Shaping Egocentric Experiences with Wearable Cybernic Interfaces

March　２０１９

Nishida Jun

Shaping Egocentric Experiences with Wearable Cybernic Interfaces

School of Integrative and Global Majors
Ph.D. Program in Empowerment Informatics
University of Tsukuba

March ２０１９

Nishida Jun

"facts is precisely what there is not, only interpretations"

Friedrich Nietzsche

Abstract

In the field of rehabilitation, it is important to share kinesthetic information such as muscle activity, which is hardly ever observed visually, between a physical therapist and a patient. For product designers and nursing teachers, it would be valuable experience to see and explore classrooms or hospital rooms from the point of view of a childs stature. Normal people also never experience inconvenience as known by Parkinsons patients, who manage the handling of eating utensils with hand tremors. These embodied experiences are broadly categorized as embodied knowledge, which cannot be acquired by conversations or visual media, but only through active physical experiences. Therefore, new media or tools that can reproduce embodied and social experiences through active and embodied actions are required to bridge the gap between the patient and the therapist.

I hypothesized that changing a person's body, including the related embodied and social experiences, to that of another person such as a child or a patient, while allowing active interaction with the surrounding objects and people in a real-world environment, would provide more valuable as well as empathic knowledge to school teachers, product designers, and medical staff when designing living environments or communicating with others. To achieve these new paradigms to acquire embodied knowledge of personal experiences, I designed the following two types of corporeal changes: 1) changing the visual and haptic perspectives into those of a child, and 2) changing the kinesthetic perspective to that of a patient. With the recent advancements in wearable technologies and virtual reality, a humans embodied experiences can be augmented beyond the limitation of space and time. Wearable devices have allowed users to not only experience new body functions but also extend their sense of ownership and presence to another person or another creature. Interestingly, it has been speculated that experiencing bodily changes with these wearable technologies also change the associated bodily sensations.

In this research, I developed wearable devices that can sense and intervene in human body functions directly for changing ones bodily sensation or perspective. This allows the wearer to experience changes in perception, action, and interaction while preserving the active, embodied, and social experiences within a real environment; this is a beneficial method for supporting the acquisition of embodied knowledge for the scenarios that are experienced. To achieve this, I have developed two wearable systems: CHILDHOOD and bioSync. The former device allows people to change their height of eyesight into a lower stature and to change their hand dimensions into that of 5-year old by using a head-mounted display, a wearable stereo camera, and passive hand exoskeletons. The latter device shares kinesthetic experiences among people by means of Electrical

Muscle Stimulation and biosignal measurement, allowing to experience Parkinsons tremor on a healthy subject including a product designer.

I setup the following research questions: 1) Can we shape our own embodied experience into another form while preserving an active manner? 2) What is the design requirements for interfaces that change ones experience? and 3) How does changing bodies change our perceptions, actions and even interactions? These questions would not only demonstrate the new techniques to gain the empathy toward different people but also contribute to reveal new aspects of human behavior.

To explore these questions, I investigated the wearers perceptions, actions, and interactions throughout lab and field studies, and discuss how the wearable systems contribute to the change of bodily sensation. These studies verified that the devices have changed the wearers embodied and social experiences, and also gained embodied knowledge and empathy toward different people through the wearers active engagement with existing environments. Interestingly, not only the wearer but also the surrounding people changed their interaction toward the wearer. It is assumed that the change in the wearers body created new social context with surrounding people, enhancing the shaping of bodily sensation. I conclude by sketching an outline for future research on changing body representation by listing technical, phenomenological, and psychological questions and challenges.

Acknowledgements

My greatest gratitude is for my supervisor Prof. Kenji Suzuki for giving me the opportunity to be part of his laboratory, for his valuable support, and guidance. He encouraged me to continue pursuing this work. The work done in this thesis could not have been accomplished without him.

My gratitude is also for Prof. Yoshiyuki Sankai, Prof. Yoshinari Kameda, Prof. Hideo Tsurushima, and Prof. Yanaga Masao for their valuable supervision and inspiring comments on this work.

This work was supported by Grant-in-Aid for JSPS Research Fellow Grant Number 16J03777 and Innovation Program, Strategic Information and Communications R&D Promotion Programme by the Japanese Ministry of Internal Affairs and Communications. I also would like to thank Microsoft Research Asia and Sony Computer Science Laboratories for providing me academic opportunities.

I would particularly like to thank Dr. Shunichi Kasahara at Sony Computer Science Laboratories, Inc. and Assistant Professor Pedro Lopes at University of Chicago for their generous and strong support.

Finally I would also like to thank the members of the Artificial Intelligence Laboratory and other members of the University of Tsukuba for their support and inspirations. This study was supported in part by CIME; Center for Innovative Medicine and Engineering, and Ph.D. Program in Empowerment Informatics, University of Tsukuba.

Contents

Abstract **iv**

Acknowledgements **vii**

1 Introduction **1**
- 1.1 Challenge 1
- 1.2 Vision: Sympathy to Empathy 2
- 1.3 Shaping Egocentric Experience 4
  - 1.3.1 Overview 4
  - 1.3.2 Benefits 5
  - 1.3.3 Experience Design Challenges 6
  - 1.3.4 Interface Design Challenges 6
- 1.4 Objective 8
  - 1.4.1 Smaller-person Experience 8
  - 1.4.2 Blending Kinesthetic Experience 9
- 1.5 Research Questions 9
- 1.6 Thesis Outline 9

2 Related Works **11**
- 2.1 Neuroscience 11
  - 2.1.1 Plastic Body Representation 11
  - 2.1.2 Simple Tool Use Changes Bodies 11
  - 2.1.3 Rubber Hand Illusion 12
- 2.2 Psychology 12
  - 2.2.1 Experiencing Child Avatars 12
  - 2.2.2 Changing Skin Colors 13
- 2.3 Interaction Research 14
  - 2.3.1 Supernumerary Body Function 14
  - 2.3.2 Extending Body Function 14
  - 2.3.3 Changing Body Function 14

3 Methodology **17**
- 3.1 Smaller-person Experience 17
  - 3.1.1 Introduction 17
  - 3.1.2 Research Goal 18
  - 3.1.3 Contributions 19
  - 3.1.4 Related Works 19
  - 3.1.5 Concept 21
  - 3.1.6 Design Considerations 23
- 3.2 Blending Kinesthetic Experience 24
  - 3.2.1 Introduction 24

3.2.2 Contribution 25
3.2.3 Related Work 26
3.2.4 Concept 28
3.2.5 Interaction Modeling 29
3.2.6 Design Considerations 30

4 Implementation 31
4.1 Smaller-person Experience 31
4.1.1 Overview 31
4.1.2 Visual Translator 31
4.1.3 Passive Hand Exoskeleton 34
4.2 Blending Kinesthetic Experience 40
4.2.1 Overview 40
4.2.2 EMG Measurement During Stimulation 40
4.2.3 EMG Measurement 41
4.2.4 Electrode Configuration 43
4.2.5 RFID-based Connection 44
4.2.6 Scalable Configuration 45

5 Performance Evaluation 47
5.1 Smaller-person Experience 47
5.1.1 Visual Translator: Latency 47
5.1.2 Hand Exoskeleton: Linke Mechanism 47
5.2 Blending Kinesthetic Experience 49
5.2.1 System Latency 49
5.2.2 Performance Measurement 49

6 User Studies 53
6.1 Smaller-person Experience 53
6.1.1 Overview 53
6.1.2 Wearer's Perception 53
6.1.3 Wearer's Action 56
6.1.4 Wearer's Hand Function 58
6.1.5 Wearer's Interaction 62
6.2 Blending Kinesthetic Experience 66
6.2.1 Subjective Perceptual Experiment 66
6.2.2 Joint Stiffness Measurement 67
6.2.3 Joint Stiffness Perception 70
6.2.4 Rhythmic Activity Synchronization 72
6.2.5 Faster Kinesthetic Reaction 74
6.2.6 Embodied Impairment Experience 78

7 Discussion 81
7.1 Smaller-person Experience 81
7.1.1 Wearer's Perception 81
7.1.2 Wearer's Action 82
7.1.3 Wearer's Interaction 84
7.2 Blending Kinesthetic Experiences 85

7.2.1 System Evaluation, Latency, and Performance . 85
7.2.2 Subjective Perceptual Experiment 85
7.2.3 Joint Stiffness Measurement 85
7.2.4 Joint Stiffness Perception 86
7.2.5 Rhythmic Activity Synchronization 86
7.2.6 Faster Kinesthetic Reaction 87
7.2.7 Embodied Impairment Experience 87

8 Future Works 89
8.1 Smaller-person Experience 89
8.1.1 Another Form of Changing Body Representation 89
8.1.2 Peripheral Visual Field 89
8.1.3 Central Visual Field 90
8.1.4 Possible Scenarios 92
8.2 Blending Kinesthetic Experience 93
8.2.1 Electrode Placement 93
8.2.2 Blending of Contraction Strength 93
8.2.3 Possible Scenarios 93

9 Conclusions 97
9.1 Smaller-person Experience 97
9.2 Blending Kinesthetic Experience 98
9.3 Shaping Egocentric Experiences 98
9.4 General Conclusion 99

Bibliography 103

List of Figures

1.1 Target Scenarios of Understanding One's Experiences . 1
1.2 Existing Tools to Convey One's Experiences 2
1.3 Conceptual Representation of Shaping Experiences . . 4
1.4 Conceptual Representation of Objectives 8

2.1 Topological Representations of Body Functions 13

3.1 Representative Image of Smaller-person Experience . . 18
3.2 Research Position of Our Egocentric Experience 19
3.3 Concept of Egocentric Small-person Experience 22
3.4 Representative Image of Blending Kinesthetic Experience 24
3.5 Model of Blended Kinesthetic Interaction 27

4.1 Overview of the Developed Wearable Device 32
4.2 System Architecture 32
4.3 System Configuration 33
4.4 Visual Perspectives 33
4.5 Conceptual Representation of Hand Exoskeleton 34
4.6 Exoskeleton Design Procedure 35
4.7 Link Model of the Prototype Version 35
4.8 Simulation experiment results of the trajectory calculation 36
4.9 CAD Model of the Prototype Version 37
4.10 Implementation of the Prototype Exoskeleton 37
4.11 Link Model of the Improved Version 38
4.12 CAD Model of the Improved Version 38
4.13 Implementation of the Improved Exoskeleton 39
4.14 Overview of the developed device, bioSync 40
4.15 System Architecture and Process Diagram 40
4.16 Timing Chart of Measurement, Stimulation and Discharge 42
4.17 System Configuration 42
4.18 Device Implementation 43
4.19 Electrodes Placement 43
4.20 Daisy-chain Configuration of the Developed I/O Device 44
4.21 Scalable Configuration of the System 44
4.22 Schematic of bioSync's Circuitry 45

5.1 Passive Hand Exoskeleton: Performance Evaluation . . 48
5.2 Experiment Setup: Performance Measurement 50

5.3 Experiment Result: Performance Measurement 50

6.1 Overview of the User Studies 53
6.2 Experiment Overview of the Personal Space Evaluation 54
6.3 Wearer's Perception: Experiment Results 56
6.4 Experiment Overview of the Handshake Evaluation . . 57
6.5 Wearer's Action: Experiment Results 58
6.6 Chronological Hand Function: Experiment Setup . . . 59
6.7 Experiment Overview of the Hand Function Evaluation 59
6.8 Hand Function: Peg Size and Movement Time 60
6.9 Hand Function: Peg Route and Movement Time 61
6.10 Wearer's Interaction: Likert Questionnaire 62
6.11 Wearer's Interaction: Body Representation 63
6.12 Wearer's Interaction: Interaction Observation 64
6.13 Wearer's Interaction: Interaction Observation 65
6.14 Experiment Result: Subjective Perceptual Evaluation . 67
6.15 Experiment Setup: Measurement of the Wrist Joint Stiffness 68
6.16 Experiment Results: Measurement of the Wrist Joint Stiffness 69
6.17 Conceptual Representation of Interactive Peg Rehabilitation 70
6.18 Experiment Setup of Sharing Joint Stiffness 71
6.19 Result of sharing the wrist stiffness 72
6.20 Experiment Setup: Rhythmic Activity Synchronization 74
6.21 Experiment Result: Rhythmic Activity Synchronization 74
6.22 Experiment Result: Rhythmic Activity Synchronization 75
6.23 Representative Image of Wired Muscle 76
6.24 System diagram of Wired Muscle 76
6.25 A detailed sequence of the kinesthetic reaction by Wired Muscle. 77
6.26 Success Rate of the Pen Grab Test 78
6.27 Reported Sense of Agency 78
6.28 Experiment Setup and Result: Impairment Experience . 80

7.1 Horizontal Error during the Handshake Experiment . . 82
7.2 Head Orientation during the Handshake Experiment . 83
7.3 Demonstration at Exhibition: Impairment Experience . 88

8.1 Possible Scenarios of Smaller-person Experience 91
8.2 Possible Scenarios of Blending Kinesthetic Experience . 96

List of Abbreviations

AC	**A**lternating **C**urrent
ADL	**A**ctivities in **D**aily **L**ife
AR	**A**ugmented **R**eality
BR	**B**ody **R**epresentation
CG	**C**omputer **G**raphics
DC	**D**irect **C**urrent
EMG	**E**lectro-**M**yo **G**ram
EMS	**E**lectrical **M**uscle **S**timulation
FOV	**F**ield **O**f **V**iew
FPV	**F**irst **P**erson **V**iew
HCI	**H**uman **C**omputer **I**nteraction
IF	**I**nter**f**ace
IO	**I**nput and **O**utput
IX	**I**nteraction (**X**)
MIS	**M**aximum **I**nvoluntary **S**tiffness
MSS	**M**aximum **S**timulus **S**tregnth
MVC	**M**aximum **V**oluntary **C**ontraction
POV	**P**oint **O**f **V**iew
PPS	**P**eri **P**ersonal **S**pace
QoL	**Q**uality **O**f **L**ife
RE	**R**eal **E**nvironment
RHI	**R**ubber **H**and **I**llusion
ROM	**R**ange **O**f **M**otion
UART	**U**niversal **A**synchronous **R**eceiver/**T**ransmitter
VE	**V**irtual **E**nvironment
VR	**V**irtual **R**eality

List of Symbols

a	Weight
C	Capacitor
d	Distance
$D(t)$	Pulse width at time t
$e(t)$	Contraction strength at time t
$f(x)$	Perceptual function
f_c	Cut-off frequency
$g(x)$	Activation function
L	Length
MT	Movement time
P	Point
R	Register
$traj$	Trajectory
T	Periodic time
θ	Angle, threshold
τ	Time

This work is dedicated to my family, Akihiko, Yuri,
Fumie, Shigeaki, Yuko and Emi for their magnanimous
understanding and their support for my research life.

Chapter 1

Introduction

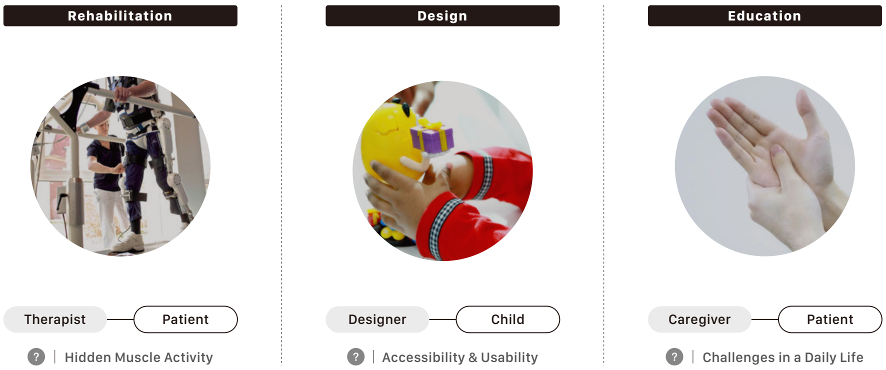


FIGURE 1.1: Target Scenarios of Understanding One's Experiences

1.1 Challenge

Understanding the embodied and social experiences of a person can play an important role in understanding individual or personal experience. There are several situations in which it would be beneficial to be able to perceive another person's embodied and social experiences, as shown in Fig. 1.1. An example of a situation where embodied experiences are useful includes interactions between physical therapists and patients during gait rehabilitation. In this scenario, it is important for the patients to learn appropriate muscle contraction timings and strength, which is usually hard to gain from observation or visual contact alone. For therapists, it is a challenge to express or describe these bodily skills using words. In the fields of product and spatial designs, it would be beneficial for designers to consider accessibility and usability when designing toys and playgrounds for children. However, there is a significant embodied difference between a

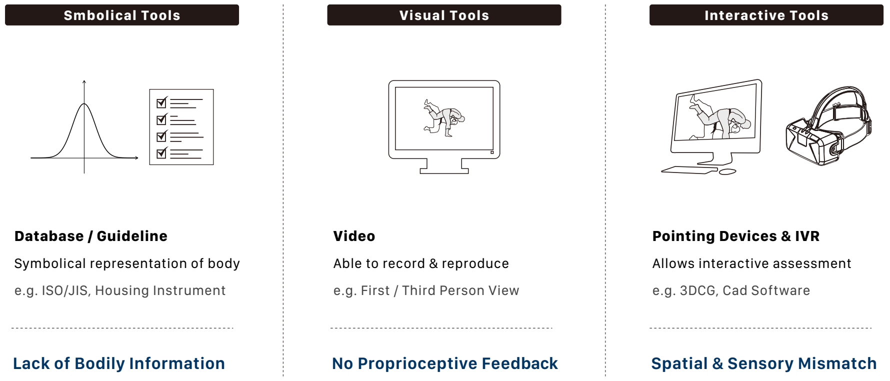


FIGURE 1.2: Existing Tools to Convey One's Experiences

designer and a child. For a family with a patient experiencing a debilitating neuromuscular condition, it would be a valuable and empathetic experience to understand the physical challenges caused by the impairment in daily life activities.

1.2 Vision: Sympathy to Empathy

These embodied experiences are collectively categorized as embodied knowledge, which are hard to be acquired by symbolical conversations or visual media but through active physical experiences. Therefore, new media and tools that can reproduce these embodied and social experiences through active and embodied actions are required. Humans hold “embodiment" which can be formed based on the summation of the physical and physiological characteristics of a person [1]. Embodied knowledge is defined as the physical techniques or skill that can be acquired through embodied actions [2, 3]. The sensory, motor, neural, and musculoskeletal systems are involved in the process of acquisition of such knowledge. If we are able to acquire the embodied knowledge of an individual's embodied and social experiences, it would be beneficial and effective for acquiring and gaining our knowledge and empathy toward different people.

Conventional Tools

To share these embodied knowledge, several tools have been developed and used, such as symbolical guidelines, video materials, and computer graphics (CG) techniques.

Symbolic Tools

Databases and guidelines have been widely used to convey the characteristics of an individual's bodily information. The Japan kids design association provides a numerical database containing the extremity dimensions of children [4] to assist product designers in evaluating usability and accessibility of toys and products. The Housing Enabler Instrument [5] was developed to assess accessibility in the housing environment based on three major scores: limitations of and dependence on mobility devices, physical environmental barriers, and housing accessibility score. JISX 8341 [6], which was published in 2004 through the Japanese Standards Association, is a guideline for designing information and communications equipment, software, and services for the use of elderly persons and people with disabilities. These guidelines are used in industries and companies to assist designers in creating universal and/or user-centered designs.

Visual Tools

In addition to the symbolic representations, video materials have also been used to record and reproduce bodily information and experiences on a screen. With the recent advancement and adoption of head-mounted displays (HMDs) [7, 8], omni-directional cameras [9, 10], and software platforms [11], the infrastructure required to share and recreate visual experiences have become popular [12, 13].

Interactive Tools

Three dimensional computer graphics are also used for evaluating the usability and accessibility of an architecture or a product, such as a 3D CAD software that renders CG models with pointing devices including AutoCAD Architecture (Autodesk Inc.) [14], and [15]. Immersive virtual reality (IVR) techniques have also become popular tools to change bodily sensations for understanding embodied characteristics [16, 17] while the users are projected onto a virtual space by a motion capture system.

Summary

These tools are able to partially transmit the characteristics or experiences of a person's embodiment and their special needs to other people symbolically and visually; however, the following drawbacks still remain:

1) Users receive the bodily information in a passive manner from these media, while embodied knowledge can be acquired actively with physical actions.

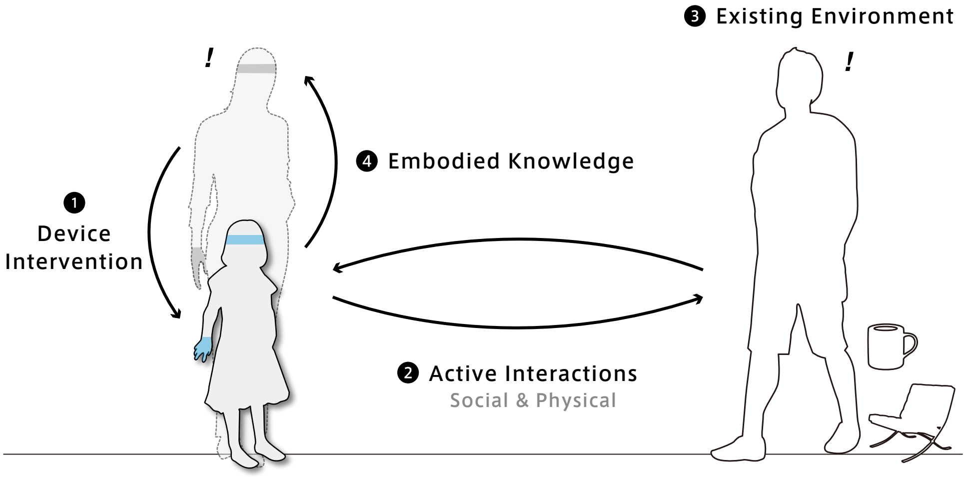


FIGURE 1.3: Acquiring Embodied Knowledge of One's Embodied and Social Experiences with Active Interactions by Shaping Body Representation

2) These media do not provide embodied interactions, which involve proprioceptive feedback that play important roles in learning or even altering bodily sensation.

3) These media do not generate social interactions with people, which is also an important form of feedback for the user's physical actions because the user is in a virtual space; this may result in isolation from the social and physical contexts.

1.3 Shaping Egocentric Experience

1.3.1 Overview

In this research, I propose a new paradigm that changes one's experience consists of perceptions, actions, and interactions by changing one's body into that of another person, while allowing active interactions with the surrounding objects and people in a real-world environment. This would provide embodied and empathic knowledge of one's experience rather than describing or simply presenting it in a symbolical or visual manner. The three human factors; one's perceptions, actions, and interactions would play important roles in defining physical and social experiences and contexts with objects and people, thus constituting the sum of one's embodied and social experiences.

Because all actions and interactions in the proposed experience style should be performed in a same interaction manner with that in an existing daily life, the user's conscious act which consists of voluntarily initiating actions, which is defined as subjective agency [18], should be preserved.

I call this experience that particularly includes both subjective agency to initiate actions and active interactions with a user's intention, as **egocentric experience** in that a user is able to have an intention to initiate, then initiate, and freely perform actions and interactions with his/her own intention and timing.

Neuroscience studies have revealed that active interactions foster the change in bodily sensation, particularly body representation [19–21]; therefore I fully exploit a user's egocentric actions and interactions for changing the bodily sensation to change the user's perceptions, actions, and interactions.

It is assumed that a user's egocentric experience and bodily sensation would continue to be changed with the active interactions, thus I call this modification of the experience as shaping, as a related study in neuroscience also uses the same term [22, 23].

1.3.2 Benefits

Embodied Knowledge

While the conventional tools provide explicit knowledge of individual experiences through databases, guidelines, and visual materials, our experience provides embodied knowledge that would effectively enable gaining empathy toward different people. Furthermore, the embodied knowledge will be provided only after the users perform actions and interact, allowing the enhancement of participation level toward the experience.

Active Experiences

Based on the acquisition procedure for embodied knowledge, the proposed experiences provide active and embodied experience, whereas the conventional tools provide passive experiences. This would foster the change of bodily sensation and acquisition of embodied knowledge.

