user reported that he could sense the stimulations when ES was applied, but he didn't notice that his gait pattern was changed. This proves that by providing haptic feedback to the feet, it is possible to intervene the human sensorimotor system and change the user's gait pattern without his cognitive engagement. However, what intrigues us is the reason behind the change. Three hypothesis are therefore proposed: (1) The increase in sensory feedback on the stimulated area changed the user's perception of the ground surface and triggered the brain to subconsciously adjust the the balance. (2) The electrical stimulation shrunk the stimulated muscle, leading the weight to be passively shifted to the other side of the feet. (3) The user subconsciously avoided walking with the stimulated side of the feet to avoid any unusual sensations. These three hypothesis will remain to be verified with additional setups in a future study.

Muscle Stimulation or Tactile Stimulation?

Throughout this paper, the actuation technique was referred as "electrical stimulation (ES)". However, it was not clear whether the stimulation happened on a muscular level or a tactile level. A user interview was conducted after the experiments. "During the calibrations, I could feel that my muscle was moving when the ES was on," the user reported, "But when I started walking, it felt more like a force constantly pushing my feet." Based on his feedback, it appears that the stimulation was either purely muscular or tactile but rather a combination of both. It remains to be thoroughly evaluated in a future study that which type of stimulation contributed the most in gait pattern changing.

Awareness of Electrical Stimulation in Movements

In a previous study which we applied ES feedback on the users' arms, users reported that they can only notice the stimulation when the arms remain static. Once they started to move their arms and engage in other things, the sensation tend to weaken that users won't even notice the ES feedback is still being applied. In this study, however, the user could sense the stimulation even when he was walking. The hypothesis is that the level of awareness is determined by the novelty of user's experience with ES and the user's engagement in the movement. In this case scenario, the user experienced with ES for the first time, and was told to walk with ES applied. Consequently, it can be assumed that the user would naturally pay more attention to his feet than usual and could therefore notice the stimulation even while he was walking. Nevertheless, the awareness of electrical stimulation in movements remain to be studied in a future study.

References

[1] Tomoya Sasaki, MHD Yamen Saraiji, Charith Lasantha Fernando, Kouta Minamizawa, and Masahiko Inami. Metalimbs: Multiple arms interaction metamorphism. In *ACM SIGGRAPH 2017 Emerging Technologies*, SIGGRAPH '17, New York, NY, USA, 2017. Association for Computing Machinery. URL: `https://doi.org/10.1145/3084822.3084837`, `doi:10.1145/3084822.3084837`.

[2] Junichi Nabeshima, MHD Yamen Saraiji, and Kouta Minamizawa. Arque: Artificial biomimicry-inspired tail for extending innate body functions. In *ACM SIGGRAPH 2019 Posters*, SIGGRAPH '19, New York, NY, USA, 2019. Association for Computing Machinery. URL: `https://doi.org/10.1145/3306214.3338573`, `doi:10.1145/3306214.3338573`.

[3] Laura A. Malone and Amy J. Bastian. Thinking about walking: Effects of conscious correction versus distraction on locomotor adaptation. *Journal of Neurophysiology*, 103(4):1954–1962, 2010. PMID: 20147417. URL: `https://doi.org/10.1152/jn.00832.2009`, `arXiv:https://doi.org/10.1152/jn.00832.2009`, `doi:10.1152/jn.00832.2009`.

[4] David J. Clark. Automaticity of walking: functional significance, mechanisms, measurement and rehabilitation strategies. *Frontiers in Human Neuroscience*, 9:246, 2015. URL: `https://www.frontiersin.org/article/10.3389/fnhum.2015.00246`, `doi:10.3389/fnhum.2015.00246`.

[5] R. M. Kenedi. *Biomechanics and related bio-engineering topics: proceedings of a symposium held in Glasgow.* Symposium Publications Division, Pergamon Press, The address, 1965.

[6] Blandine Bril and Yvon Brenière. Postural requirements and progression velocity in young walkers. *Journal of motor behavior*, 24:105–16, 04 1992. `doi:10.1080/00222895.1992.9941606`.

[7] Y Brenière and Blandine Bril. Development of postural control of gravity forces in children during the first 5 years of walking. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, 121:255–62, 09 1998. `doi:10.1007/s002210050458`.

[8] Daniela De Bartolo and Marco Iosa. The walking brain: Factors influencing human gait. 11 2018. `doi:10.13140/RG.2.2.22453.93927`.

[9] et al. Bernstein, N.A. Tbiodynamics of locomotion. 1935. VIEM, Moscow, USSR.

[10] Walter Schneider and Richard Shiffrin. Controlled and automatic human information processing: I. detection, search, and attention. *Psychological Review*, 84:1–66, 01 1977. `doi:10.1037/0033-295X.84.1.1`.

[11] Walter Schneider and Jason M. Chein. Controlled automatic processing: behavior, theory, and biological mechanisms. *Cognitive Science*, 27(3):525 – 559, 2003. 2002 Rumelhart Prize Special Issue Honoring Richard Shiffrin. URL: `http://www.sciencedirect.com/science/article/pii/S0364021303000119`, `doi:https://doi.org/10.1016/S0364-0213(03)00011-9`.

[12] David A. Winter. *Biomechanics and motor control of human movement.* Hoboken, N.J. : Wiley, c2009, 4 edition, 2009.