Existing Environments

Because our experiences can be felt in a real-world environment whereas users of VR tools act within a virtual space, important physical and social interactions with existing objects and people can be provided. This would help the application of the proposed experiences to actual scenarios in rehabilitation, education, and design. The existing knowledge on objects allow wearers to identify the physical relationships between body and space, and the individual knowledge of people allow creation of social contexts between the wearers and other people in the surroundings, such as attitude, conversation, and social relationship. Through egocentrically experiencing these embodied and social experiences, empathetic understanding toward different people would be enhanced.

1.3.3 Experience Design Challenges

To achieve shaping of one's perceptions, actions, and interactions, I introduce the following requirements in this interaction design.

Changing Bodily Sensation in the Real World

As mentioned previously, I hypothesize that active physical actions with changing bodily sensations allow people to acquire new embodied knowledge. In this research, this modification should be achieved in real-world scenarios to support communication among people in existing environments in rehabilitation, education, and design; therefore, new techniques to change bodily sensations in the real world while preserving active actions and interactions are required.

Securing Reachability to Objects and People

To allow active physical interactions with objects and social interactions with people, the reachability of the wearer should be preserved. For example, proprioceptive feedback from walking provides the sense of distance to the user.

Preserving Physical and Social Contexts

Securing the reachability to objects and people would allow preserving the physical and social contexts. By experiencing a handshake with an acquaintance, the wearer can recognize differences in attitude, conversation, social relationship, and physical relationship during the action of handshaking.

1.3.4 Interface Design Challenges

To make the proposed interactions egocentric in the real-world environment, the following design goals are outlined. In addition, I call an interface which satisfies these design goals, as a **wearable cybernic interface**.

Wearable Form Factor

This allows users to 1) freely walk around and explore real environments, 2) reach out and interact with objects, and 3) have conversations with other people based on their own intention, action, and timing. Allowing the reception of visual and proprioceptive feedback will foster a modification of the body representation, in addition to enhancing the senses of presence and immersion [24, 25]. Securing reachability allows users to voluntarily initiate their interactions, allowing to encourage explorative and active actions in the existing environment.

Input and Output of Body Function

To change the sensation of body in the real world, it is necessary to intervene in the relationship between human actuation (the efferent active signal) and sensory feedback (the afferent signal). Prior researches have used biosignal measurement or a motion tracking as sensors, and a robotic exoskeleton or a VR HMD as an actuator [26–28]. Gruneberg et al. noted that closed proprioceptive loop of physical interaction between the efferent active neural signal and the afferent signal of consequential sensation of the intended motion is critical for enhancing neurorehabilitation of the brain [18].

Interactivity

Interactions with objects and people such as recognizing known person's face or grabbing a familiar object would play an important role in defining the relationship of the body and space, and in forming own body representation. In contract to VR applications where users perform actions within a CG-based VE, the proposed interaction is performed in a real environment; therefore the interfaces should be designed so as not to compromise an existing manner of interaction.

To achieve this, I preserve and exploit human's existing body function as much as possible. For instance, in the research of shaping experiences into a smaller-person, users wear a pair of passive hand exoskeleton in which no link mechanism is attached to users' thumb finger, thus allowing to use their own thumb finger for sensing tactile feedback during touching objects or shaking hands. In the research of reproducing kinesthetic experience of Parkinson's impairment, users attach electrodes and change the physiological attributes of their forearm by reproducing tremors. This interaction style allows them to grab objects or to shakehand with their own hands.

Input and Output Correspondence

Spatial correspondence between the user's actions and the control device should be established to allow the wearer to easily understand how to control their viewpoint in the system, which is a natural head orientation in the proposed configuration.

Modality correspondence between the real and presented environments should be accurate. In the proposed system, the real world is presented in an immersive manner, and the wearers are thus able to recognize their space, objects, and other people by using their own

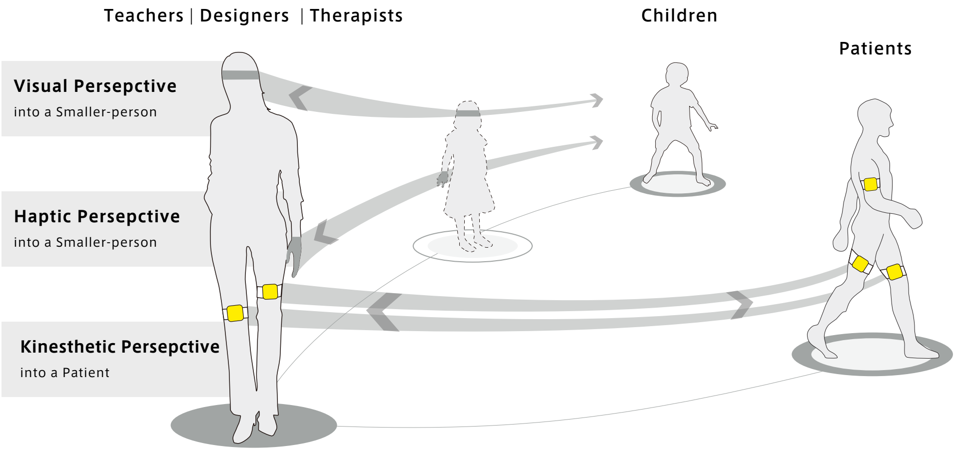


FIGURE 1.4: Shaping Visual, Haptic, and Kinesthetic Perspectives into that of a Smaller Person and a Patient

existing social and motor knowledge. This will enable easier definition of their physical and social relationships and enhance the feeling of presence and the reality of people and objects.

Temporal correspondence between the user's input and the device's output plays an important role in preserving the sense of agency. Therefore, I carefully designed and evaluated the latency of the camera-HMD system so that the wearer could feel that the presented images were associated with his/her actions and that the device was a part of the their body.

1.4 Objective

To achieve these new paradigms to acquire embodied knowledge of experience in the scenarios described, I designed the following two types of corporeal changes: 1) changing visual and haptic perspectives to those of a child, and 2) changing kinesthetic perspective o that of a patient.

1.4.1 Smaller-person Experience

To support the understanding of the experience of a smaller-person including a child, I attempt to reproduce it by shaping the wearer's visual and haptic perspectives. I developed wearable visual and haptic translation systems and then investigated how the wearer's perceptions, actions, and interactions could be modified through lab studies, a field study, and public demonstrations.

1.4.2 Blending Kinesthetic Experience

Further, to support the understanding of the experiences of a neuromuscularly challenged patient, such as a Parkinson's patient, I attempted to reproduce it by shaping the wearer's kinesthetic perspective. I developed a wearable device that shares and changes kinesthetic perspectives among people and then investigate how the wearer's perceptions, actions, and interactions could be modified through lab studies and public demonstrations.

1.5 Research Questions

Through these developments, evaluations, and demonstrations of the two studies, I discuss the following research questions.

- Can we shape our own embodied experience into another form while preserving an active manner?
- What is the design requirements for interfaces that change one's experience?
- How does changing bodies change our perceptions, actions and even interactions?

These questions would not only demonstrate how the new techniques are effective for gaining the empathy toward different people but also contribute to reveal new aspects of human behavior.

1.6 Thesis Outline

The researches presented in this thesis are organized by different chapters. Chapter 2 introduces the related work regarding conventional tools to convey embodied knowledge and methodologies to change one's bodily sensation with simple tools. This chapter also shows the advantages and the limitations of the conventional tools for skill acquisition. Chapter 3 presents conceptual representations of the smaller-person experience and the blending kinesthetic experience with design considerations, contributions and relate works. Chapter 4 presents engineering contributions including implementations of 1) visual translator that reproduce a smaller-person's lower perspective by using a HMD and a wearable camera, 2) a pair of hand exoskeletons to reproduce a smaller-person's haptic perspective by using passive mechanism, and 3) a pair of wearable kinesthetic devices that shares kinesthetic perspective among people. Chapter 5 and chapter 6 will introduce a series of performance experiments used to characterize the developed device, and also introduce a series of user studies to investigate how the user's perceptions, actions, and interactions can be changed by the proposed experiences.

These are discussed in Chapter 7. Finally, considerations about future work, and conclusions are presented in Chapter 8 and Chapter 9 respectively.

Parts of the thesis have been already published or are in the process of being submitted for publishing. The interaction designs about shaping egocentric experiences into that of a smaller-person and a patient in this Chapter, along with methodologies in Chapter 3, implementations in Chapter 4, and results of the user studies in Chapter 6, have been published in conference full papers and journals. Part of the background interaction paradigm in this Chapter will be submitted as a conference paper.

Chapter 2

Related Works

There have been several attempts and approaches to change individual perceptions, actions, and interactions in the neurosciences, psychology, and design research fields.

2.1 Neuroscience

2.1.1 Plastic Body Representation

Our brain has a constantly updated map of the body shape, called body representation [19]. Multisensory experiences including proprioceptive and visual feedback contribute to its construction. Interestingly, our body representation is plastic [29, 30], and it is clear that tool-use changes body representation [20, 31].

2.1.2 Simple Tool Use Changes Bodies

Japanese macaques were able to use a rake to pull objects closer, even though they rarely perform tool-use behaviors in their natural habitats [19], thus demonstrating that the tool enhanced the monkeys' reaching distances. Furthermore, neural responses were recorded from the intraparietal cortex, showing that visual receptive fields had expanded to include the entire length of the tool after training. The important fact here is that this expansion of the visual receptive field was observed only after active and intentional tool use, and not after passively grasping the tool.

A related phenomenon was also reported in humans with a simple tool or even a wheelchair [32]. Another study demonstrated that tool users can sense where an object would contact a wooden rod more accurately during active sensing [33]. Visually challenged people who use canes in their daily lives also have their peri-personal space enlarged to the tip of the cane [34]. Amputation and prosthesis implantation to a body also shape body and peripersonal space representations [35].

2.1.3 Rubber Hand Illusion

Another example that active actions foster changes in body representation have been reported with a Rubber Hand Illusion (RHI) technique [36]. RHI is an illusion technique in which a participant feels his/her ownership is transferred to a dummy rubber hand with the aid of visual and tactile stimulations [37, 38]. The RHI technique uses a brush to provide visual and tactile stimulations to both the participant's hand and the rubber hand to create an illusion that the participant feels the rubber hand becoming a part of his/her body while receiving these stimulations in a passive manner. This study has demonstrated that an active tapping mechanism, where the participant can directly control the rubber hand's finger movement according to that of the participant, has enhanced the feeling of ownership toward the rubber hand rather than using the conventional passive stimulations. Conclusion.

Summary

These studies have demonstrated that our body representation is plastic and can thus be modified by simple tool practices. Most importantly, it has proven that the active and intentional use of tools have fostered changes in our bodily sensations. This research also takes advantage of this phenomenon in that the wearer initiates their actions and interactions themselves, and also investigate how active and passive experiences generate differences in the change of bodily sensations.

2.2 Psychology

After J. Lanier first discussed immersive virtual reality systems could be used for changing bodies in the late 1980s [39], many studies tackled this topic in the field of psychology.

2.2.1 Experiencing Child Avatars

When a user has an illusionary ownership toward a virtual child body in an immersive virtual environment in which the virtual and real body movements are synchronized, it causes overestimation of object sizes due to the shrinkage of bodily sensation [17]. A similar phenomenon of the size of one's own body directly influences the object size and distance perception was also reported in a real world setup where the ownership of a participant laying on a bed was transferred to a small doll by means of RHI technique [40, 41]. These studies mentioned that changing one's own body changes not only their perceptions but also actions such as attitude, self-identification, and subsequent real speaking [42].

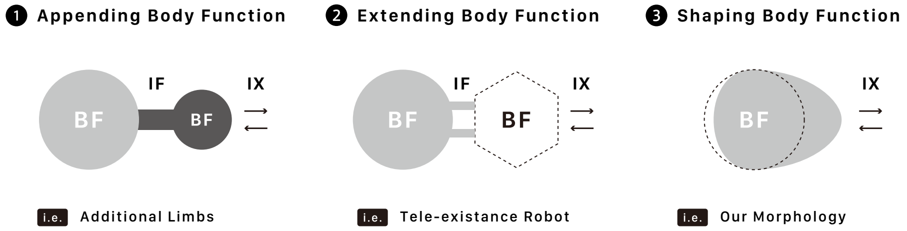


FIGURE 2.1: Topological Representations of Body Functions in Interaction Research: 1) Appending, 2) Extending, and 3) Shaping Body Functions

2.2.2 Changing Skin Colors

Not only is changing the physical height of body but also changing the color of skin has been performed to investigate how this experience changes racial bias toward dark-skinned people, for instance. Before and after five-minutes trial of having dark skin on a virtual avatar, racial implicit association test was performed, suggesting that light-skinned people in a dark skinned body have reduced implicit racial bias [16, 43, 44]. Another study reported that having higher ownership toward a dark-skinned rubber hand is associated with becoming more positive towards individuals with dark skin [45].

Summary

These psychological studies have demonstrated that changing bodies in a virtual environment achieved the change in perceptions, actions and even attitude including implicit bias which would help gaining empathy toward different people. One major challenge is that users in the setup of these studies are immersed in a virtual environment, which isolates them from existing physical environments and social relationship with surrounding people. Especially social interactions with actual people which would play an important role in understanding the gap is not fully reproduced. While the neuroscience studies have been conducted with simple tools and the psychological studies have been conducted within a virtual space or with a passive manner, the recent advancement in wearable technologies have allowed to append, extend, and change our body function with a more complex tool in a real-world environment.

2.3 Interaction Research

2.3.1 Supernumerary Body Function

Recent studies have allowed to append supernumerary bodily functions to users such as a third eye [46] to see one's back through a wearable camera and a HMD, a robotic sixth finger [47–49] to help user's physical hand performance, and a secondary brain memory [50] to record one's daily life by a wearable camera based on a wearer's gaze attention. These wearable devices are capable of simulating or working with body function.

As shown in Fig. 2.1(1), there exists custom designed interfaces (IF) between the body and the supernumerary body because the additional body does not originally belong to the body. Thus, the interfaces should have a mechanism that accurately predicts a user's intentions. In addition, interactions (IX) will be performed with a different body form factor, resulting in compromising existing social interactions.

2.3.2 Extending Body Function

These wearable technologies have not only increased physical capabilities of one person but also embodied and social experiences beyond the limitations of space and time. Tele-existence communication techniques have achieved an extension of the user's presence in a remote place by sharing their first-person perspective [51] or by surrogating one's body into a robot [52] or other person as an actuator [53, 54]. Interestingly, it has been proved that these wearable technologies have an enough capability to change not only body function but also to change one's bodily sensation.

As shown in Fig. 2.1(2), users interact with the remote environment through the different type of body such as a robot or a person. Thus users could have a difficulty in feeling sense of agency or ownership towards their interaction. In addition, interfaces are capable of sharing a few number of modalities, resulting in decreasing the sense of immersion.

2.3.3 Changing Body Function

Several design tools that changes one's bodily sensation to gain empathy have been proposed, such as begin an elderly by degrading visual and motor capabilities [55], having a child's perspective by narrowing horizontal and vertical fields of view (FOVs) using cardboard goggles [56], or having a Parkinson's tremor by using a desktop haptic interface [57].

These design tools have successfully changed the wearer's bodily sensation into another form in a statical manner, allowing people to gain empathy toward different people. In this research, we modify the relationship between human actuation (the efferent signals) and sensory feedback (the afferent signals) by measuring and intervening in human's body function.

Summary

As shown in Fig. 2.1 (3), the proposed morphology shapes body representation itself without adding or extending extremities or modalities. This allows users to perform full body interaction with objects and people in a real and existing environment. Because the shaped body inherits its spatial and modal attributes from that of original body, users are able to understand the interaction manner and to perform physical and social interactions by an existing manner.

Chapter 3

Methodology

3.1 Smaller-person Experience

3.1.1 Introduction

With the recent advancement of wearable technologies and augmented reality techniques, humans' egocentric experiences are augmented beyond the limitations of space and time. Several studies have been conducted aiming to reproduce another person's experiences such as extended first-person view [12, 51, 58] and surrogation technology using a haptic controller [52].

It is noted that not only visual and auditory experiences but also subjective embodied interactions with the surrounding environment play an important role when trying to understand another person's perceptual and physical characteristics (e.g., children, elderly [55], and impaired individuals [59]). Especially in case of children, because there is a significant embodied and perceptual gap with adults, it is hard to understand the difference in embodiment without experiencing it for oneself. If these characteristics could be reproduced and presented in an egocentric and embodied manner, it would provide valuable and empathic experience for teachers and product designers, when communicating with children in a nursing school or trying to design living environments for them.

Visual Gap

As an example of the gaps between children and adults, there is a difference in eyesight level [60]. This causes several unique experiences: when looking up a vending machine or a store shelf, children would be dazzled by fluorescent lights because they would see the lights directly from a lower viewpoint; when children are surrounded by adults, they would have strong feeling of oppression; and when seeing an approaching car, it would be very scary experience because the size perception of objects and people is different from that experienced by adults.

FIGURE 3.1: We explore a wearable visual device that allows a user to change their body representation, in realtime, to that of a small-person

Haptic Gap

In addition to these differences in visual perception, there also exists embodied gaps, such as the dimensions of the hands and length of the limbs. They would have a difficulty when trying to grab an item that is placed at higher level on a shelf. Their tiny hands often cause an inability to pick up items up with one hand, such as a plastic bottle, and the task occupies both hands even the item is relatively small for adults. A psychological study have demonstrated that scaled hand changed perceived object size [61]. Therefore changing hand size and ROM of the upper-limb in a real environment while allowing active interactions would change one's size and distance perception since forearms and hands are used as a perceptual ruler [62].

3.1.2 Research Goal

Conventionally, video materials [60], an illusion technique used to extend the sense of ownership to a small doll [40], or an immersive virtual reality technique for converting the user's body into a smaller avatar have been used to create the sense of being a smaller person [17], through which the user's experience may feel involuntary or unrealistic.

Therefore, in this research, we provide the experience of a smaller person in an embodied and voluntary manner in a real world environment, by changing the user's body representation, such as their visual and haptic perspectives, into that of a small-person on the user's body by means of a wearable system. With this form, the

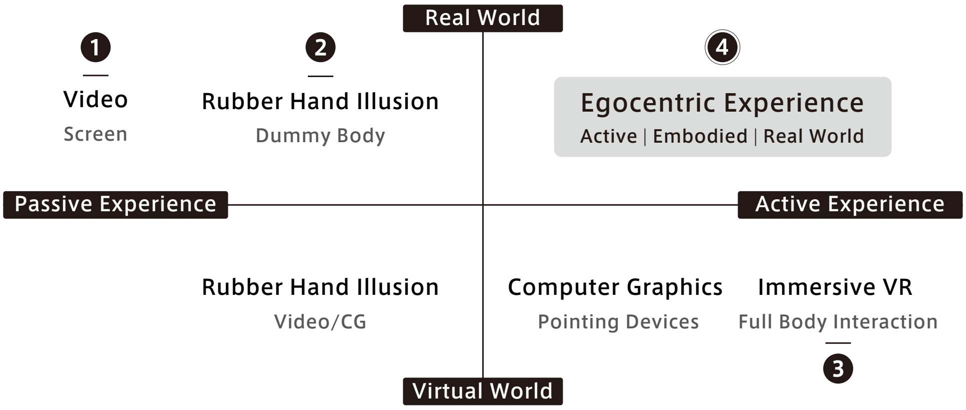


FIGURE 3.2: Research Position: The proposed egocentric experience is in an active and embodied manner

user's fundamental interaction capabilities, including reaching, walking, touching, and carrying on a conversation voluntarily would be preserved; therefore it would provide more egocentric experience.

The contributions of this research are as follows:

3.1.3 Contributions

- proposed conceptual representation of shaping visual and haptic perspective into that of a smaller-person
- developed two wearable devices: 1) a visual translator for mapping the wearer's eyesight level onto his/her waist position by using a head-mounted display (HMD) and a wearable camera module, and 2) a pair of passive hand exoskeletons for miniaturizing hand gestures by using motion conversion mechanisms
- conducted a field study at a nursing school, and lab studies to explore how a wearer's experience regarding perceptions (interpersonal distance), actions (handshake action), and interactions (demonstrations) can be changed
- conducted a lab study to investigate how the hand exoskeletons change the wearer's developmental and chronological hand functions
- included design implications regarding how active visual and proprioceptive experiences in a real environment contribute to a modification of one's self-representation.

3.1.4 Related Works

There are several attempts to simulate or reproduce the sense of being a smaller-person in a virtual environment (VE) or in a real world environment (RE).

Passive Visual Experience in RE

A hand-held video camera placed at a child's eye level was used for recording a smaller person's perspective in order to investigate the usability of objects and the architecture in a public space [60]. The users observed a bookstore, a grocery store, and vending machines from a lower perspective, and reported that such new tools helped in exploring and finding new discoveries in an existing environment. Under this scenario, the camera direction was fixed, and this passive and allocentric visual experience did not provide any somatosensory feedback such as a sense of position or muscle fatigue from the head orientation (Fig.3.2 (1)).

Passive Visual and Tactile Experience in RE

Several studies have used visual feedback through a head-mounted display (HMD) and a video camera, along with the rubber hand illusion (RHI) [37] for creating a sense of being another person [58], a small doll [40], and even a ghost [63] (Fig.3.2 (2)). These psychological studies have reported that changing one's body representation modifies their perception toward humans and objects because our bodies are used as a reference in the visual perception of size and distance. For instance, when a participant's ownership was extended to the body of a small doll by means of the RHI, the participant perceived objects to be larger and farther away [40]. Although these studies achieved a change in body representation to that of another body in a real environment, the users had to sit or lay down to receive a passive visual and tactile stimulation for creating a stable illusion, and to keep body posture for preserving the effect of illusion. This would provide egocentric feelings toward another; however their interaction would be in a passive manner.

We also explore how our egocentric small-person experience contribute to the change of the wearer's perception, especially the perception toward human in study 1.

Active Visual and Proprioceptive Experience in VE

Virtual reality (VR) techniques are also used for producing a smaller height [17] [42] or a smaller hand [64]. These systems achieved the experience of being a smaller person through visual and motor experience in a VE (Fig.3.2 (3)). Changing the bodily sensation in a VE also changes perceptions and actions. Reducing person's height in a social situation such as a VR train ride resulted in more negative views of the self and an increase of the occurrence of paranoia [65]. Participants assigned taller avatars in a VE behaved more confidently in a negotiation task than participants assigned shorter avatars [66]. Having a different skin color on one's virtual avatar reduces implicit racial bias [16, 43, 44].

Our study attempts to change the body representation in a RE; therefore, not only will the actions of the wearer change, so will the actions the surrounding people. We also discuss this topic based on observations conducted through the user studies, conference demonstrations, and exhibitions in science museums.

Active Visual and Proprioceptive Experience in RE

Several studies have achieved to reproduce one's bodily sensation into that of elderly or impaired individuals [57, 59, 67] in a RE by visual, haptic, or kinesthetic systems. Child vision kit (distributed by Honda Motor Co., Ltd.) reproduces static child vision properties including narrow horizontal and vertical fields of view (FOVs) using cardboard goggles [56]. This kit aims to gain the awareness and knowledge of a child, and to encourage safe driving. The age gain now empathy system (AGNES), developed by MIT AgeLab, is a wearable suit that can reproduce an elderly individual's physical characteristics on a wearer's body by inducing motor and visual impairments [55]. It consists of three pieces of equipment: 1) wire dampers to degrade the walking ability, 2) goggles to restrict the wearer's field of vision, and 3) gloves to dull wrist and finger movements. It provides embodied knowledge of elderly people, such as difficulty of picking up and holding objects, and inability to walk a long distance. They conducted a user study in which the wearers could explore the difficulties in performing activities in daily life, including using public transportation and shopping at grocery stores, with simulated embodiment. It is also reported that such embodied elderly interaction is effective for nursing students to change of their perceptions of being elderly [68]. This suggests that reproducing embodied aging experience on a wearer's body can induce strong emotional and subjective memories, allowing them to gain empathy for elderly people. In our study, we explore the methodology and effectiveness of reproducing a child's embodiment on a wearer's body to gain the empathy and awareness toward children.

These studies indicated that reproducing one's embodied experience on a wearer's body helped to acquire one's embodied knowledge with more emotional and subjective memories, allowing them to gain empathy for other people.

3.1.5 Concept

In this study, we attempts to change the wearer's body representation to have a small-person's perspective in a RE, with a capability of full body interaction by using wearable devices (Fig.3.2 (4)). We investigate the feasibility and properties of active small-person experience in RE through both field and lab studies, and discuss its challenges and opportunities.

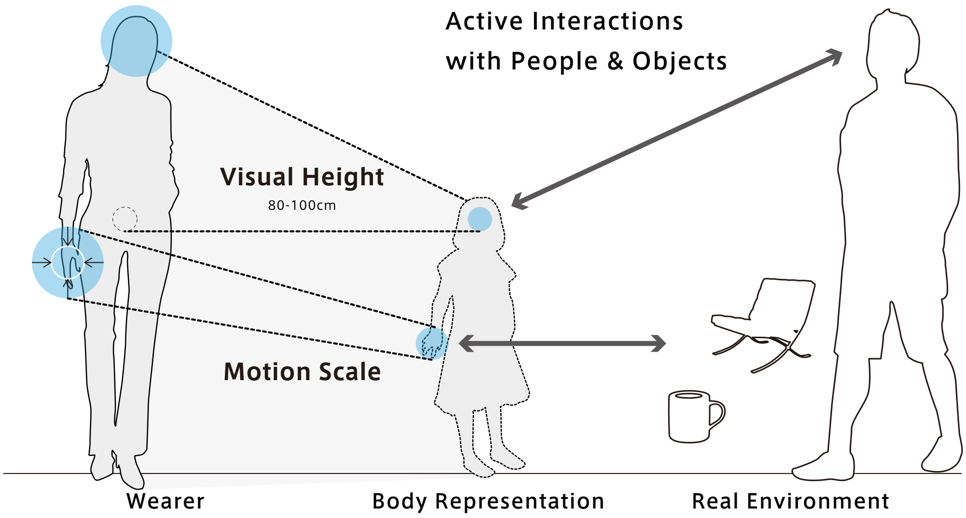


FIGURE 3.3: Concept of Egocentric Small-person Experience

To allow this, the concept of a body representation transformation into a smaller person using a wearable VR device has been proposed [69, 70], as depicted in Fig. 3.3.

Visual Perspective

Visual stimuli plays an important role in recognizing the relationship between a user's own body representation and the surrounding environment. Changing the height of the eye level to a lower position while allowing for FOV control will allow an egocentric visual perspective of a smaller person to be achieved.

Haptic Perspective

As another important factor to enhance the sense of being a child, we propose to change two haptic factors: miniaturizing the grabbing motion scale of the wearer's hands and constraining the range of motion (ROM) of the wear's upper limb. By changing the maximum dimension of the hands, the wearer is able to experience the difficulty of grabbing objects with a tiny hand. This induces the wearer to use both hands at the same time, even for small objects, resulting in even minor tasks occupying both. Another haptic factor is to constrain the ROM of the upper limb to reproduce the short length of the upper limbs of a child. Especially the ROM affects the sense of peripersonal space (PPS), defined as the space immediately surrounding the body, which is considered to be a region of integration of somatosensory, visual, and auditory information [71, 72]. The peripersonal space is an important interface for interaction with nearby objects, whether one performs a goal-directed action, or wants to protect oneself from an incoming threat. Because there is a significant physical gap between children and adults, there would be many places where children can not reach and interact. Reproducing these haptic perspectives of that of a smaller person enhances the sense of being a child through the interaction with actual objects and people.

3.1.6 Design Considerations

To make our interactions egocentric in a real-world environment, we focused on the following design goals.

Wearable form

This allows users to freely walk around and explore a real environment, to reach and interact with objects, and to have conversations with other people based on their own intention, action, and timing. Allowing visual and proprioceptive feedback to be received will foster a modification of the body representation, in addition to enhancing the sense of presence and immersion [24, 25]. Such reachability and voluntary interactions will encourage explorative actions of the user.

Spatial Correspondance

Spatial consistency between the user's actions and the device control should be established to allow the wearer to easily understand how to control their viewpoint in the system, which is a natural head orientation in our configuration.

Modality Correspondance

Modality consistency between the real and presented environment should be matched. In our system, the real world is presented in an immersive manner, and thus the wearers are able to recognize their space, objects, and other people by using their own existing social and motor knowledge. This will make it easier to define their physical and social relationships, and enhance the feeling of presence and the reality of people and objects.

Temporal Correspondance

Temporal consistency between the user's input and the device's output plays an important role in preserving the sense of agency. We carefully designed and evaluated the latency of the camera-HMD system so that the wearer can feel that the presented images are associated with the wearer's action, and that the device is a part of the wearer's body.

FIGURE 3.4: (a) Synchronizing and combining muscle activities among people (b) Reproducing kinesthetic experience of Parkinson's impairment for use in supporting product design (c) Participants express surprise when the muscle activity is jacked in by the demonstrator

3.2 Blending Kinesthetic Experience

3.2.1 Introduction

Perceiving one's own muscle activity is important to understanding one's physical actions. There are several situations in which it would be beneficial to be able to perceive another person's muscle activity and share their kinesthetic experience. Examples of such situations are interactions between sports players and coaches during physical training and interactions between physical therapists and patients with neuromuscular disorders, such as Parkinson's disease during their rehabilitation. However, it is difficult for one person to perceive another person's muscle activity, and a suitable interface for perceiving and transmitting kinesthetic experience accurately in real time has not been developed yet.

In this research, we propose a system for blended kinesthetic interaction between two persons using wearable kinesthetic input-output (I/O) devices, called bioSync, is illustrated in Fig. 3.4(a). In developing this system, we attempted to achieve both perception and expression of bodily motions and muscle activity. Using this system, which consists primarily of a pair of devices worn by the two users, muscle contractions of one user are detected by means of electromyogram (EMG) measurement and are reproduced, by means of electrical muscle stimulation (EMS), as muscle contractions of the other user, and vice versa. We have explored the possibilities of kinesthetic synchronization and implemented very early prototypes that used five independent electrodes for the measurement and stimulation [59, 73, 74]. We hypothesized that combining the muscle activities between users in real time with the spatial consistency of muscle exertion and output presentation and with the consistency of sensation modality would provide an intuitive and easy-to-learn means of understanding both muscle activities and bodily motion.

3.2.2 Contribution

- Modeling of the blending of kinesthetic interaction between two persons based on EMG measurement and EMS
- Implementation of bioSync devices with the same electrodes used for EMG measurement and EMS to achieve kinesthetic I/O at 100 Hz via wireless communication
- Development of a method for muscular stimulation with dynamic adjustment over a wide frequency range
- Assessment of the interaction and the system by means of a user study in which kinesthetic I/O with low communication latency (approx. 20 ms) allowed synchronization of rhythmic muscle contraction without visual and auditory feedback

The main contribution of this research is the presentation of a novel style of interpersonal kinesthetic communication called blended kinesthetic interaction. A key property of the blended kinesthetic interaction is that the kinesthetic feedback can be both shared and merged in that the wearers are able to simultaneously perceive the strength of voluntary contractions produced by the wearers and involuntary contractions produced by stimulation. The bioSync devices developed in this study are kinesthetic I/O devices that can estimate and interrupt a wearer's muscle activity at the same time. The devices are wearable and easy to attach to a wearer's body. We validate this concept by conducting a rhythmic synchronization experiment and demonstrating the reproduction of disease experience using bioSync devices.

3.2.3 Related Work

Many studies on the transmission and sharing of users' sensations or skills have been conducted in field of computer-supported cooperative work.

Perspective Sharing

One effective way to convey a person's physical interactions and presence in an immersive manner is by transferring, exchanging, or blending their first-person views (FPVs) while presenting them on a head-mounted display (HMD). For instance, a wearable vision system that transfers a 360° FPV to a remote viewer has been developed to assist in remote collaboration between two people [51]. Another study reported that showing multiple FPVs in parallel on a HMD allowed people to complement and enhance each other's memories and decisions in executing a drawing task [12]. Such techniques have also been used to transfer motor performance between a teacher and a learner [13, 75]. In an user study on motion synchronization between an expert and a beginner performing juggling actions, the mixing ratio of their FPVs was found to indicate the type of motion skill to be transmitted. For example, exchanging views was found to be useful for synchronizing motion velocity, whereas blending views was useful for synchronizing the positions of limbs.

These studies have shown that perspective sharing enables the transmission of a person's bodily motions and skills to another in an immersive manner. However, it is difficult to share muscle activity since it is hard to observe it visually. We incorporate the findings on the importance of blending ratio in the proposed kinesthetic interaction model by using a blended perceptual function f and blended stimulus function p, which are illustrated in Fig. 3.5.

Haptic and Kinetic Sharing

A number of devices have been developed that convey one's haptic or kinetic performance to another person for enriching mediated communication by amplifying another person's social presence. inTouch [76] allows separated users to feel virtual sensations of a shared object through somatosensory interactions by using connected mechanical rollers. Similarly, a paired shape-shifting stick [77] was proposed that allows users to feel the movements and presence of a performer by mimicking the remote user's stick movements. Another study demonstrated the ability of haptic devices to convey several emotions, including anger, disgust, fear, and joy, using handshaking actions [78]. Sharing video and haptic, or video and physical interaction with a remote user also enhances the feelings of being close to another person [79, 80]. As previous research shows, interpersonal haptic communication makes it possible to enhance not only

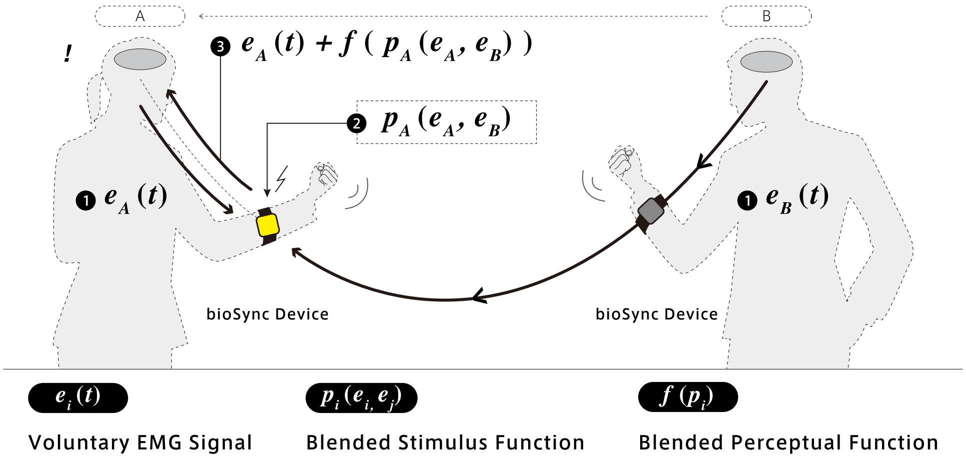


FIGURE 3.5: Model of Blended Kinesthetic Interaction

task performance but also remote users' sensations of presence, reality of existence, and users' ratings of trust and togetherness [81]. In this study, we propose a novel style of interpersonal kinesthetic communication that permits people to perceive other people's muscle activities. We consider these the social and psychological aspects of the haptic feedback provided by this system by means of user studies and demonstrations.

Kinesthetic Representation

Some wearable devices have been developed for identifying and representing muscle activity in medical applications. Conventional desktop-type electromyography is capable of displaying muscle activity in the form of waveforms on a monitor [82]. This provides accurate and quantitative kinesthetic information but requires frequent sightline movement between the monitor and the measurement point. To resolve mismatches in the spatial consistency between the presentation point and the measurement point, a wearable, light-emitting suit for sensing contraction strength using light fibers [83] or LED arrays [84], and a wearable audio device that converts contraction strength into acoustic waves [85, 86] have been proposed. Research with these devices has shown that identifying and sharing kinesthetic experience with therapists assists in medical rehabilitation and sports training. However, in these visual and acoustic systems, the presentation area is limited to the user's field of vision, and the amount of information provided is limited to that from a single muscle tissue when the feedback is acoustic in nature. Furthermore, the substitution among different types of sensation modalities requires adequate prior learning procedures.

EMS Interfaces

The direct approach to presenting kinesthetic information to a body is through EMS in which muscles are actuated involuntarily through electrodes on the skin. This technique was developed for use in biofeedback therapy [87], and has recently been used in the HCI field such as Pose-IO [88] by Lopes et al. and PossessedHand by Tamaki et al. [89]. The Pose-IO system makes use of the fact that users are able to estimate the wrist angle posed by EMS without visual feedback. They demonstrated that users could perceive the playback time of a movie through their wrist angles, and control it using hand gestures. EMS systems have the unique characteristic of being able to induce and trigger bodily motions that involve strong motion memories after stimulus, without using any actuators. This allows body actuation systems to be configured in wearable dimensions. This concept has also been used in perceiving affordance for manipulating tools and objects [90] or drawing lines [91]. Wearable EMS systems are also used to generate haptic feedback from virtual reality environments to users for enriching visual feedback [92, 93]. In this manner, EMS techniques have been used for achieving communication between a user and objects or a virtual world.

3.2.4 Concept

In this study, we aim to assist mutual understanding of one's bodily activity with multiple persons, such as muscle contraction and joint rigidity, which are difficult to observe visually. To achieve this, we propose a blended kinesthetic interaction that allows the following operations: 1) Sharing (=): Synchronizes two persons' muscle activities including not only contraction strengths but also the contraction timings, 2) Subtraction (-): Perceives their difference in persons' muscle contraction strengths, and 3) Addition (+): Assists in adjusting a person's contractions by adding the other person's contraction strength. These blending operations are accomplished using a muscle I/O technique. In contrast to previously developed approaches to sharing haptic sensation [76, 77], the system developed in this study focuses not on an individual user's specific interactions with a physical interface but rather with the kinesthetic activities associated with a wide variety of interactions between two people in several situations. In previous EMS studies [88, 90], accelerators or motion capture systems were used to acquire wearer's hand gestures. The device developed in this study measures biosignals related to muscle activity, making it possible to estimate bodily activities even though the user does not move any limbs but just contracts muscles. These advantages allow physical therapists or sports instructors to understand a patient's or learner's invisible but voluntary intentions concerning bodily motions in an easy and intuitive manner through a somatosensory channel. In this paper, we discuss the validity of the interaction and feasibility of possible scenarios through its modeling, implementation, performance evaluation, and user studies.

3.2.5 Interaction Modeling

Figure 3.5 illustrates the proposed model for an interaction involving users A and B. A situation in which user A receives kinesthetic information from user B (one-way communication) is illustrated. $e_i(t), p_i(e_i, e_j)$, and $f(p_i)$ represent the wearer i's voluntary EMG signal at time t, the stimulation pulse based on the EMG signals of wearer i and the partner j, and the kinesthetic blending function, respectively. Each user's muscle contractions are detected by an EMG sensor and conveyed to the bioSync device worn by the other user via a wireless module. Each user's voluntary contractions are reproduced as the other user's muscle exertions by means of EMS. Since the stimulation and measurement are achieved at the same position, modality, and time, users are able to understand each other's activities without depending on visual observation. The interaction sequence is as follows:

Voluntary actions

Both users A and B perform their voluntary muscle activities. These activities $e_A(t), e_B(t)$ are estimated from measurement of surface EMG signals by the bioSync devices worn by the two users.

Muscle actuation

The users' muscles are stimulated based on the blending pulse function $p_i(e_A, e_B)$, which is described by using stimulus frequency (1/T)[Hz] and pulse width $D(t)$[us] at time t as shown in Eq.(3.1). The stimulus frequency (1/T [Hz]) ranges from 1Hz to 100Hz while measuring e_i (Eq.(3.2)), and the pulse width $D(t)$ is defined by using the weighting factor $a_{i,j}$, contraction strength $e_{i,j}$, time constant $\tau_{i,j}$ of the wearer i and j, and activation function g (Eq.(3.3)). We used a simple step function as the activation function g with threshold θ when we conducted rhythmic action synchronization experiment. For the demonstration, we adapted another function that presents the subtraction between two users' contraction strengths.

$$p_i(e_i, e_j) = u(T, D(t)) \tag{3.1}$$

$$T : 1Hz < 1/T < 100Hz \tag{3.2}$$

$$D(t) = g(a_i e_i(t - \tau_i) + a_j e_j(t - \tau_j))[us] \tag{3.3}$$

Blended feedback

The perceived kinesthetic feedback is represented as $e_A(t)+f(p_i(e_A, e_B))$. The function f is a perceptual function that represents the blended kinesthetic feedback of a user's voluntary and involuntary movement. We investigated the behavior of the perceived function f experimentally and verified that it is a linear function.

3.2.6 Design Considerations

The proposed interaction has the following characteristics and benefits:

Spatial Correspondance

In the bioSync device, the stimulus circuit and biosignal measurement circuit share specially designed electrodes. The electrode matches the spatial relations of the input and output. In addition to this, the electrode positions of the two users are the same. We assume spatial consistency to simplify user interaction learning.

Sensory Correspondance

As the user's muscle actuation and the device's EMS presentation are performed in the same modality, kinesthesia provides a more intuitive understanding and easier perception of motion sensation, compared to sensory substitution methods, in that minimal prior learning is required. The reason for adopting EMS is that it induces strong motion memories, which assist in self-learning after training.

Temporal Correspondence with Interactivity

The musculoskeletal systems of the users are synchronized while they share the same time and space. This allows the device to be used to teach and be taught the contraction timings between users.

Chapter 4

Implementation

4.1 Smaller-person Experience

4.1.1 Overview

To realize the concept of changing a body representation into that of a smaller person, we have been developing a wearable device to change the visual perspective, as shown in Fig. 4.1. It consists of two wearable devices, a visual translator and passive hand exoskeletons. The visual translator comprises an HMD, a stereo camera module, a sensor belt, a single-board computer with processing software, and a mobile battery (Fig. 4.2).

4.1.2 Visual Translator

We use an Oculus HMD (Development Kit 2, Oculus, Inc.) to provide an immersive experience. The HMD is connected to a single-board computer (Intel Compute Stick, Intel, Inc.) or a laptop (MacBook Pro, Apple, Inc.) via an HDMI cable to display stereo images, and a USB2.0 cable for acquiring The wearer's head orientation can be captured in yaw-pitch-roll format. The Oculus HMD has a six-axis motion sensor (MPU-6500, Invensense, Inc.), and is capable of outputting the wearer's head orientation in yaw-pitch-roll format. Figure 4.3 shows the developed stereo camera module and the sensor belt, which is equipped with two fish-eye cameras (ELP-USBFHD01M-L180, Ailipu Technology Co., Ltd, HD@60fps). Each camera module has a 180° fish-eye lens and is capable of streaming HD video at 60 frames per second (fps). The two camera modules are placed at a distance of 62 mm. Their dimensions are $148 \times 44 \times 18$ mm (depth), and the total weight is 107 g. The wearer attaches the sensor belt at their waist position. It has a nine-axis motion sensor (MPU-9250, Invensense, Inc.) and a microcontroller (Atmel SAMD21, Atmel) for measuring the wearer's waist orientation in the yaw-pitch-roll format. It also has a hook and loop tape for securing the stereo camera module such that the wear can move their eyes from the HMD position to the belt position. This interaction causes a strong feeling of being a smaller. The dimensions are $97 \times 66 \times 12$ mm (depth), and the total mass is 146 g. Figure 4.4 shows a wearer's

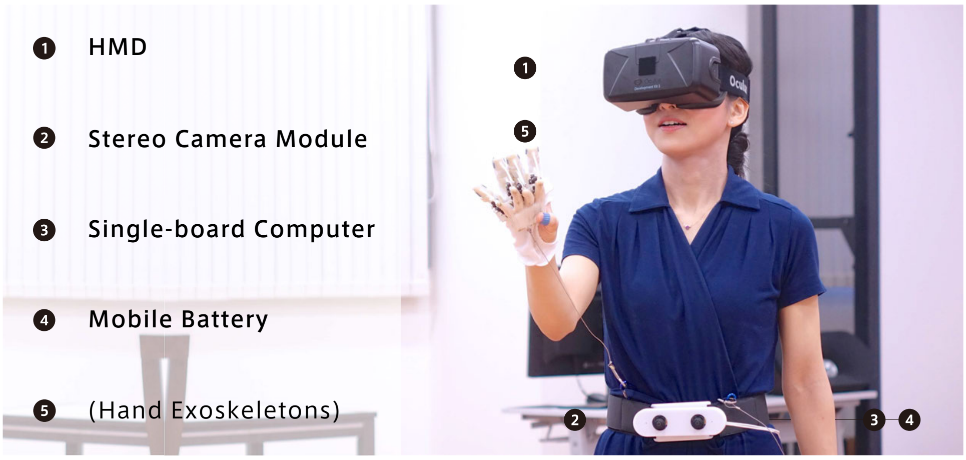


FIGURE 4.1: Overview of the Developed Wearable Device

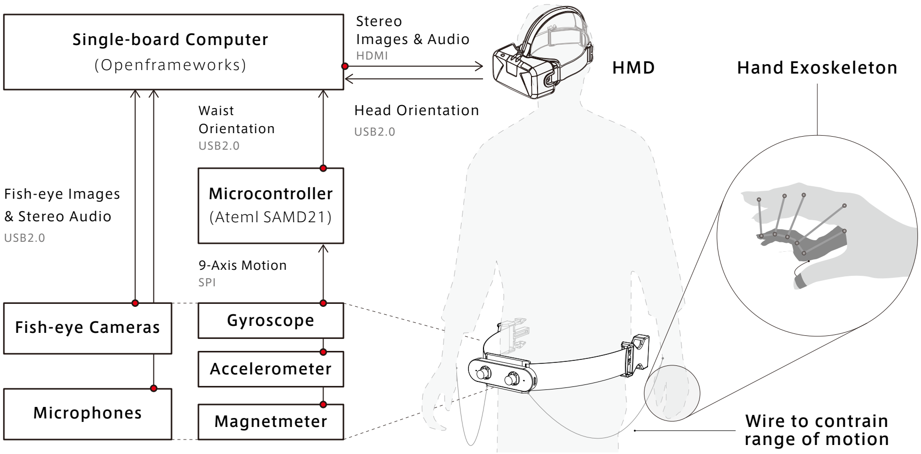


FIGURE 4.2: System Architecture

normal view, and a reproduced view of a smaller person. Two microphones are also embedded into the camera module to transfer the captured sound around the wearer's waist to a headphone.

Image Processing

The images are captured from 180° lenses, and thus they should be transformed into rectilinear images, as shown in Fig. 4.4. We configured the rendering software, which can map the captured spherical image onto a 3D sphere model as a texture, and then project onto a 2D image using an openFrameworks environment. When the stereo camera module is attached to the sensor belt, the waist motion directly affects the stability of images on the HMD. Fluctuation movements while walking and small swinging movements while looking up at something should be eliminated from the captured images. Thus low-pass and high-pass filters which eliminate both a sudden movements to the camera module and slow posture drifts are implemented.

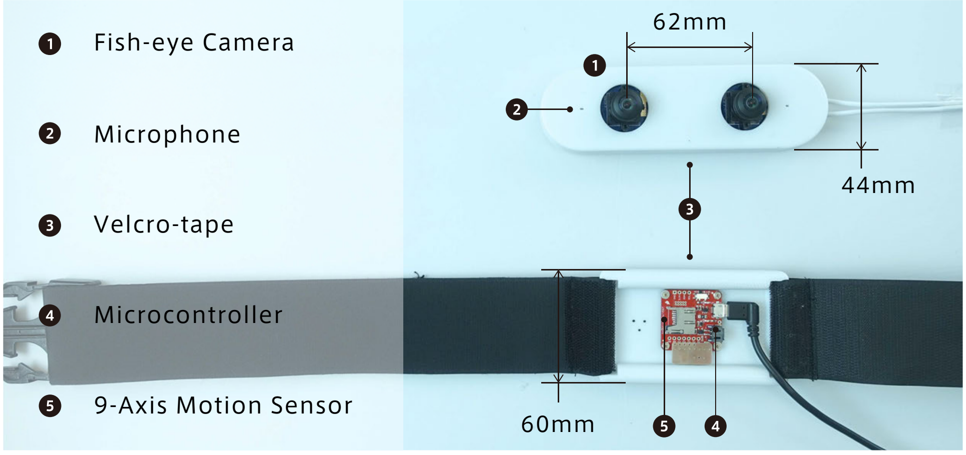


FIGURE 4.3: System Configuration of the Visual Translator

FIGURE 4.4: Visual Perspectives: (a) Captured image (b) Usual level (c) Waist level (d) Looking up from the waist level

We measured the FOV of the developed device as $\pm 40^\circ$ for the horizontal axis and $\pm 80^\circ$ for the vertical axis. Because the corrected images are cropped to a ratio of 16 × 9 and then rotated by 90°, the horizontal FOV is slightly limited compared with that of the vertical axis. However, the wearers tend to look up when someone is facing them because they are perceived as being bigger, and thus a wider FOV on the vertical axis is preferred.