[13] Alexandra Pfister, Alexandre West, Shaw Bronner, and Adam Noah. Comparative abilities of microsoft kinect and vicon 3d motion capture for gait analysis. *Journal of medical engineering technology*, 38:1–7, 05 2014. `doi:10.3109/03091902.2014.909540`.

[14] F. Gholami, D. A. Trojan, J. Kövecses, W. M. Haddad, and B. Gholami. A microsoft kinect-based point-of-care gait assessment framework for multiple sclerosis patients. *IEEE Journal of Biomedical and Health Informatics*, 21(5):1376–1385, 2017.

[15] Edmund Y.S. Chao. Justification of triaxial goniometer for the measurement of joint rotation. *Journal of Biomechanics*, 13(12):989 – 1006, 1980. URL: `http://www.sciencedirect.com/science/article/pii/0021929080900445`.

[16] Morey Kolber and William Hanney. The reliability and concurrent validity of shoulder mobility measurements using a digital inclinometer and goniometer: A technical report. *International journal of sports physical therapy*, 7:306–13, 06 2012.

[17] Lorraine M Lanningham-Foster, Teresa B Jensen, Shelly K McCrady, Lana J Nysse, Randal C Foster, and James A Levine. Laboratory measurement of posture allocation and physical activity in children. *Medicine and science in sports and exercise*, 37(10), October 2005.

[18] D. Gafurov, E. Snekkenes, and P. Bours. Gait authentication and identification using wearable accelerometer sensor. In *2007 IEEE Workshop on Automatic Identification Advanced Technologies*, pages 220–225, 2007.

[19] RO Robinson, W Herzog, and BM Nigg. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *Journal of manipulative and physiological therapeutics*, 10(4):172–176, August 1987. URL: `http://europepmc.org/abstract/MED/2958572`.

[20] Maarit Piirtola and Pertti Era. Force platform measurements as predictors of falls among older people – a review. *Gerontology*, 52:1–16, 02 2006.

[21] Pui W. Kong and Hendrik [De Heer]. Wearing the f-scan mobile in-shoe pressure measurement system alters gait characteristics during running. *Gait Posture*, 29(1):143 – 145, 2009. URL: `http://www.sciencedirect.com/science/article/pii/S0966636208001513`, `doi:https://doi.org/10.1016/j.gaitpost.2008.05.018`.

[22] L. Shu, T. Hua, Y. Wang, Q. Li, D. D. Feng, and X. Tao. In-shoe plantar pressure measurement and analysis system based on fabric pressure sensing array. *IEEE Transactions on Information Technology in Biomedicine*, 14(3):767–775, 2010.

[23] Simona Crea, Marco Donati, Stefano De Rossi, Calogero Oddo, and Nicola Vitiello. A wireless flexible sensorized insole for gait analysis. *Sensors*, 14(1):1073–1093, Jan 2014. URL: `http://dx.doi.org/10.3390/s140101073`.

[24] S. K. Banala, S. H. Kim, S. K. Agrawal, and J. P. Scholz. Robot assisted gait training with active leg exoskeleton (alex). *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 17(1):2–8, 2009.

[25] Cutkosky MR Besier TF. Shull PB, Lurie KL. Training multi-parameter gaits to reduce the knee adduction moment with data-driven models and haptic feedback. *Journal of biomechanics*, 44(9):1605–1609, 2011. URL: `https://doi.org/10.1016/j.jbiomech.2011.03.016`.

[26] Anne Kavounoudias, Régine Roll, and Jean-Pierre Roll. Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation. *The Journal of Physiology*, 532(3):869–878, 2001. URL: `https://physoc.onlinelibrary.wiley.com/doi/abs/10.1111/j.1469-7793.2001.0869e.x`, `doi:10.1111/j.1469-7793.2001.0869e.x`.

[27] Marguerite Wieler, Richard Stein, Michel Ladouceur, Maura Whittaker, Andrew Smith, Saad Naaman, Hugues Barbeau, Joanne Bugaresti, and Elaine Aimone. Multicenter evaluation of electrical stimulation systems for walking. *Archives of physical medicine and rehabilitation*, 80:495–500, 05 1999. `doi:10.1016/S0003-9993(99)90188-0`.

[28] Michinari Kono, Yoshio Ishiguro, Takashi Miyaki, and Jun Rekimoto. Design and study of a multi-channel electrical muscle stimulation toolkit for human augmentation. In *Proceedings of the 9th Augmented Human International Conference*, AH '18, New York, NY, USA, 2018. Association for Computing Machinery. URL: `https://doi.org/10.1145/3174910.3174913`, `doi:10.1145/3174910.3174913`.

[29] Max Pfeiffer, Tim Duente, and Michael Rohs. Let your body move: a prototyping toolkit for wearable force feedback with electrical muscle stimulation. pages 418–427, 09 2016. `doi:10.1145/2935334.2935348`.

[30] Pedro Lopes and Patrick Baudisch. Demonstrating interactive systems based on electrical muscle stimulation. In *Adjunct Publication of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, page 47–49, New York, NY, USA, 2017. Association for Computing Machinery. URL: `https://doi.org/10.1145/3131785.3131806`, `doi:10.1145/3131785.3131806`.