System advantages: In the related preliminary prototype [69, 70], a pan-tilt mechanism composed of servo motors was used to change the viewpoint; however, this makes the device much larger, resulting in a 20 cm distance created between the cameras and the waist, which reduces the spatial correspondence along the horizontal axis between the device and the human eye, thereby decreasing the feeling of integration with the device. In addition, the total weight of the device was heavy at 600 g, resulting in reducing the responsiveness and lifetime of the pan-tilt. The wearer requires help from another person when attaching the device. In this paper, we solved these problems by using a pair of fish eye cameras, allowing a reduction in the total weight and allowing a simple structure and easy attachment

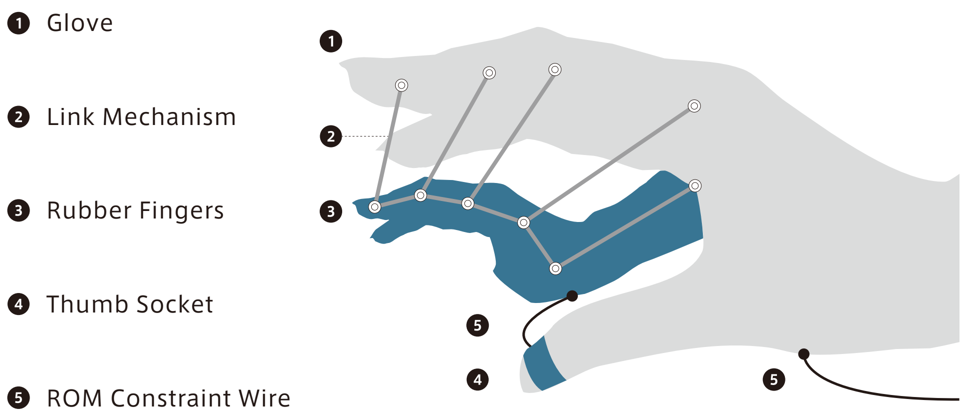


FIGURE 4.5: Conceptual Representation of the Passive Hand Exoskeleton

by a single person. We aslo implemented high-pass (0.05 rad/s), low-pass (1.74 rad/s) filters, and a digital image stabilizer to reduce both angular drift in the sensors and fluctuations caused by walking.

4.1.3 Passive Hand Exoskeleton

Hand exoskeletons are often used for providing haptic feedback when touching an object in a virtual space [94] or controlling a remote manipulator [95]. In the proposed method for changing the haptic perspective, we designed a new type of hand exoskeleton that remaps the wearer's hand gesture into a small range within their hand, as illustrated in Fig. 4.2. The exoskeleton transforms the scale of the wearer's hand gestures into the smaller hand size by using a custom link mechanism, called a multiple quadric crank mechanism. The exoskeleton has small urethane finger skins connected to the wearer's hand by link mechanisms so that the wearer's finger movement can be transmitted to the finger part directly. Because the urethane-made child hand is actuated by the mechanical link system, the wearer is able to receive real-time haptic feedback from objects while interacting. One of the ways in which humans interact with and understand the environment is by touching, grasping, and moving objects. Transforming the dimensions of the user's hands to a child's level would be an important factor for reproducing a child's chronological aspects.

Device Configuration

The exoskeletons are divided into the following parts:

1. Finger sockets to attach the exoskeleton to the user's hand
2. A link mechanism to transmit the grasping motion

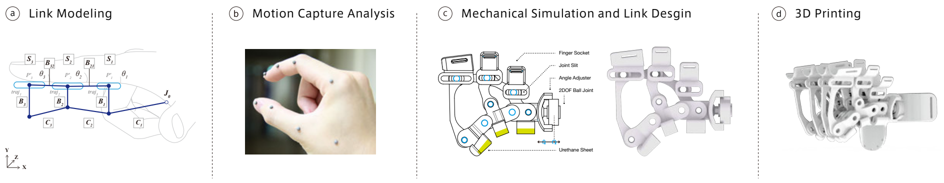

ⓐ Link Modeling ⓑ Motion Capture Analysis ⓒ Mechanical Simulation and Link Desgin ⓓ 3D Printing

FIGURE 4.6: Exoskeleton Design Procedure: (a) Mechanical modeling using a multiple quadric crank mechanism. (b) Measurement of finger joint angles by using a motion capture system (c) Trajectory simulation and Link design on a 3DCAD software (d) Fabrication by using a 3D Printer

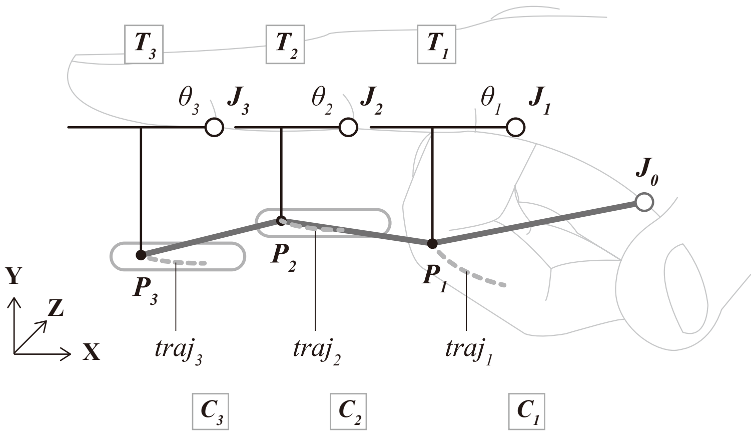


FIGURE 4.7: Link Model of the Prototype Version

3. Flexible urethane skins for child-sized fingers to simulate skin-like haptic feedback
4. A thumbstall with a 4 cm wire to constrain the thumb's range of motion
5. A carabiner (spring hook) with a 70 cm wire to constrain the range of motion of the user's upper limbs

The proposed exoskeletons have no actuators or sensors, and are passively manipulated by the user's subjective actions, allowing to receive complete and real-time haptic feedback from a touching object.

Prototype Modeling

Figure 4.7 shows a link model of the proposed mechanism. The link mechanism consists of three T-shaped finger sockets with links (T_1, T_2, T_3), three small links that act as a child's fingers (C_1, C_2, C_3), a ball joint with two degrees-of-freedom (DOF), and a link that connects the small links to the ball joint. We calculated the trajectory $traj_{1,2,3}$ of points $P_{1,2,3}$ in order to ensure effective grasping capability, when attaching the exoskeleton to the palm of the hand. The

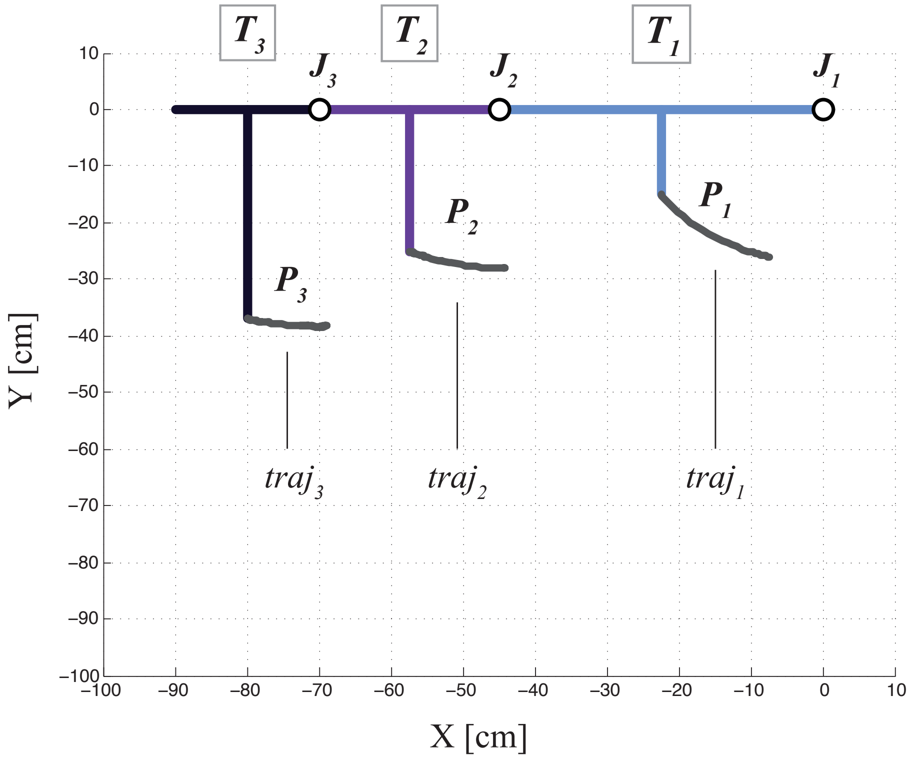


FIGURE 4.8: Simulation experiment results of the trajectory calculation

length and shape of the joint slit for each trajectory was determined based on the angular displacement of each finger joint while grasping an object by using a motion capture system (V100: R2, OptiTrack Inc.). We then conducted a simulation to calculate each trajectory by using Eq. 4.1 from the acquired angle into $theta_i$:

$$P_i(x,y) = \big(-\frac{1}{2}L_i\cos\theta_i + d_i\cos(\frac{\pi}{2}-\theta_i), -\frac{1}{2}L_i\sin\theta_i + d_i\sin(\frac{\pi}{2}-\theta_i)\big) + J_i \tag{4.1}$$

L_i represents the i-th length between any two finger joints and d_i represents the distance between the i-th part of each finger and the mechanical joint, as shown in Fig.4.7. Fig. 4.8 shows the result of the simulation for each trajectory. Based on these results, we designed each link shape and joint slit, as shown in Fig. 4.9. Due to the small size of the links, the joint slit $traj_1$ for link T_1 was omitted. Instead, link C_1 and the 2-DOF ball joint were not attached together, hence resulting in a 3-DOF joint that complemented the joint slit function for $traj_1$.

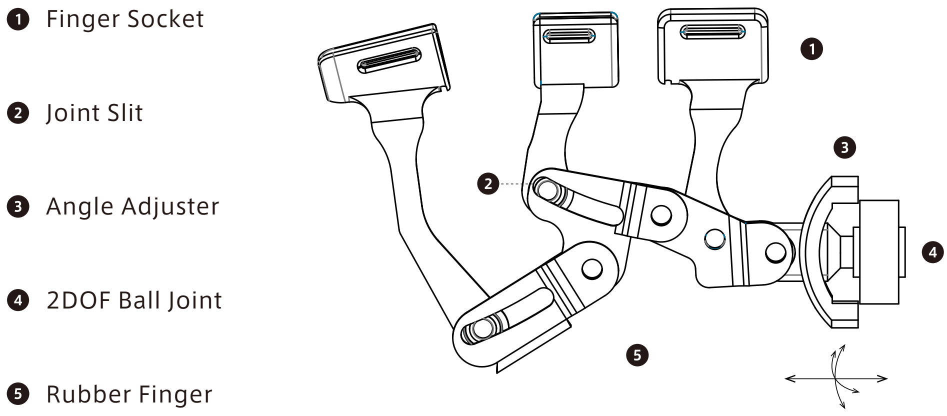


FIGURE 4.9: CAD Model of the Prototype Version

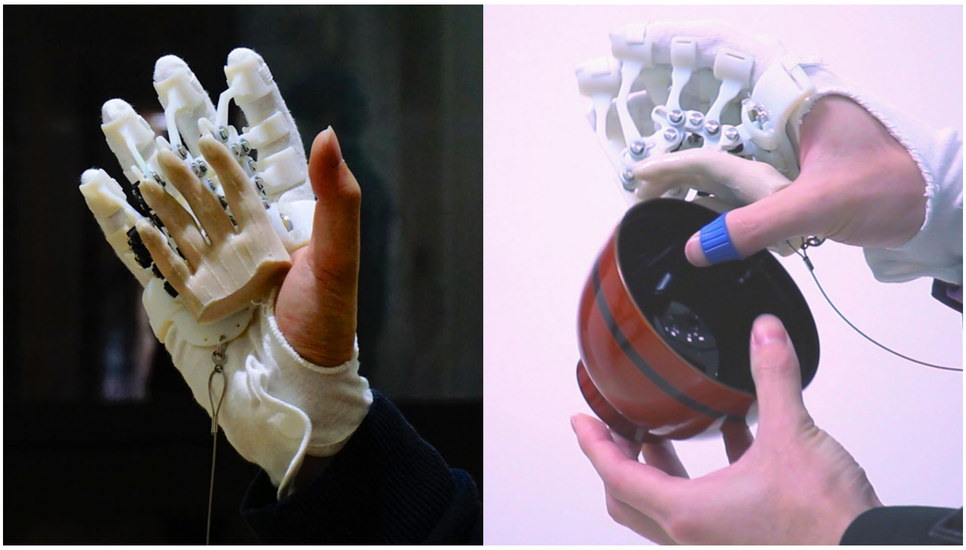


FIGURE 4.10: Implementation of the Prototype Version

Link Modeling

To achieve this interface, we propose a passive link system which uses a multiple quadric crank mechanism for transmitting the grabbing motion to the finger part, as shown in Fig 4.6 (a). The link mechanism consists of three finger sockets with joint slits (T_1, T_2, T_3), three small links that act as a child's fingers (C_1, C_2, C_3), five bridge links ($B_1, B_2, B_3, B_{32}, B_{21}$), a ball joint with two degrees-of-freedom (DOF), and a short link that connects the C_3 link to the ball joint. We calculated the trajectory $traj_{1,2,3}$ of points $P'_{1,2,3}$ in order to ensure effective grasping capability, when attaching the exoskeleton to the palm of the hand. The length and shape of the joint slit for each trajectory was determined based on the angular displacement of each finger joint while grasping an object by using a motion capture system (V100: R2, OptiTrack Inc.), as shown in Fig. 4.6 (b). We then

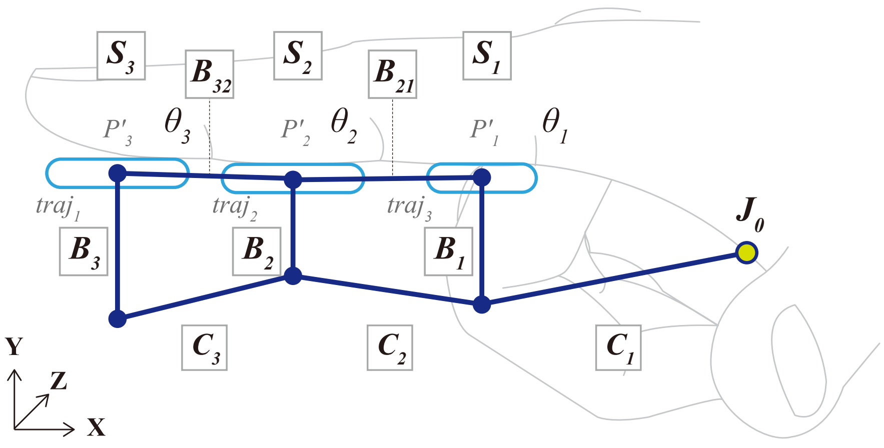


FIGURE 4.11: Link Model of the Improved Version

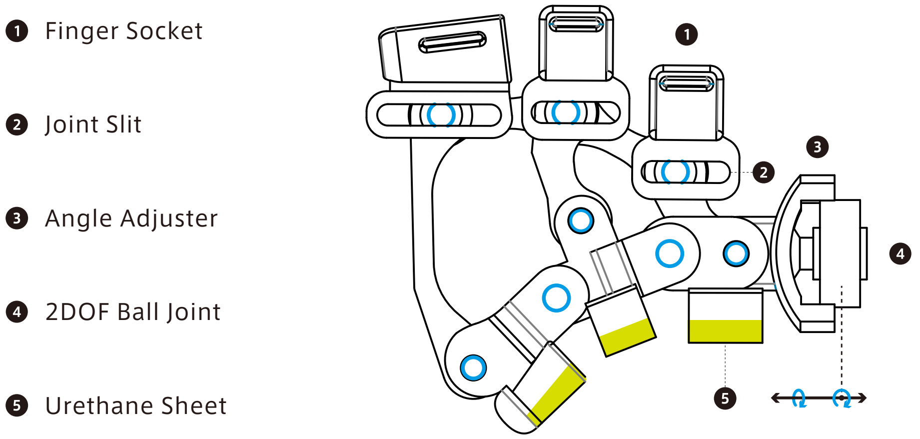


FIGURE 4.12: CAD Model of the Improved Version

conducted a simulation to calculate each trajectory by a 3DCAD software (SolidWorks, Dassault Software, Inc.) from the acquired angle into θ_i: L_i represents the i-th length between any two finger joints and d_i represents the distance between the i-th part of each finger and the mechanical joint. Based on these results, we designed each link shape and joint slit, as shown in Fig. 4.6 (c). Due to the small size of the links, the joint slit $traj_1$ for link T_1 was reduced. Instead, link C_1 and the 2-DOF ball joint were not fixed together, hence resulting in a 3-DOF joint that complemented the joint slit function for $traj_1$ (Fig. 4.13).

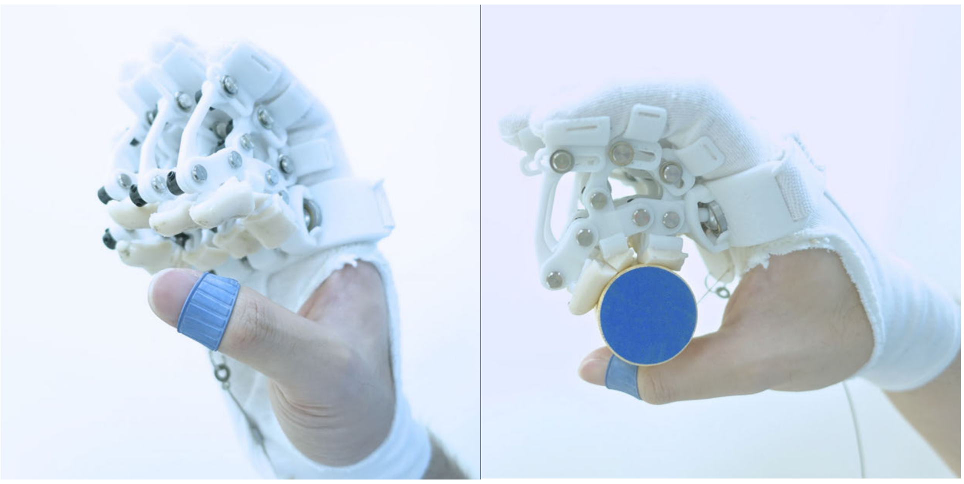


FIGURE 4.13: Implementation of the Improved Exoskeleton

FIGURE 4.14: Overview of the developed device, bioSync

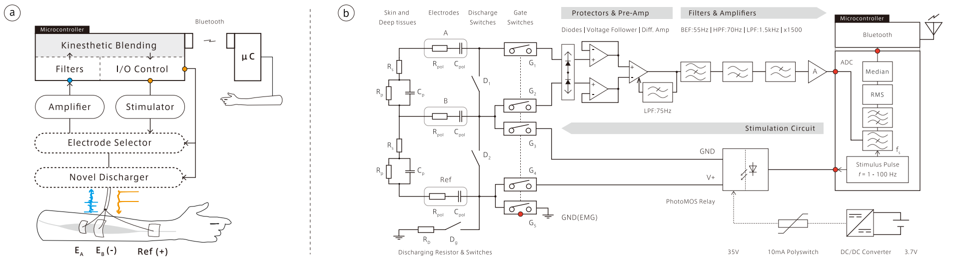


FIGURE 4.15: (a) System Architecture (b) Process Diagram

4.2 Blending Kinesthetic Experience

4.2.1 Overview

To achieve the proposed interpersonal kinesthetic communication in an actual environment, we developed a pair of wearable kinesthetic I/O devices, called bioSync (Fig. 4.14). Each bioSync device is equipped with a custom designed electrode system that performs EMG measurement and EMS simultaneously. Each bioSync is also equipped with a wireless communication module and a radio-frequency identification (RFID) tag, which is used to detect and pair with other bioSync devices by touching the wearer's wrist to the partner's bioSync device.

Figure 4.15(a) shows the system architecture for the proposed system. It consists of electrodes, a stimulation circuit, an EMG measuring circuit, a microprocessor, and a Bluetooth module to communicate with other bioSync devices.

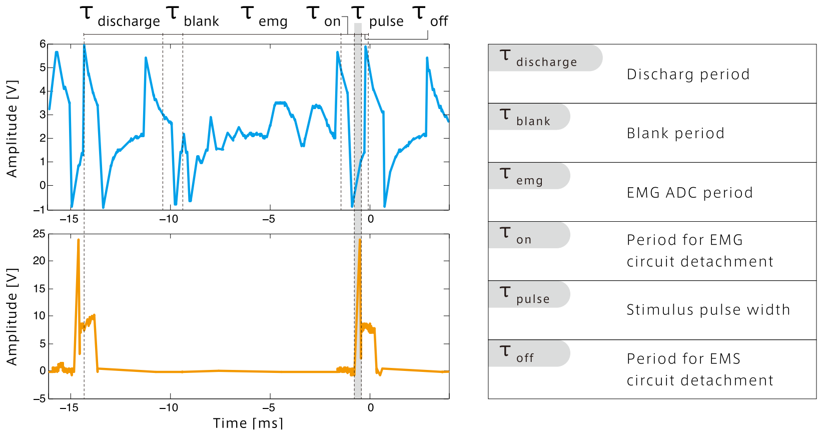
4.2.2 EMG Measurement During Stimulation

Figure 4.15(b) illustrates the processing diagram of the developed device. In order to achieve fast and simultaneous measurement and stimulation operations using common electrodes, a gate switching mechanism and a mechanism for discharging residual potential (the body retains a net charge following the stimulus) are required. The former is designed for protecting the measurement circuit from the stimulus voltage, and the latter is used for modifying the connection path of the electrodes. Hence, the system includes three electrodes (A, B, Ref), discharge switches (D_i), and gate switches (G_i) along with an EMG measurement circuit and a stimulation circuit. Each switch is activated based on an operation timings as shown in Fig. 4.16. The period of discharging, blank, EMG acquisition, EMG circuit detachment, stimulus pulse width, and EMS circuit attachment are defined as $\tau_{discharge}, \tau_{blank}, \tau_{emg}, \tau_{on}, \tau_{pulse}$, and τ_{off}, respectively. The stimulation cycle can be adjusted from 1 to 100Hz, and stimulus pulse width can be adjusted from 0 to 800us. The process sequence is as follows: 1) the electrodes are connected to the input ports of the measurement circuit by the gate switches ($G_{1,2,5}$). The measurement starts after τ_{blank}[ms] which is required for stabilizing the waveform; 2) after the measurement (τ_{emg}[ms]), the electrodes are detached from the measurement circuit and connected to the stimulation circuit by the gate switches ($G_{3,4}$) after τ_{on}[ms]; 3) when the stimulus (τ_{pulse}[us]) ends, the electrodes are detached again and wait for τ_{off}[ms]. Finally, the discharging switches ($D_{1,2,g}$) are activated for $\tau_{discharge}$[ms]. This type of simultaneous operation, using a fewer number of electrodes, allows to reduce the size of the device and facilitates the configuration of the electrodes array. The timings τ_i and resistor R_D values for a stimulus frequency of 40Hz are; $\tau_{discharge} = 7ms, \tau_{blank} = 3ms, \tau_{emg} = 10ms, \tau_{on} = 2ms, \tau_{off} = 2ms, \tau_{pulse} = 0us - 800us$, $R_D = 180k\Omega$.

A conventional discharging method is to short each electrode after stimulus in order to discharge the naturally existing capacitors of the body (C_p, C_{pol}) [87]. In the proposed method, a ground (0V) voltage connection following the electrode shorts is established using the discharge switch, D_g. In addition to this, a discharging register R_D is inserted between the electrodes and the ground for consuming the residual voltage, resulting in a reduction in the overshoot noise in the EMG signal. This mechanism helps in discharging of the residual potential, and stabilizing the measurements after the stimulus. We also propose a method that permits dynamic adjustment of the stimulus frequency. The stimulation cycle can be adjusted from 1Hz to 100Hz, thereby enabling dynamic adaption to various skin conditions and purposes, compared to related devices [96].

4.2.3 EMG Measurement

A diagram of the EMG measurement system is also shown in Fig. 4.15(b). The system consists of two electrodes, one reference electrode, single-pole-dual-throw analog switches (AQV252, Panasonic,



$\tau_{discharge}$	Discharg period
τ_{blank}	Blank period
τ_{emg}	EMG ADC period
τ_{on}	Period for EMG circuit detachment
τ_{pulse}	Stimulus pulse width
τ_{off}	Period for EMS circuit detachment

FIGURE 4.16: Timing Chart of Measurement, Stimulation and Discharge

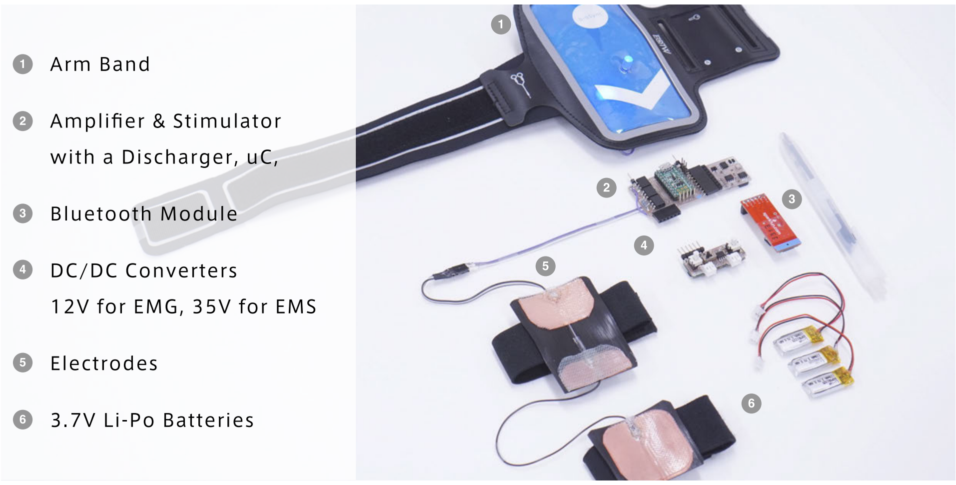


FIGURE 4.17: System Configuration

Inc.) that function as a protection gate to protect the measuring circuit from stimulation pulses, a voltage follower for impedance adjustment, a differential amplifier, a Twin-T-type RC notch filter (f_c = 55Hz) to cut out AC noise, a second-order RC low pass filter (f_c = 1kHz) to remove high-frequency noise, an inverting amplifier, and a voltage limiter to protect the microprocessor (Atmel, Inc., ATmega 32U4). While the system is acquiring EMG signals, the input ports of the voltage follower are connected to the electrodes. During the period of stimulation, the input ports are grounded in order to stabilize the signal wave. Fig. 4.18 shows the implementation of the device.

Digital Filters

High-order digital filters are used to cut out AC noise and pulse noise which comes from the EMS. We use bi-quad filter systems that are computationally inexpensive and easy to implement on a microcontroller. A third-order notch filter is used for reducing pulse noise

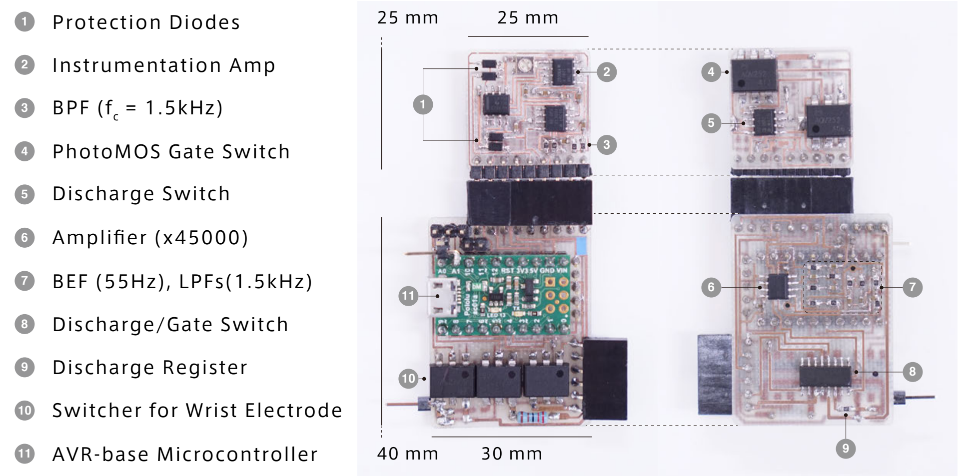


FIGURE 4.18: Device Implementation

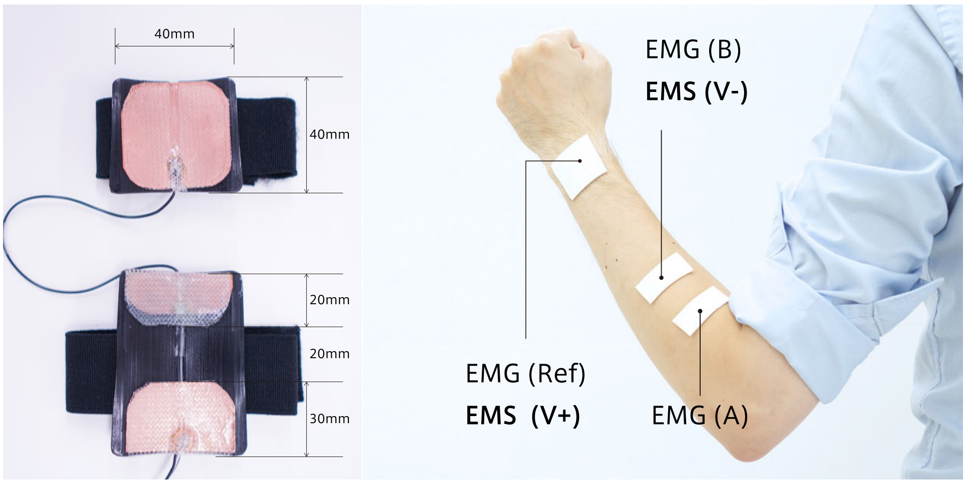


FIGURE 4.19: Electrodes Placement

from EMS. The cut-out frequency(f_c) is dynamically set to the stimulation frequency. A second-order low-pass filter is used for eliminating frequencies other than the EMG frequencies (60Hz to 1kHz). The root mean square (RMS) of 20 measured samples is calculated to estimate the muscular tension. Finally, to screen out pulse noise caused by artifacts or outliers, the median of five RMS samples is calculated and sent to the other bioSync device.

4.2.4 Electrode Configuration

Figure 4.19 illustrates the electrode placement and configuration. We used three electrode pads, A, B, and Ref of sizes 30mm × 40mm, 20mm × 40mm, and 40mm × 40mm, respectively. We set the distance between electrodes A and B to 20mm to avoid a strong effect on the measurement electrode A from the stimulus electrode B. PMMA

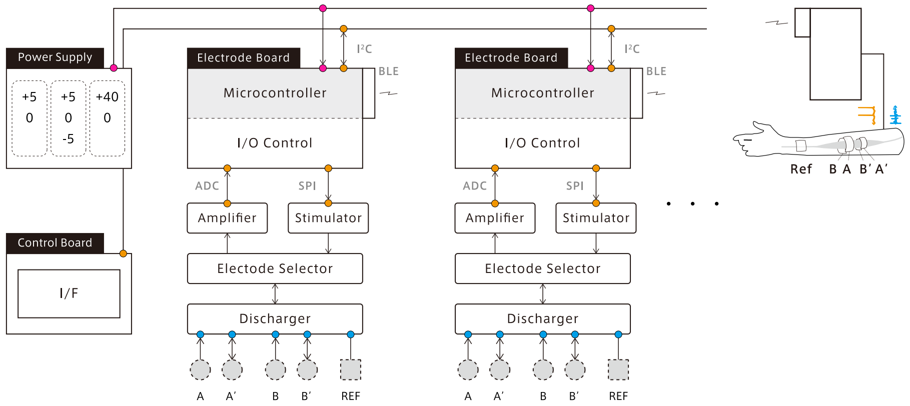


FIGURE 4.20: Daisy-chain Configuration of the Developed I/O Device

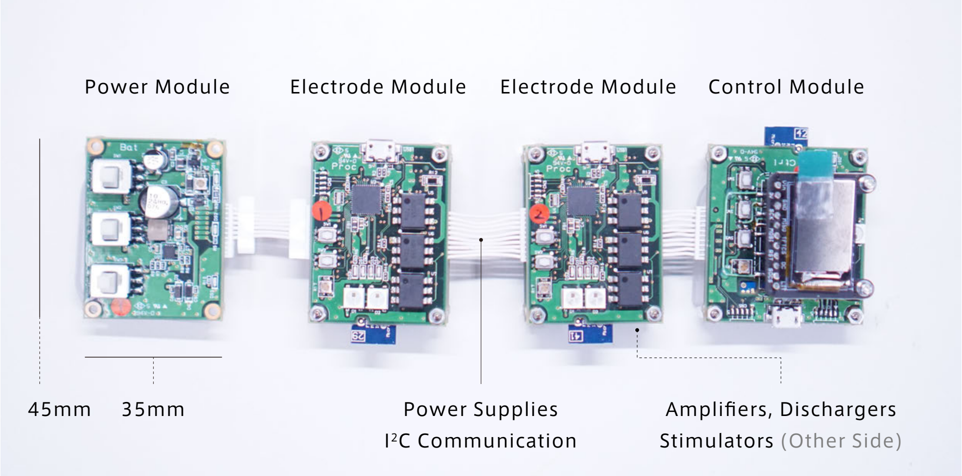


FIGURE 4.21: Scalable Configuration of the System

gel pads (HV-DOUSI-310, OMRON, Inc.) were used. A pulse amplitude of 35V is generated by a DC/DC converter (INA226, Texas Instruments, Inc.) using a 3.7V Li-Po battery.

4.2.5 RFID-based Connection

To enable users of the bioSync devices to interact intuitively with each other, an RFID tag (ISO 14443A standard tag) is embedded in the wrist electrode of each device, and an RFID receiver (NXP Semiconductors, Inc., MFRC552) is encased in the arm band. The bioSync devices can be paired by one user touching a user's wrist to the other user's arm band.

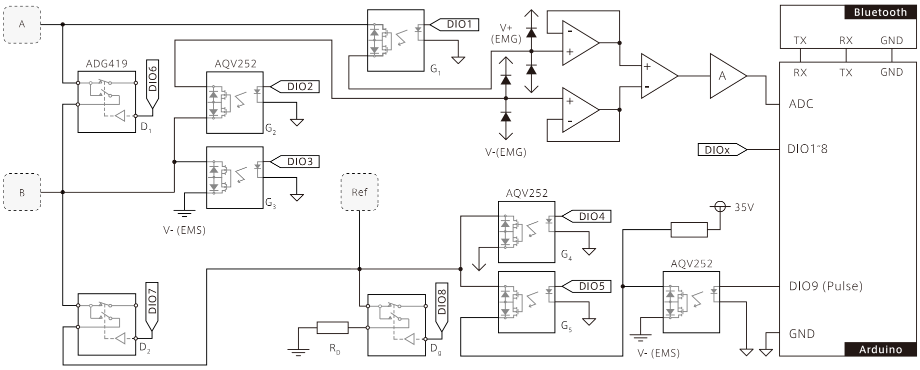


FIGURE 4.22: Schematic of bioSync's Circuitry

4.2.6 Scalable Configuration

When trying to recognize and reproduce an increased number of muscle activities with high spatial resolution, additional I/O electrodes are required. When a number of I/O electrodes share one measurement circuit, the stimulus frequency has to be lowered. This is because a certain period is required for stabilization when connecting the set of electrodes to the circuit from the other. Therefore, the developed device was functionally separated and configured in a scalable manner. One module is capable of measuring and intervening four muscle activities at the same time by using two measurement circuits, and of communicating with other modules via expansion ports. This allows to preserve 1) high stimulus frequency (up to 70Hz), 2) wearable dimensions in which the device can be placed along the limbs, and 3) flexibility to adjust the number of I/O electrodes (up to 32 channels) to fit target muscle structure and any purpose.

Therefore, the developed device was functionally separated and configured in a scalable manner, as shown in Fig. 4.20. One module is capable of measuring and intervening in four muscle activities simultaneously by using two measurement circuits. Furthermore, it is capable of communicating with other modules via expansion ports. This allows the preservation of 1) high stimulus frequency (up to 70 Hz), 2) wearable dimensions in which the device can be placed along the limbs, and 3) flexibility to adjust the number of I/O electrodes (up to 32 channels) to fit the target muscle structure and any related purpose.

The expansion ports include isolated power supplies (5 V for the microcontroller, ± 5 V for the analog circuit, and 40 V for the stimulus circuit) and I^2C communication ports to send and receive data by two wires, allowing to establish a form of daisy-chain connection to increase the number of I/O modules. The timings of the stimulus and the measurement are synchronized via I^2C communication in order to avoid interference between the modules.

Chapter 5

Performance Evaluation

5.1 Smaller-person Experience

5.1.1 Visual Translator: Latency

We evaluated the system latency of the image processing in the visual translator to verify that the device was capable of capturing the sphere images and displaying processed stereo images with a low latency so that the wearer can maintain the sense of agency toward the device.

Task and Apparatus

The entire loop process consists of the following functions: acquiring kinetic sensor data from the HMD and sensor belt via virtual serial ports, filtering the acquired sensor data, capturing stereo image from the camera module, correcting fisheye image distortion, cropping image and rendering distortion-corrected stereo images on the HMD. The duration between the LED light emission in front of the camera module and its display on the HMD was measured by using a high-speed camera (240 fps).

Results

The rendering latency was measured as 117.6 ms (SD = 15.8 ms). As the camera module outputs HD images at 60 fps, the developed device is capable of displaying each frame of the camera in near real time.

5.1.2 Hand Exoskeleton: Linke Mechanism

We then evaluated the performance of the link mechanism in the hand exoskeleton to verify that the developed exoskeleton is capable of transmitting the wearer's finger movements into the flexible urethane finger part. We measured joint angles of the wearer's index finger and C_i links, and calculated angular displacements between opened and closed hands states. The results were used to confirm

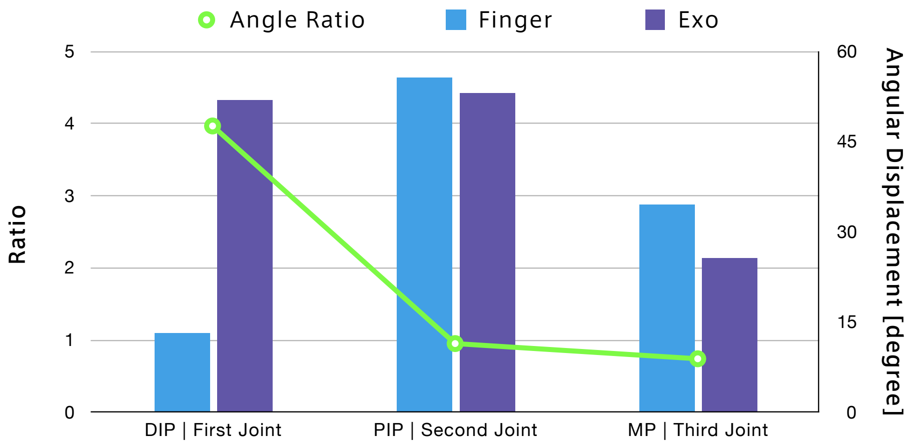


FIGURE 5.1: Passive Hand Exoskeleton: Performance Evaluation

whether the link mechanism is capable of reproducing a dexterous finger action such as a pick-up operation by a fingertip.

Task and Apparatus

Small black dots (diameter = 1 mm) were placed on each joint of the wearer's index finger and C_i links, and its images were captured when the hands were opened and closed. The images were imported to a 3DCAD software (Fusion 360, Autodesk Inc.) for measuring the angles between the interphalangeal joints and links.

Results

Figure 5.1 shows the angular displacement of each joint and the ratios of joint angles of the exoskeleton to that of the wearer's finger. It was verified that finger movements of the wearer were transmitted in the following manner: for the metacarpophalangeal (third) joint, the joint movement was downscaled by a factor of 0.74; for the proximal interphalangeal (second) joint, it was transmitted to the urethane finger part at almost the same magnification (0.95); and for the distal interphalangeal (first) joint, the angular displacement of the wearer's finger was magnified by a factor of 3.97 at the urethane finger part.

5.2 Blending Kinesthetic Experience

5.2.1 System Latency

We evaluated the communication latency of the devices using a wireless configuration for verifying that the devices were suitable for use for bi-directional haptic communication.

Task and Apparatus

Signal triggers are generated when a bioSync measures a biosignal and the other bioSync device produces a stimulus signal. We measured the triggers from both devices by using an oscilloscope (Agilent Technologies, Inc., MSO-X3034A) and defined the temporal difference between them as the latency. The Bluetooth modules were paired before the start of the experiment and were placed 40cm apart, with no obstacle in their communication path. The switching (stimulus) frequency f_s was set to 40Hz in order to achieve the most intense muscle contraction in this particular subject (25-year-old male). We conducted 25 trials in this evaluation.

Results

The average latency was 20.9ms (SD=5.6ms). The device performed a loop program consists of the measurement with discharging, a filtering process, UART output and reading via the Bluetooth module, and stimulation. Thus, the maximum latency depends on the stimulation frequency. In this experiment, the frequency was 40Hz, and the theoretical maximum latency was 25ms. This is almost the same as the average measured latency. In the bioSync device, the stimulus frequency can be adjusted from 1Hz to 100Hz. Muscle actuation is usually achieved when the stimulus frequency is higher than 20Hz. We therefore set 20Hz as the minimum stimulus frequency.

5.2.2 Performance Measurement

We next evaluated the biosignal measurement performance under various stimulus conditions for understanding the electrical characteristics of the I/O circuit. EMG signals can be affected by the stimulus signals even if the discharging time $\tau_{discharge}$ is fixed. By investigating the relation between the applied pulse strength and the measured contraction strength, we were able to identify the appropriate software compensation for the electrical characteristics.

Task and Apparatus

Figure 5.2 illustrates the experimental setup. Each participant wears a bioSync device, and pulls the tip of the digital force sensor (IMADA,

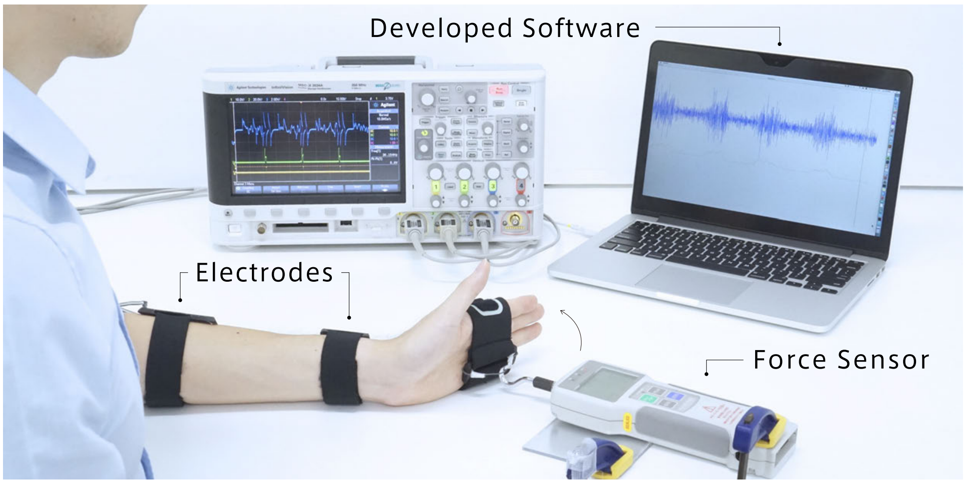


FIGURE 5.2: Experiment Setup: Performance Measurement

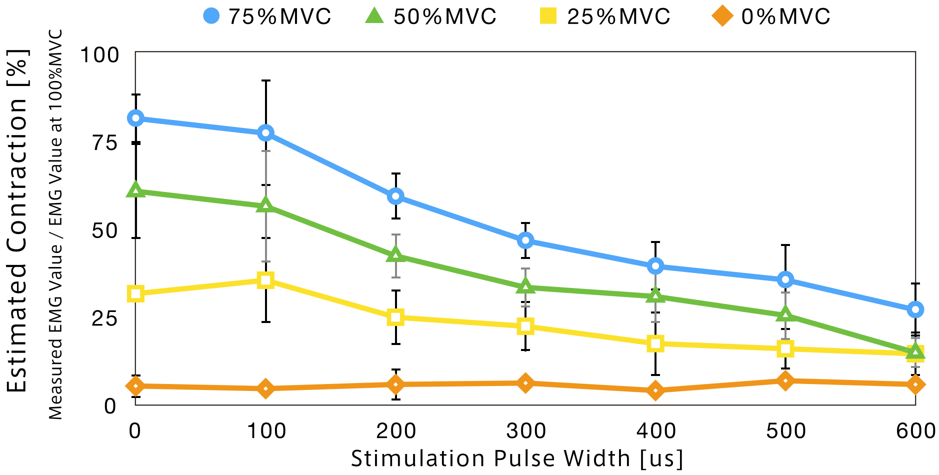


FIGURE 5.3: Experiment Result: Performance Measurement

Inc., ZP-1000N) using the cuff, by extending the wrist. Before the experiment is started, each participant's 100% maximum voluntary contraction (MVC) is measured using the force sensor and the developed EMG recording software. Then each participant is asked to reproduce his 75%MVC[N], 50%MVC[N], 25%MVC[N] and 0%MVC[N], while stimulus with durations in the range of 0 to 600 us (in increments of 100 us) were applied. The measured EMG signals were converted to percentages of the EMG value at 100%MVC. The participants were able to see a display of the force sensor to check the accuracy of each percentage of the MVC. The electrodes were placed on the extensor digitorum muscle.

Participants

Five healthy subjects from our local organization participated in a total of 420 trials (5 participants × 7 stimulus strengths × 4 levels of %MVC strengths × 3 repetitions). The trials required approximately 20 minutes per participant.

Results

Figure 5.3 illustrates the measured contraction percentage and applied stimulus width results. As the stimulus pulse width increased, the measured contraction decreased almost linearly.

Chapter 6

User Studies

6.1 Smaller-person Experience

6.1.1 Overview

To investigate how the wearer's perceptions, actions, and interactions can be modified through the proposed egocentric experience of a smaller person, we investigated the following three factors, which are essential for the understanding of the users: 1) **wearer's perception** on social relationship with other humans by measuring their personal space, 2) **wearer's action** during handshake task, and 3) **wearer's interaction** with people and objects through observations during the demonstrations and experiments. (Fig. 6.1)

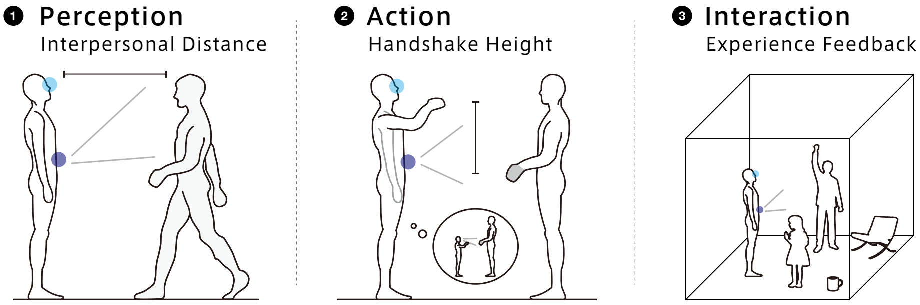


FIGURE 6.1: Overview of the User Studies

6.1.2 Wearer's Perception

Objective

To observe the changes in social relationship through the egocentric experience of a smaller person, we measured the wearer's personal space. A personal space is the physical space surrounding an individual, an encroachment into which can feel threatening or uncomfortable [97]. Previous studies have demonstrated that the size of one's own sensed body, triggered by visual perception, directly influences the perception of object sizes and distances when the participants laid on a bed during the experiment [40]. Another study investigated one's personal space toward different persons and objects

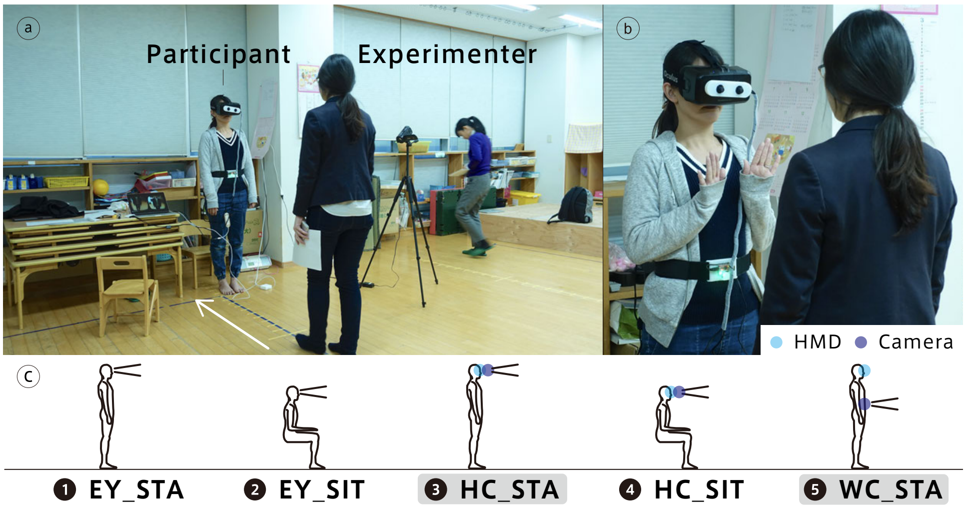


FIGURE 6.2: Wearer's Perception: (a) Experiment overview (b) When the participant calls "stop" (c) Experiment conditions

in a virtual environment [98]. We examined whether such phenomena are also effective when the wearer's body representation is modified using our wearable devices in a real environment. We focused particularly on the perception of size and distance toward people, as a way to investigate how the proposed experience can change the relationship between two persons, which would be valuable knowledge for an educational staff. We used a stop-distance method for measuring the personal space. This method is typically used in psychological studies [99], and many studies have been conducted to investigate differences in personal space between people under various conditions such as age, gender [100], or with/without disease [101].

We especially focus on how the personal space can be changed by two conditions; when the camera is placed at HMD (usual POV, condition (3)); and at the waist (lower POV, condition (5)), to observe the effect of eye level in shaping personal space in a RE.

Task

In this study, the experimenter approached each participant until the participant said stop, as shown in Fig. 6.2 (a, b). The distance between their toes was measured using a ruler on the floor. We tested five conditions, as illustrated in Fig. 6.2 (c): without the device while standing ((1) EY_STA) or sitting ((2) EY_SIT); wearing the HMD and the camera module placed at the HMD (see-through mode) while standing ((3) HC_STA) or sitting ((4) HC_SIT); and wearing the HMD and the camera module at the participant's waist position ((5) WC_STA).

Setup

The participants were instructed to call out stop when the encroachment of the experimenter felt threatening. The genders of the experimenter and the participant were matched, and the conditions were arranged in a random manner. The participants tried on the device for 5 min before the study.

Participants

Nine healthy caregivers from a nursing school participated in a total of 180 trials (9 participants × (4 repetitions for each condition), 8 females and 1 male. The minimum and maximum height were 146cm and 174cm respectively (mean=160.5cm, SD=7.7cm). No participants had any experience using an HMD prior to the experiment. The trials required approximately 20 min per participant. They were able to control FOV by their head orientations under all conditions.

Results

Figure 6.3 shows the results of the personal space experiment. A Friedman test was performed (χ^2=23.2, $p < 0.001$). A p-value adjustment was applied using the Benjamini-Hochberg method in which the false-discovery rate (FDR) was set to 0.10 [102, 103]. The results of a Wilcoxon signed rank test showed that there is a significant difference between (5)WC_STA and (3)HC_STA ($p = 0.036$), (2)EY_SIT ($p = 0.017$), and (1)EYE_STA ($p = 0.012$).

(5)WC_STA condition: Under the (5) WC_STA condition, in which the participants were asked to observe their surroundings from a lower POV, the largest amount of personal space (114.1 cm) was observed. The participants reported that the approaching experimenter looked bigger than in reality. Although the difference was not significant, several of the participants mentioned that, under the (5) WC_STA condition, the experimenter looked bigger when compared with the (4) HC_SIT condition.

STA and SIT conditions: In comparison with the standing conditions, the participants reported a larger distance when sitting and looking up at the approaching experimenter ((2)EY_SIT > (1)EY_STA; and (4)HC_SIT > (3)HC_STA).

EY and HC conditions

Compared with EY conditions in which the participants were asked to observe the experimenter with their eyes, they reported larger distances when they were looking the experimenter through the HMD and the camera (HC_STA and HC_SIT). In addition to this, the standard deviation was increased when the participants were using the HMD and the camera.

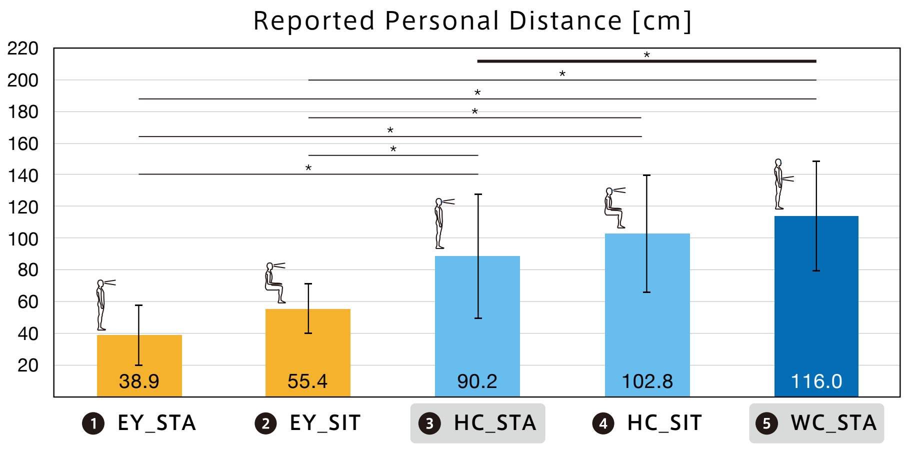


FIGURE 6.3: Wearer's Perception: Experiment Results

6.1.3 Wearer's Action

Objective

Based on our observations through conference demonstrations and exhibitions, it was often observed that when the exhibitor extended their hand for a handshake with the wearer, the wearer raised their hand much higher than that of the exhibitor, as shown in Fig. 6.4 (b). This could be have occurred because the wearers recognized that they had become smaller from the visual feedback, and tried to grab the exhibitor's hand, which they perceived to be positioned at their shoulder height. Such hand adjustment in the air, in which changes to one's bodily sensations create a new spatial relationship between the user and surrounding objects, can become visible through the user's own actions. We hypothesized that this adjustment action can be used as evidence that the wearer's body representation changed into that of a smaller person.

Therefore, in this study, we investigated whether adjustment action can occur under a controlled stimulation and environment with a larger number of participants. We are particularly interested in the effects of agency in viewpoint control on the strength of the adjustment action; therefore, we set up a control condition utilizing a video player in which the wearer simply watches a handshake video from a lower stature, and the wearer's head orientation does not affect the viewpoint control. If there is a difference in the height of a handshake between the condition of the video and the condition of a smaller person, the effect of FOV control based on the head orientation in a changing body representation in a RE can be discussed.

Task

We instructed the participants to stand up and try to shake hands with the experimenter under the following two conditions: **(1) Video condition:** A video was recorded from a waist-level perspective,

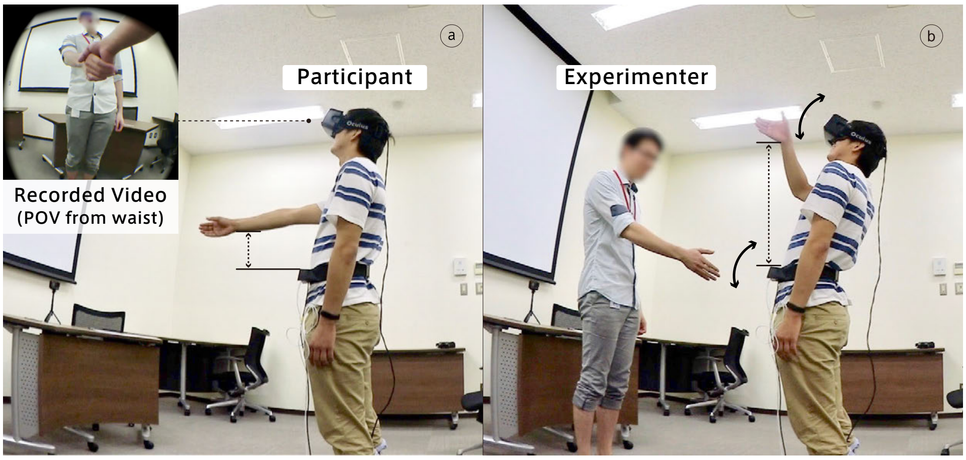


FIGURE 6.4: Wearer's Action: Experiment Setup and Conditions: (a) Watching a Video (b) Small-person Experience

during which an experimenter tried to shake hands with a participant, and is played on the HMD, **(2) Smaller person condition:** The participant is able to observe the experimenter through the camera module attached at the waist, and to change their viewpoint using their head orientations. The wearer's head orientations, and first- and third-person videos, were recorded to compare the height of the participant's hand between two conditions.

Setup

The conditions were arranged in a random manner. The participants tried on the device for 10 s before the experiment started. The distance between the two persons was set at 73 cm, which was determined in advance based on the previous literature [97] which defines far phase of personal distance (starting from 75cm) where humans can touch one's finger when he/she extends their arm. The positions of the two persons were fixed during all sessions. The participant used their dominant hand to conduct a handshake. All instructions were given by a secondary experimenter sitting 2 m away from the participant. The second experimenter validated the first experimenter's hand position to confirm whether they performed the motion at the same position each time (fidelity check). Three video cameras were placed to record the participant's handshake from the front and side. The hand height was measured by counting the pixels between the camera module and the wrist in the recorded image under both conditions, as shown in Fig 6.4.

Participants

Fifteen healthy participants from our local organization participated in a total of 30 trials (15 participants × 2 conditions, mean height =

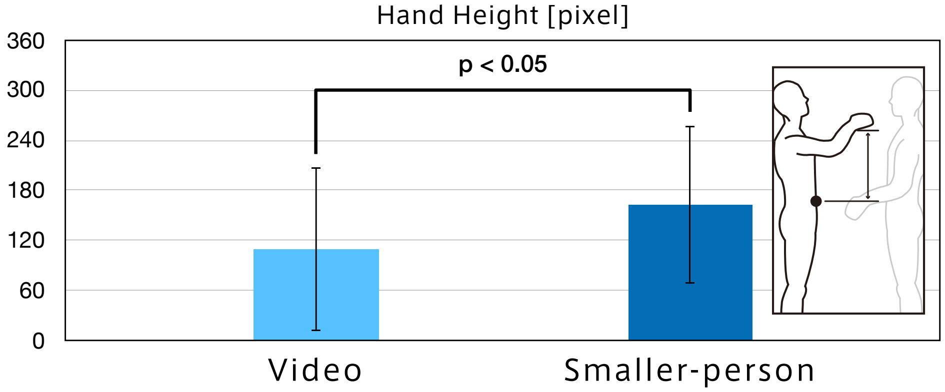


FIGURE 6.5: Wearer's Action: Experiment Results

170.6 cm, SD = 5.67 cm). They have never tried the system before. The trials required approximately 15 min per participant.

Results

Figure 6.5 shows the results of the histogram of the hand states. A paired T test showed that there is a significant difference between the two conditions ($p < 0.05$). Under both conditions, the participants raised their hand higher than usual. When comparing these two conditions, twelve of the participants raised their hand higher under the smaller person condition.

6.1.4 Wearer's Hand Function

Objective: Chronological Hand Function

Next, we investigated how the wearer's hand function is modified when using the developed exoskeleton. One's hand function is directly affected by two major factors: cognitive capability such as motor command for reaching and grasping, and physical capability such as lengths of the limbs and muscle structures. The former ability is correlated with one's developmental age, and the latter is correlated with one's chronological (real) age. In this and the next experiment, we quantified how the developed exoskeleton modified the wearer's chronological and developmental hand motor function by measuring time required to move a peg from one hole to another with or without wearing the exoskeleton.

The objective of this experiment is to determine whether there is an effect of the exoskeleton on the capability of the wearer's physical hand manipulation by using pegs of various diameters. If the participant took more time for handling bigger pegs when using the exoskeleton, it would mean that his/her chronological (physical) hand function is decreased owing to the use of the exoskeleton, in a similar manner to a child.

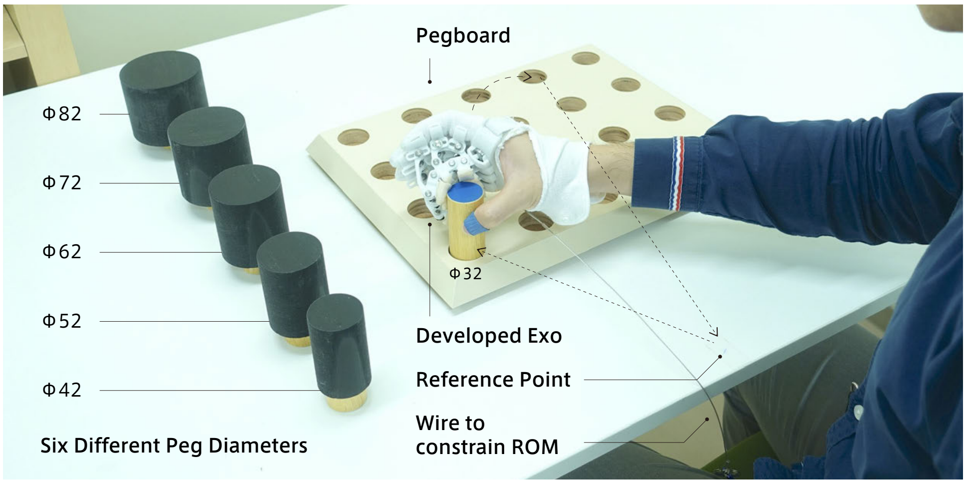


FIGURE 6.6: Chronological Hand Function: Experiment Setup

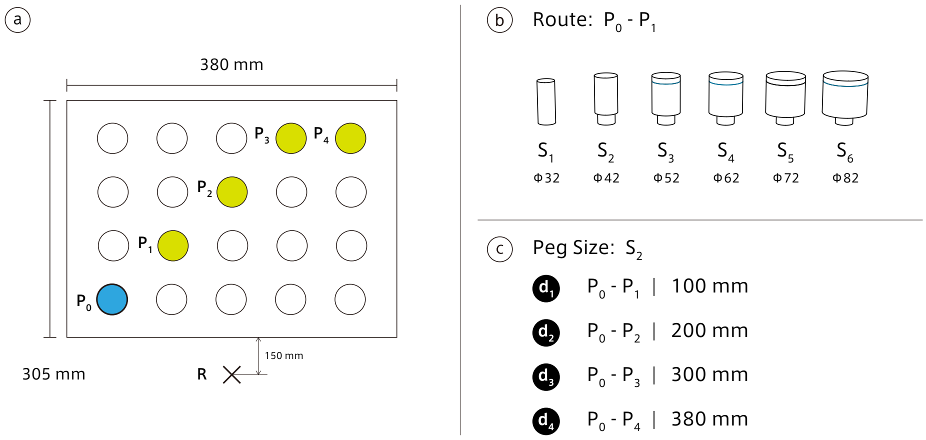


FIGURE 6.7: Hand Function: (a) Pegboard setup (b) Six different peg diameters S_i (c) Four different peg route distances d_i

Task

Figure 6.6 shows the experimental setup. The participant tries to place the peg S_i from P_0 to P_1 location, then put back to P_0 location. Before and after the peg movement, the participant places their hand on the reference point R. The elapsed time between when the participant removes his/her hand from the reference point R and when it gets back to R was measured by a stopwatch, and defined as the movement time MT.

Setup

The pegboard (SOT-2101, SAKAI Medical Co., Ltd.) consists of 20 peg holes, each 20 mm (depth) × ϕ32 mm, arranged in an array of four rows and five columns (Fig. 6.7 (a)). Five black adaptors were

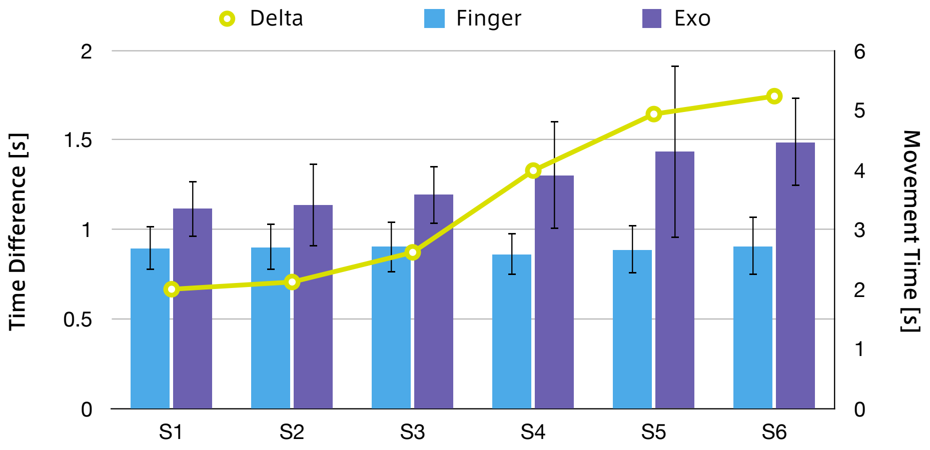


FIGURE 6.8: Hand Function: Peg Size and Movement Time

prepared by a 3D printer for changing the diameter of existing pegs ($S_{2,3,4,5,6}$), as shown in Fig. 6.6 and Fig. 6.7 (b). While the participant is wearing the exoskeleton, the wire with a carabiner is connected to his/her belt loop for constraining the ROM of the upper limb.

Participants

Six healthy participants from our local organization participated in a total of 360 trials (= 6 participants × 6 peg diameters × 5 repetitions × with/without the exoskeleton; 5 male and 1 female, mean age = 24.3 years, SD=1.89 years). Each participant used his/her dominant hand, and tested the exoskeleton for 2 minutes before the experiment started. No participant had experience of using the developed exoskeleton. The trials required approximately 20 min per participant.

Results

Figure 6.8 shows the results of movement time MT by the wearer's finger and exoskeleton for different peg diameters. While the wearer used his/her own fingers to move the pegs S_i, there were no big changes in the movement time. On the other hand, when the wearer used the exoskeleton and moved the pegs with a tiny hand, the movement time increased as the peg diameter became larger. The green line shows the time difference between when using and not using the exoskeleton. It was verified that the time difference became larger as the peg diameter increased. It is noted that one participant could not pick up the largest peg S_6, and its time is not included in Fig. 6.8. Another participant dropped the peg S_5 and S_6 while moving to another hole.

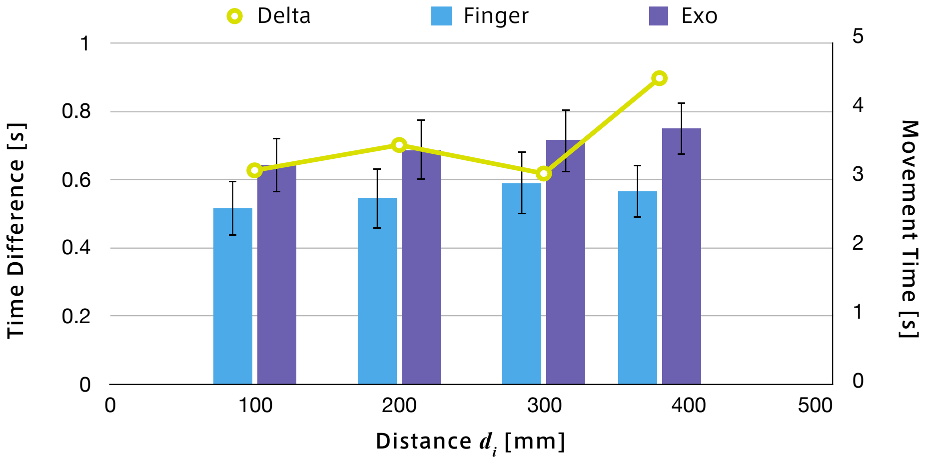


FIGURE 6.9: Hand Function: Peg Route and Movement Time

Objective: Developmental Hand Function

In this section, we assessed the wearer's developmental hand function by measuring movement time of the peg MT for different routes on the pegboard. The objective of this experiment is to investigate whether there is an effect by the exoskeleton in cognitive competence related to developmental age, such as reaching planning to another peg hole, by measuring movement time with trials of different peg routes d_i.

Task and Setup

The participants try to move the S_2 peg on different routes, as shown in Fig. 6.7 (c), and its movement time is measured. We used the same equipment as for the previous experiment. In this experiment, only the peg S_2, of diameter is 42mm, is used to eliminate the effect of peg size on movement time.

Participants

The same participants from our local organization conducted 240 trials (= 6 participants $\times$ 4 distance values $\times$ 5 repetitions $\times$ with/without the exoskeleton). The trials required approximately 20 min per participant.

Results

Figure 6.9 shows the results of movement time MT for different peg routes. The green line shows the time difference between when using and not using the exoskeleton. The result in the longest distance (D4 illustrated in Fig. 6.7 (c)) is different from other three results because

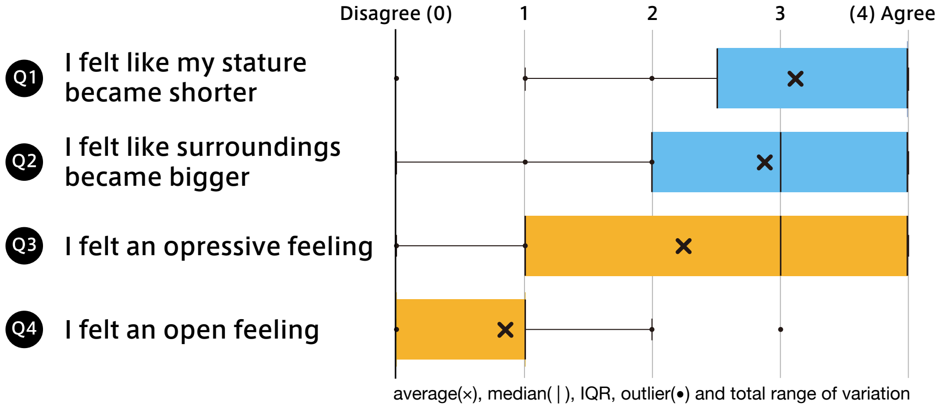


FIGURE 6.10: Wearer's Interaction: Likert Questionnaire

we consider that it is the effect of the wire for constraining ROM of the upper limbs. It is not affected less than the distance of 350mm.

6.1.5 Wearer's Interaction

Objective

In addition to the previous quantitative studies, we also observed the wearer's interactions in the experiment and demonstration spaces, for investigating interactions in a different scenario such as the wearer versus multiple persons, moving objects, or different actions. The venue includes two science museums, a university hospital, two conference demonstrations and two art exhibitions.

Task and Participants

Twenty-five participants who joined the previous experiments (mean height = 166.5 cm, SD = 8.1 cm) were asked to answer five questions on a 5-point scale (0 = disagree, 4 = agree), as shown in Fig. 6.10. We also asked them to answer another questionnaire regarding how the smaller person experience had changed the participant's body representation, as shown in Fig. 6.11. Comment feedback, and the actions and interactions of the demonstration visitors were recorded onto video.

Results

Questionnaire using the Likert Scale

As show in Fig. 6.10, the questionnaire results indicate that the participants had a feeling of being a smaller person (Q_1; score=3.12, SD=1.21), and felt that the surrounding objects and people looked bigger (Q_2; socre=2.88, SD=1.27). Based on their answers to Q_3 and

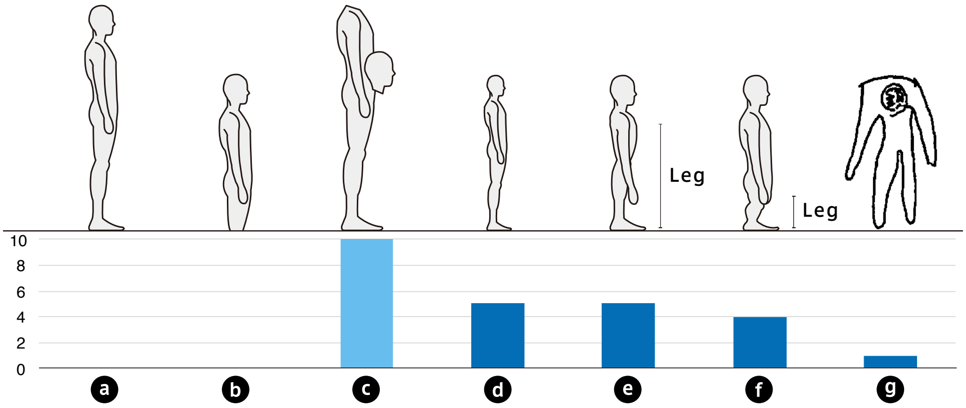


FIGURE 6.11: Wearer's Interaction: Body Representation

Q_4, they tended to experience an oppressive feeling (score=2.24, SD=1.48) rather than an open feeling (score=0.84, SD=0.83).

Questionnaire about a body representation

Figure 6.11 depicts six states of body representations as follows: (a) nothing have changed; (b) my legs felt under the ground; (c) only my head moved to the waist position; (d) my entire body became smaller; (e) my upper body shrank; and (f) my legs shrank. For (g), the participant drew a figure representing their own body.

As a result, all participants chose from (c) through (g), which indicates that their eye level moved to a lower position while standing. Ten participants chose (c), mentioning that they saw their arms through the camera, and reported that this visual feedback affected the physical relationship between their eyes and arms. Another participant who chose (f) reported that they did not experience a strange feeling when seeing their arms from the side, which occurred because the participant is familiar with first-person gaming, which also displays arms close to the player's face.

Observation and Comment Feedbacks

Participant and Setup: We observed interactions and collected comments from not only the 25 participants of the previous studies but also the visitors at a conference, museum, and hospital, which totals more than 500 people. The experience duration ranges from 3 to 5 minutes.

Results: In most of the cases, the wearers first expressed their surprise toward the difference in perspective, as shown in Fig. 6.12 (a). Because they perceived their surroundings has having become bigger and themselves as having become smaller, many of the participants and visitors felt afraid when the experimenter or exhibitor suddenly moved close to them. As a reaction to such an encroachment,

FIGURE 6.12: Wearer's Interaction: Interaction Observation

some wearers bent backward (Fig. 6.12 (b)), or performed protective pose toward the exhibitor (Fig. 6.12 (c, d)). It was also observed that some visitors behaved like a child, such as talking as if the wear had become a child or posing their arms like a baby, when surrounded by adults (Fig. 6.12 (e)). During a user study of personal space conducted at a nursing school, a teacher spoke loudly to another teacher wearing the device in an oppressive manner by looking down at the wearer (Fig. 6.12 (f)). Interestingly, the surrounding people including young students also treated the wearer as a child, and changed their behavior into that of a teacher or parent by acting in an overbearing manner with comments such as *"Bring me candies right now !"*, *"Hey, I'm taller than you now."* The children were observed a few times trying to talk to the camera module positioned at their parent's waist (Fig. 6.12 (g)). In a demonstration, neurosurgical doctors were asked to wear the device and walk around in a children's ward in a hospital. A medical staff noted that a bracing strut in a floor looked much bigger and it gave a strong oppressive feeling. An approaching cart also gave a scary feeling to a medic (Fig. 6.12 (d)(h)). They stated the importance of maintaining the same eye level with that of a smaller person, and securing a certain distance when trying to talk to them to avoid an oppressive impression. They also mentioned that it was difficult to talk with the receptionists face to face because the monitors placed on the desk prevented the doctors from seeing the receptionist's face (Fig. 8.2 (a)). Collected comments suggested the experience provided empathic and proprioceptive understanding of a small-person. One mother stated, *"Wow, you see the world like this ...?"*, one father said *"They live such a hard place !"*, one grandmother claimed *"My neck hurts."* These interactions and comments were observed throughout the all demo places.

Another participant noticed that it is difficult to hold a plastic bottle by the exoskeleton, and suggested a new grip attachment in

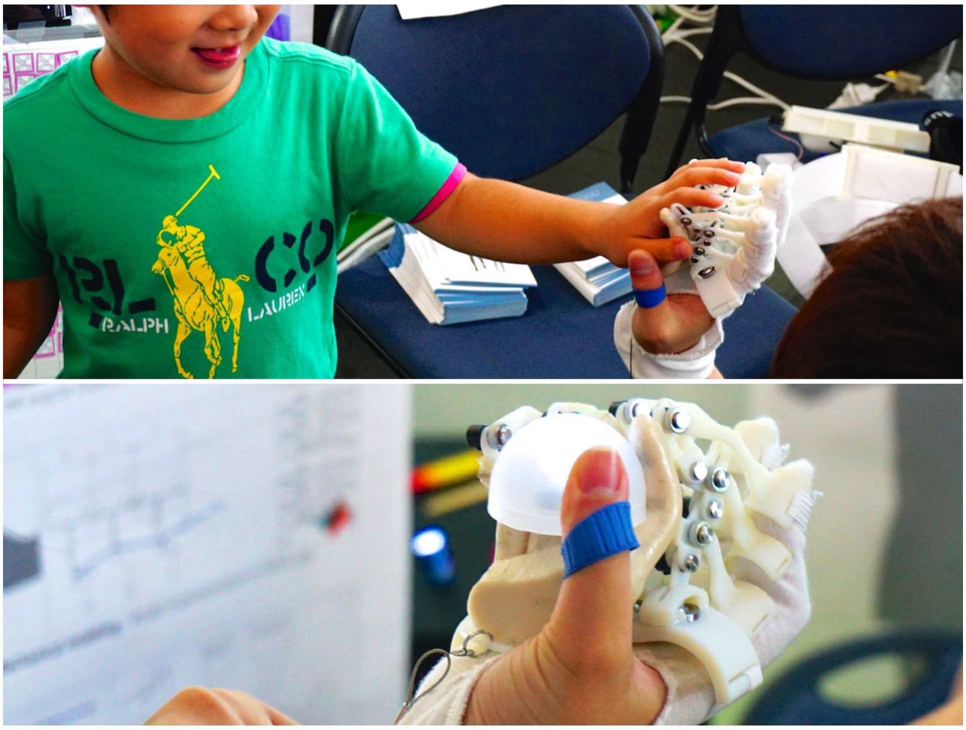


FIGURE 6.13: Wearer's Interaction: Interaction Observation

which a child with a tiny hand can hold it easily. Several participant stated that it is frustrating when trying to hold a rice bowl since they had a difficulty in picking up and holding it in a manner they usually do. One of the participant claimed that his/her existing knowledge to grab an object interfered when trying picking up the rice bowl.

6.2 Blending Kinesthetic Experience

6.2.1 Subjective Perceptual Experiment

In this experiment, we investigated how bioSync users recognized their partners' contraction strength, as reproduced by the stimulation, while the users were contracting their own muscles simultaneously. The results were used to identify the blended perceptual function f illustrated in Fig. 3.5.

Task

The participants evaluated and reported the applied stimulus level on a five-point scale while they contracted their own muscles at 50%MVC, 25%MVC, and 0%MVC.

Setup

The bioSync device, the force sensor, and the cuff were used in the same manner as the previous experiment, but this time the participants were only able to look at the display of the force sensor only before the start of each session. In addition, to eliminate the influence of visual feedback, they were not allowed to look at their arms during the session. The 100%MVC was measured before the start of the experiment, in the same manner as in the previous performance experiment.

Participants

Five healthy participants from our local organization participated in a total of 375 trials (5 participants $\times$ 5 stimulus strengths $\times$ 3 type of %MVC strength $\times$ 5 repetitions; 2 female, mean age = 24.6 years, SD=1.85 years). Two out of five participants had experienced EMS before. The trials require approximately 20 minutes per participant.

Results

Figure 6.14(a) illustrates the results for the perceived strength. The results confirm that the users were able to recognize both their voluntary contractions and reproduced muscle contractions at the same time on a five-point scale. The perceived strength can be approximated linearly. Fig. 6.14(b) illustrates the normalized standard deviation of each pulse width. As the stimulus strength increased, the standard deviation increased.

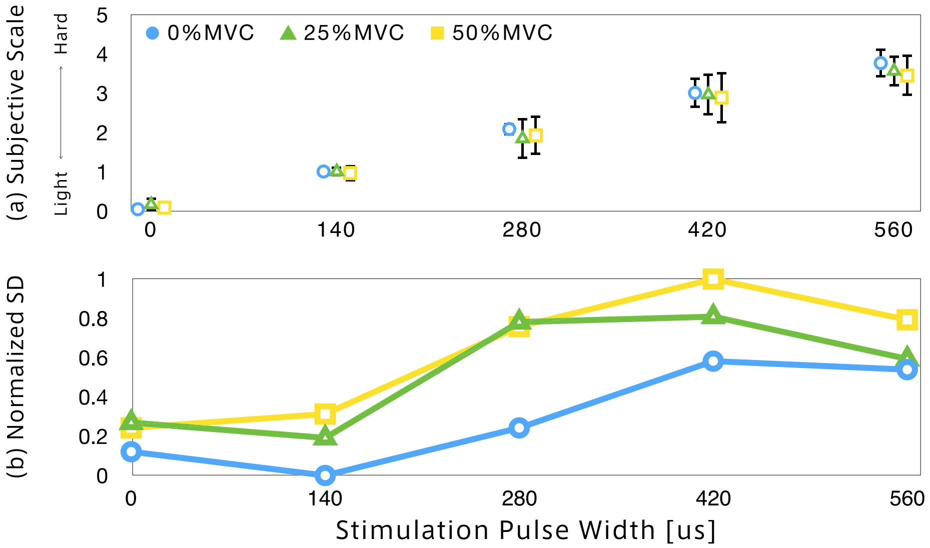


FIGURE 6.14: Experiment Result: Subjective Perceptual Evaluation

6.2.2 Joint Stiffness Measurement

Objective

In this study, we aim to identify the mapping function f and g for 1) the applied EMS value (x_{stim}) and the joint stiffness (V_s), and 2) the joint stiffness produced voluntarily (V_s) and the measured EMG value (x_{emg}) respectively. Using these two functions, it is possible to calculate appropriate strength of EMS for one person from the measured EMG value of another person, as shown in Eq. 6.2 where MSS represents maximum stimulus strength, in order to share accurate joint stiffness between two persons.

$$\begin{cases} V_s = f(x_{stim}) \\ x_{emg} = g(V_s) \end{cases} \tag{6.1}$$

$$x_{stim} = f^{-1}(g^{-1}(x_{emg}))\ [\%MSS] \tag{6.2}$$

Setup

The experiment setup is shown in Fig. 6.15. Two sets of I/O electrodes were placed on the extensor digitorum and flexor digitorum superficialis, and one Ref electrode was placed on the wrist. Participants hold a peg during the measurement. The wrist joint stiffness was calculated by using a force sensor and a goniometer which was attached to a hand cuff and to the participant's wrist joint respectively. MATLAB software developed in previous works [104][105] was used to record and display the measured stiffness in realtime.

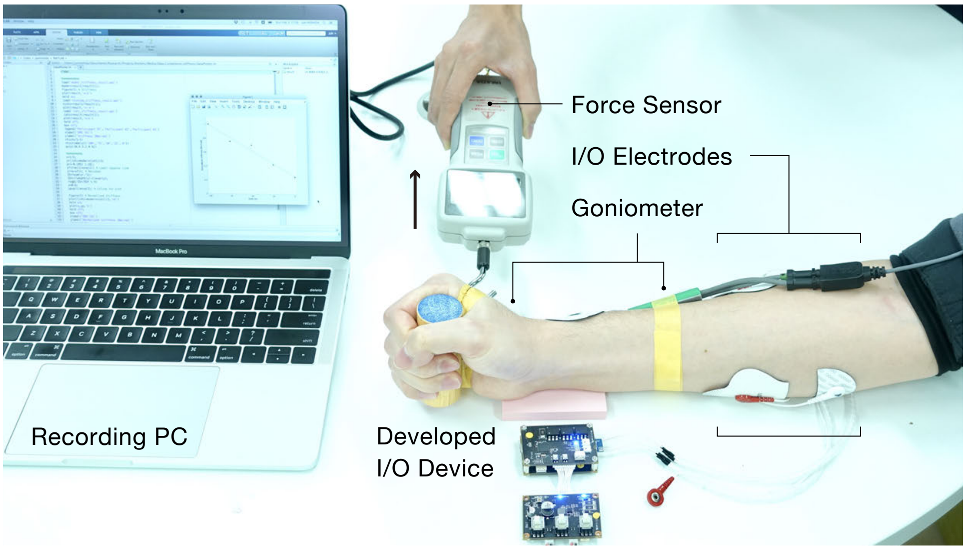


FIGURE 6.15: Experiment Setup: Measurement of the Wrist Joint Stiffness

Task

Before the experiment, maximum stimulus strength (MSS) was recorded for each participant beforehand because each participant has a different skin condition, pain sensitivity, and musculoskeletal construction. The EMG value at the maximum voluntary contraction (MVC) level was also recorded.

In the first condition, the stiffness of the wrist joint was recorded while EMS is applied at the level of 100%MSS, 75%MSS, 50%MSS, 25%MSS, and 0%MSS [us]. In this condition, participants did not exert muscle power. The stiffness value at the level of 100%MSS was recorded as maximum involuntary stiffness (MIS) [Nm/rad].

In the second condition, EMG values at five different levels of the wrist joint stiffness were recorded by the developed I/O device. While the EMG signal was recorded in this condition, participants grabed a peg for 5 seconds at the level of 100%MIS, 80%MIS, 60%MIS, 40%MIS and 20%MIS [Nm/rad].

Participants

Three participants, with no history of neurological or musculoskeletal disorders, from our local organization participated in a total of 75 trials (3 participants ×5 type of stiffness strength ×5 stimulus strengths; 3 seconds for each trial; 3 male; age= 27.7 ±2.5 yo). The trials required approximately 40 minutes per participant.

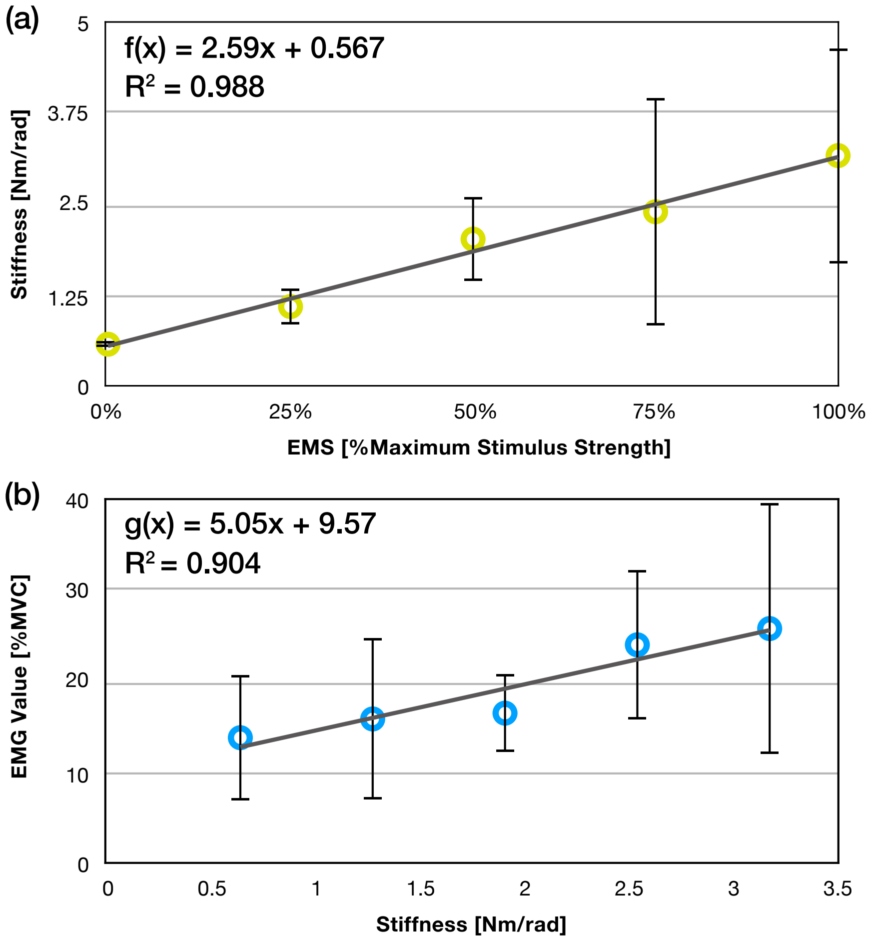


FIGURE 6.16: Experiment Results of Stiffness Measurement (a) the applied EMS and the measured joint stiffness, and (b)the produced joint stiffness and the measured EMG value

Result

Figure 6.16 (a) and (b) shows the results of the measured joint stiffness in conditions 1 and 2 respectively. The results in the first condition demonstrated that the wrist joint stiffness value bear a proportionate relationship to the applied EMS strengths, which can be fitted linearly ($R^2 = 0.988$). As the stimulus strength increase, the standard deviation become larger.

The results in the second condition demonstrated that the EMG value also bear a proportionate relationship to the wrist joint stiffness generated by the the participant's voluntary grabbing action, which can be fitted linearly ($R^2 = 0.904$). Certain standard deviations were observed across all stiffness conditions. From the direct function fitting, the stimulus strength x_{stim} was identified using Eq. 6.2 as follows:

$$x_{stim} = \frac{x_{emg}}{13.08} - 0.95\ [\%MSS] \tag{6.3}$$

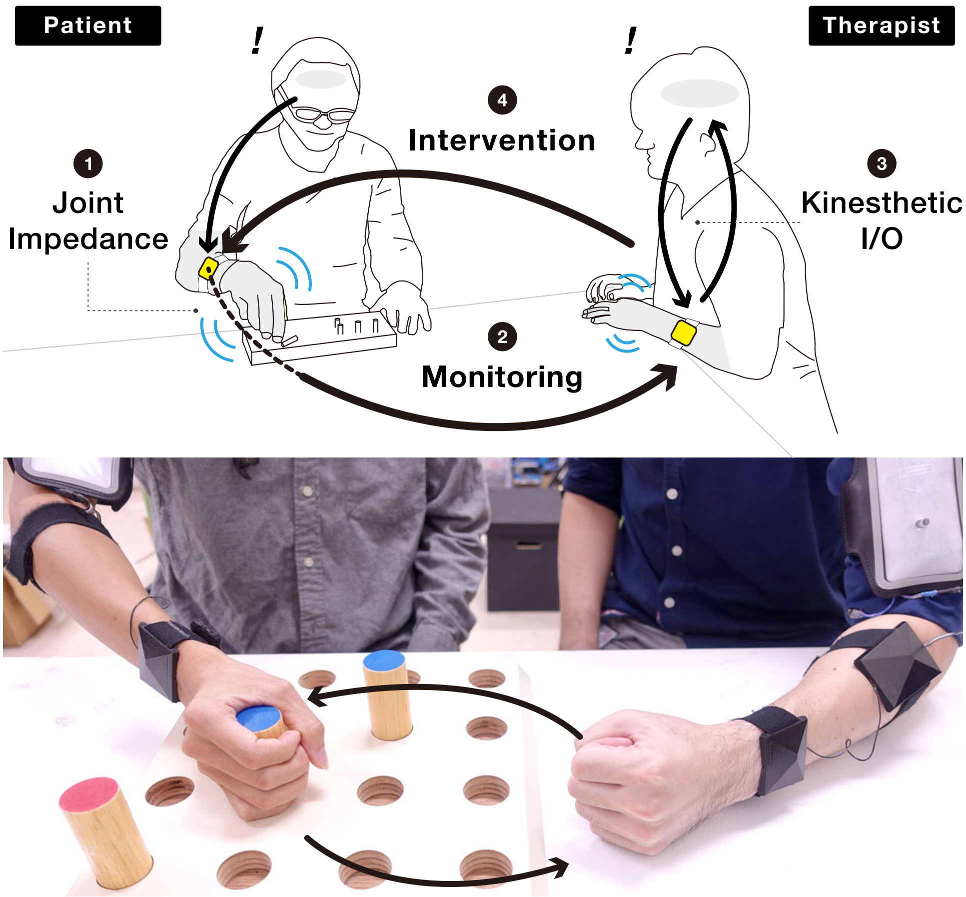


FIGURE 6.17: Conceptual Representation: A pair of wearable devices that allow to monitor and intervene in joint stiffness between a therapist and a patient

6.2.3 Joint Stiffness Perception

Objective

An example is the interaction between physical therapists and patients with neuromuscular disorders, during hand function rehabilitation with a pegboard. It is usually difficult to perceive whether the patient is handling the peg with certain contraction strength and correct timing in a visual contact to evaluate functional recovery of the hand. Thus, it would be valuable if the therapist is able to perceive the patient's wrist joint stiffness generated by grasping actions. Not only the monitoring but also direct intervention in that of the patient would enhance communication regarding muscular conditions between the therapist and the patient during a peg rehabilitation.

In this study, we propose a new interaction style for monitoring and intervening in the patient's joint stiffness by means of biosignal measurement and electrical muscle stimulation (EMS) so that both therapists and patients are able to teach and learn their physical conditions through proprioceptive interactions, as shown in Fig. 6.17. This allows simultaneous physical intervention and monitoring of

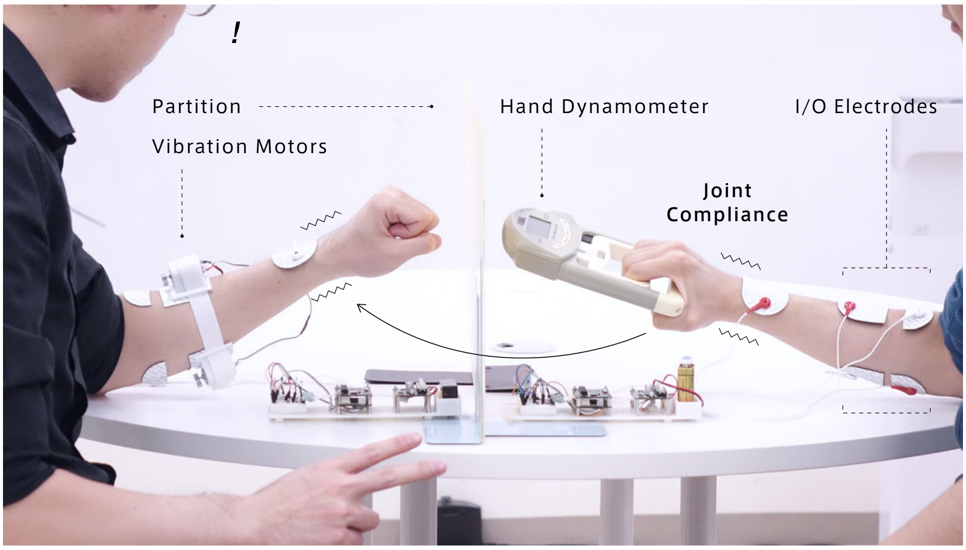


FIGURE 6.18: Experiment Setup: Transferring the wrist stiffness by sharing antagonist muscle activity

the hand activity, enhancing its kinesthetic communication and functional recovery. To achieve this, we developed a pair of wearable devices that are capable of performing simultaneous operation of the electro-myo-graphy (EMG) signals of multiple muscle tissues to estimate the joint stiffness, and the stimulation on multiple muscles to control the wrist joint stiffness.

There have been attempts to use EMS to modulate joint stiffness for suppressing tremors associated with Parkinson's disease and essential tremors [106][107][108]. Another research proposed an EMG-based controlling system for a robot manipulator with two pairs of pneumatic artificial muscles in which a user can adjust its stiffness using their muscle contractions [109]. Our device is capable of simultaneously applying an EMS, in order to control the joint stiffness, and measuring the EMG. This allows the sharing of physical hand conditions and skills among people. In order to explore the effectiveness and feasibility of the developed I/O system in hand rehabilitation, we conducted a perceptual study of sharing the level of wrist stiffness between two persons [110].

Task

The confederate grips a hand dynamometer with 0%, 25%, 50%, and 75% of his/her maximum voluntary contraction (MVC) strength for 1 s. The measured EMG values are transmitted to the paired device via Bluetooth and, consequently, stimulate the participant's antagonist muscles of the forearm. Subsequently, the participant estimates the level of the confederate's wrist stiffness and reports it using a 4-point Likert scale.

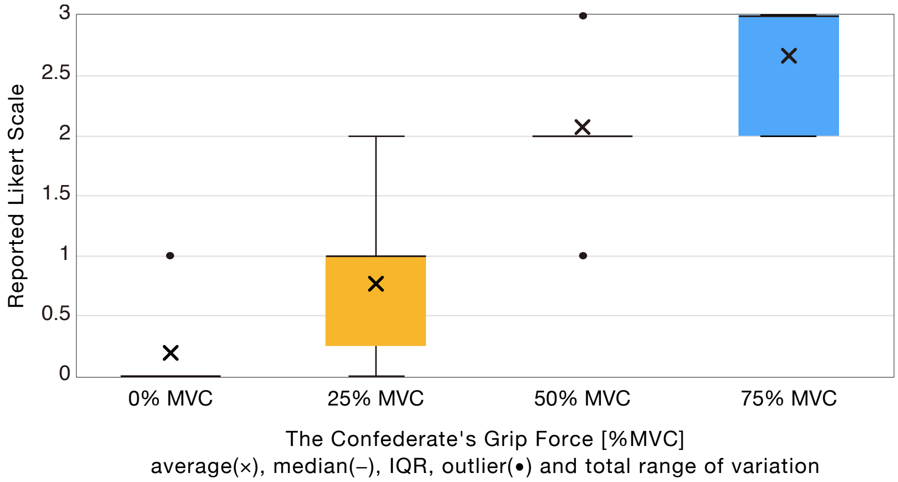


FIGURE 6.19: Result of sharing the wrist stiffness

Setup

Figure 6.18 shows the experiment setup. Two sets of I/O electrodes are placed on the extensor digitorum and flexor digitorum superficialis, and one Ref electrode is placed on the wrist. Vibration motors are placed on each electrode in order to mask the tactile sensation on the skin generated by the stimulus, allowing the participant to estimate the strength only from the kinesthetic feedback. The participants tried each stimulus level two times before the experiment.

Participants

Eight healthy participants (24.3±1.71yo) from our local organization joined in a total of 160 trials (8 participants × 4 levels of %MVC × 5 repetitions). The trials required approximately 15 min per participant.

Result

Figure 6.19 shows a boxplot of the confederate's grip force and the reported Likert points. It is shown that the participants recognized the level of the confederate's wrist stiffness at four levels.

6.2.4 Rhythmic Activity Synchronization

We also conducted a series of tests to verify that the interpersonal communication via the kinesthetic channel could support the synchronization of two persons' rhythmic muscle contraction timing. The results were used to assess whether the bioSync device could be employed in practical scenarios, such as clinical gait rehabilitation and sports training, in which the synchronization of timing plays an important role.

Task

Figure 6.20 illustrates the experimental setup. Each participant and the experimenter participated in a follower-experimenter and experimenter-follower session twice. The experimenter was a colleague (25 years old), who participated in the entire experiment (24 trials).

Initially, both the experimenter and the participant performed rhythmic wrist actions according to their own frequencies. After 3-4 seconds, the bioSync devices were activated, and then kinesthetic cues were exchanged between these two persons. Once the participant recognized that the rhythmic action was synchronized with the master side, time measurement was commenced using a stopwatch to record the sync time reported by the participant.

Setup

A partition was placed between the demonstrator and the participant so that the participant and the demonstrator could not recognize the partner's contraction timings. The wrist angles and periods of the rhythmic action were calculated from the measured marker positions (OptiTrack Inc., V100:R2). The thresholds were adjusted before the experiments were started. In this experiment, to simplify the exchanging signals, we configured weighting factors a as $a_i = 0$, $a_j = 1$. Hence, the wearer i's stimulus function p_i was a stepping function using threshold θ as shown in Eq.(6.4).

$$D(t) = \begin{cases} 600us & (e_j(t) > \theta) \\ 0us & (otherwise) \end{cases} \tag{6.4}$$

Participants

Six healthy participants from our local organization participated in a total of 24 trials (6 participants × 2 follower-experimenter sessions × 2 experimenter-follower sessions). The trials required approximately 35 minutes per participant.

Results

Figure 6.21 presents the measured sync time and sync time reported by the participant (the participants followed the experimenter's timing). The average measured sync time was 8.1s (SD=3.91s), and the average reported sync time was 13.8s (SD=3.94s). In all cases, the measured sync time was shorter than the reported sync time. Note that Subject 1 required more time to synchronize with the experimenter than the other subjects did. After the experiment, Subject 1 stated that the contractions reproduced by the stimulus were strong

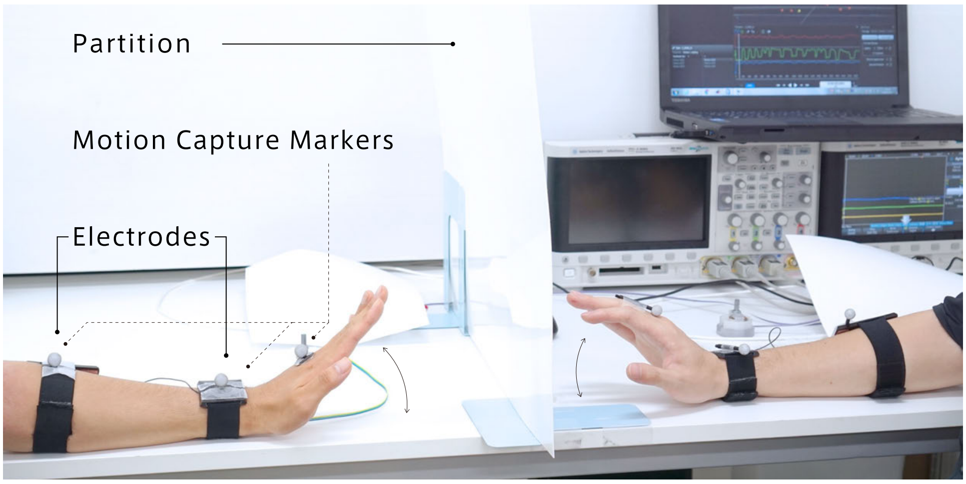


FIGURE 6.20: Experiment Setup: Rhythmic Activity Synchronization

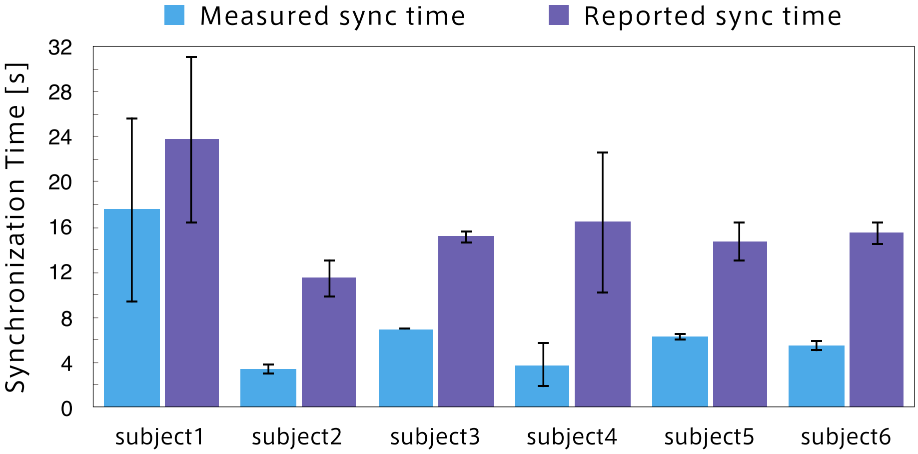


FIGURE 6.21: Experiment Result: Rhythmic Activity Synchronization

and that his voluntary contractions were interrupted excessively, resulting in his having difficulty in controlling his voluntary movements. Figure 6.22 shows the time-series graph of the rhythmic action period for Subject 2 and the experimenter. After the sync started, the follower immediately changed his rhythm to that of the experimenter and tried to maintain the same period.

6.2.5 Faster Kinesthetic Reaction

Objective

In this experiment, we investigated how the developed pair of wearable kinesthetic devices is able to speed up one's kinesthetic reaction during a particular task which involve two persons. Instantaneously generating own body movements in response to the movement of

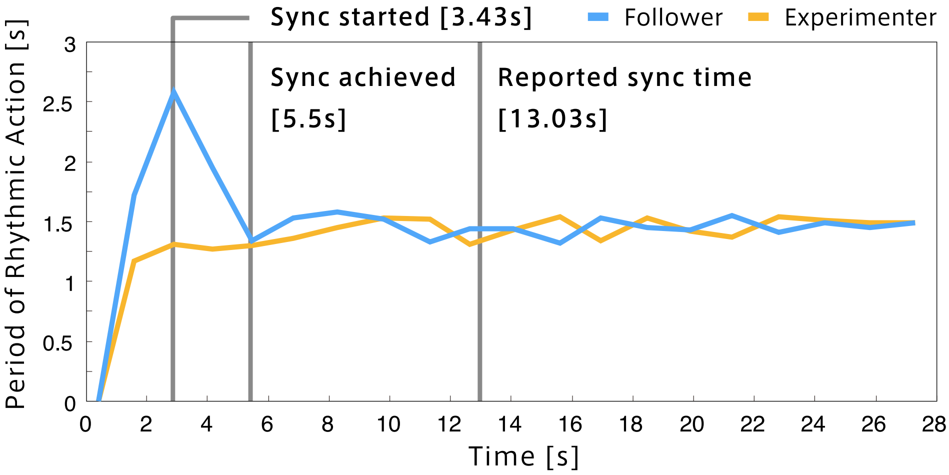


FIGURE 6.22: Experiment Result: Rhythmic Activity Synchronization. Subject 2 successfully followed the experimenter's rhythm.

others, such as establishing defensive posture in sports and learning kick-out timing from therapists in gait rehabilitation, is an essential aspect of interpersonal exercises and contact sports. However, ignition of movement based on a visual stimulus requires approximately 250 milliseconds (ms), which is too late for certain interpersonal physical interactions that require immediate reaction. Thus, we introduce "Wired Muscle," a system that connects muscle activities between two persons using electromyogram (EMG) measurement and electrical muscle stimulation (EMS) to generate responsive movement that are faster than those generated by the visual information-based process [111]. The developed system detects the muscle activity of a person by the EMG and triggers the EMS to drive the muscle of the other person to induce corresponding counter movements.

Figure 6.23 shows the representative image of the task, which is a pen drop test where one person release a bar, then another try to grab the dropping bar. Usually the grabber can not perform a quick action to catch the bar because the reaction time of visual response takes 250 ms which is too slow to grab the pen. Using the device, a kinesthetic trigger of the releasing person, which is muscle activity of the hand motion, can be transmitted to the grabbing person immediately, generating grabbing motion by means of EMG measurement and EMS (Fig. 6.24).

In this experiment, we observed 1) how WiredMuscle is able to speed up the reaction time of the grabbing person' responsive action by measuring the success rate of the pen drop test with or without using the device, and 2) how the participant felt responsive in initiating the grab motion of the pen with the support of the device intervention. Investigating theses factors in EMG research would reveal a new methodology to preserve sense of agency while intervening

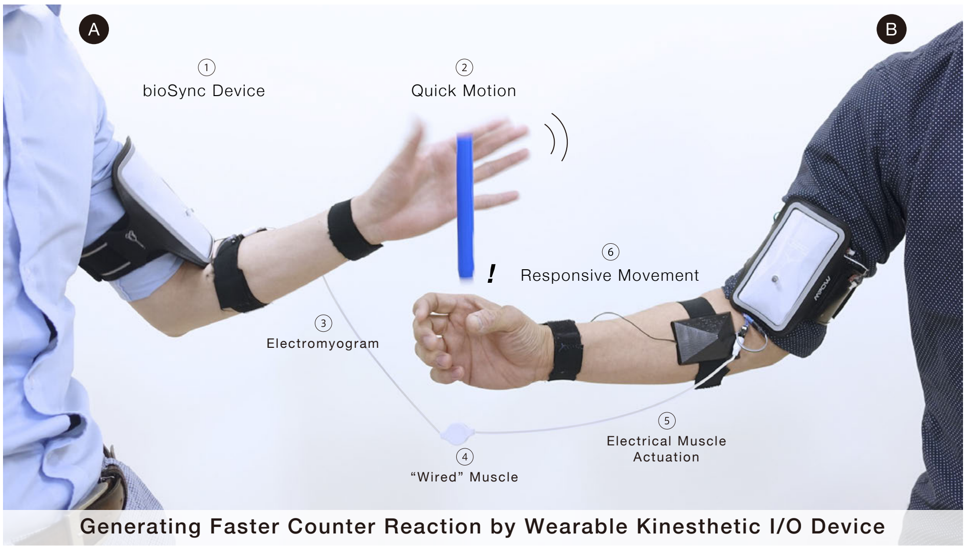


FIGURE 6.23: Wired Muscle: a system for directly connecting muscles of two persons. The EMG detects the muscle activity of a person A, which triggers the EMS to drive the muscle of person B to produce rapid corresponding movements.

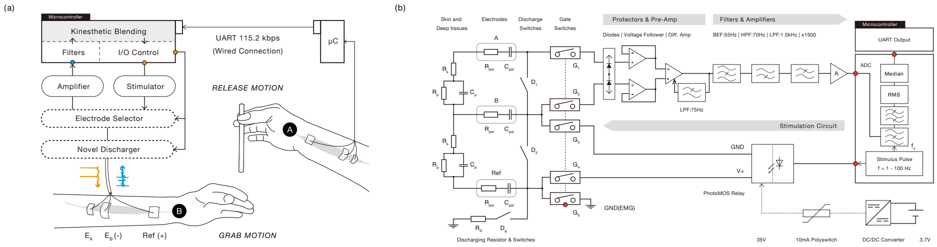


FIGURE 6.24: System diagram of Wired Muscle. The system consists of a pair of wearable kinesthetic I/O devices, which performs EMG measurement and EMS simultaneously.

a user's action, which would contribute to preserving the sense of satisfaction and engagement toward the interactions during rehabilitation or physical training.

Task

The participants wore and tried the device for several times before the experiment in order to adjust the electrode placement so that the device can perform the grabbing motion completely. Then they performed the pen drop test under the two conditions; 1) with and 2) without wiring the muscles. After the test, the participants answered a 7-point likert questionnaire regarding the sense of agency. The conditions were arranged in a random manner.

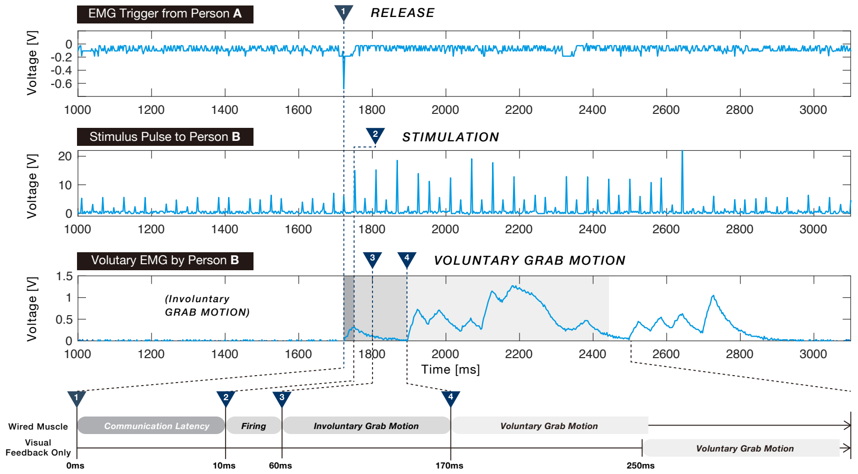


FIGURE 6.25: A detailed sequence of the kinesthetic reaction by Wired Muscle.

Participants

We recruited 271 participants at a conference demonstration (30 ±8.94 years old) joined in a total of 3252 trials (271 participants × 2 conditions (with and without wiring muscles) × 2 repetitions × 3 trials). The trials required approximately 5 min per participant.

Results

Figure 6.25 shows a detailed sequence of the kinesthetic reaction while using the device. The release motion of the person A in Fig. 6.24 was detected by EMG measurement (Fig. 6.25(1)). The device on the person B received the trigger 10 ms later, which is communication latency, via a wired serial communication (UART), and then start EMS. After 50 ms, involuntary grab motion has performed for 110 ms. After this, the person B started voluntary grabbing motion which was observed from the measured EMG signal. When compared with the condition without the device, the grabbing motion was initiated 190 ms earlier.

Figure 6.25 represents the success rate of the pen grab test. While their muscles are not wired, the success rate was around 15 to 25 %, whereas the rate was raised to around 80 % while wiring the muscles. The success ratio was slightly improved in the second trial in each condition.

Figure 6.25 represents the reported sense of agency by the participants after the trials. The average was 3.30 (SD=1.86). 105 participants chose 3.0 or higher (38.6%). Some participants stated that “Oh, I could grab this!" or “I did it!"

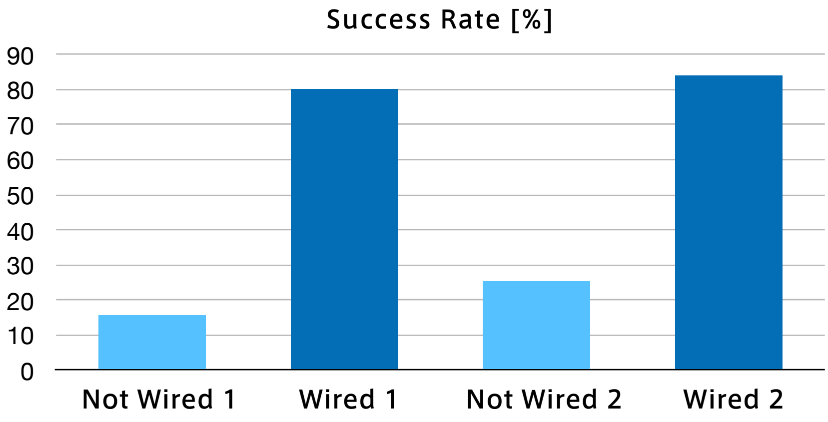


FIGURE 6.26: Success Rate of the Pen Grab Test

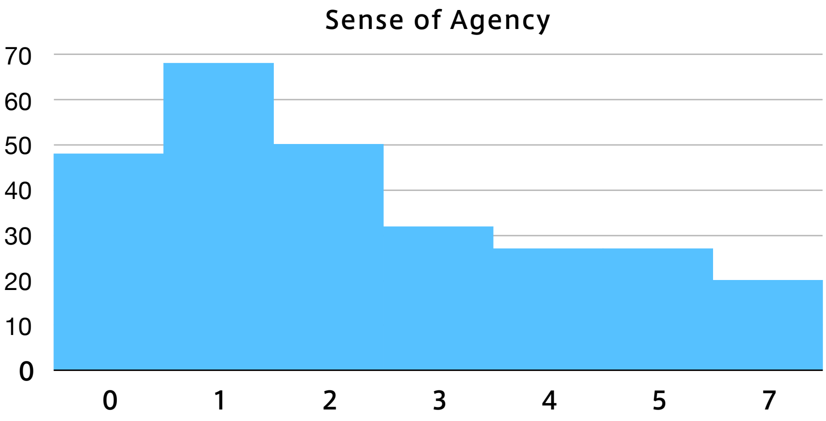


FIGURE 6.27: Reported Sense of Agency

6.2.6 Embodied Impairment Experience

Using the bioSync devices, it is possible to not only blend users' kinesthetic experiences but also simulate Parkinson's motor impairments by providing stimulus in the frequency range of 8Hz to 15Hz. We employed this capability to gain insight into the bodily movements of Parkinson's sufferers during the activities in daily life (ADL). As described in the applications section, simulating and/or transferring physiological tremors from patients to healthy people, including designers and caregivers, could assist in product design procedures and their understanding of the disease. In this pilot study, we simulated Parkinson's tremors in participants to investigate the similarity of the simulated tremors with actual tremors and the feasibility of using the bioSync device to observe users' tremor behaviors.

Task

Figure 6.28(a) illustrates the experimental setup for the tremor evaluation. One participant wore a bioSync while holding a spoon. A three-axis accelerometer was placed on the tip of the index finger, as shown in Fig. 6.28(b). In the observation experiment, demo visitors tried to scoop up gummy candies by using various types of spoons, as shown in Fig. 7.3(b), while undergoing the reproduced action of physiological hand tremors. We then asked the visitors to choose the spoon type best suited to the task, and collected feedback comment about the experience.

Setup

The spoon types used in the experiment are described next. The (b-1) sample is a spoon that is available in the market. The dimensions are 33mm × 50mm × 8mm (depth). The (b-2) spoon has an additional 5 mm of depth. The (b-3) spoon has a bend added to the b-1 form to make it easier to keep food inside. The (b-4) spoon has a curved handle added to the b-3 spoon to make it easier to pick up.

Participants

One healthy participant (25 years old) participated in the preliminary evaluation. The other participants consisted of more than 100 visitors whose age ranged from 20 to 60 years.

Results

Figure 6.28(b) illustrates the measured fingertip accelerations. Frequencies in the range of 3Hz to 20 Hz were measured. This frequency range is almost the same as that of actual Parkinson's tremors, as described in related study [57].

All of the visitors agreed that the b-4 spoon shown in Fig. 7.3, which had a handle and a bend, was the most useful spoon and the easiest to maintain in a stable grasp. Most of the visitors reported that it was somewhat difficult to hold the candies inside the b-1 spoon because the depth was not sufficient to keep the candies inside with shaking hands. In addition, some participants dropped the b-1 spoon as shown in Fig. 7.3(a)-1,2. Some visitors reported that the b-2 spoon was easy to use to hold candies while subjected to tremors because of its greater depth; however, they found it slightly difficult to place all of the scooped candies into their mouths because of the depth. The b-3 spoon was described by some as being a usable spoon; however, the visitors commented on not only the ease of using the spoon to scoop up candies but also the ease of picking up the spoon itself. The b-4 spoon was identified as the most usable spoon and the easiest spoon to pick up by hand when experiencing tremors (Fig. 7.3(a)-3). We also obtained several feedback comments from the visitors that indicate their surprise at the new experiences and difficulties in manipulating their fingers and objects such as: "I never imagined tremors would be like this!", "Now I understand what the disease is like and the difficulties patients face in daily life", "It's very

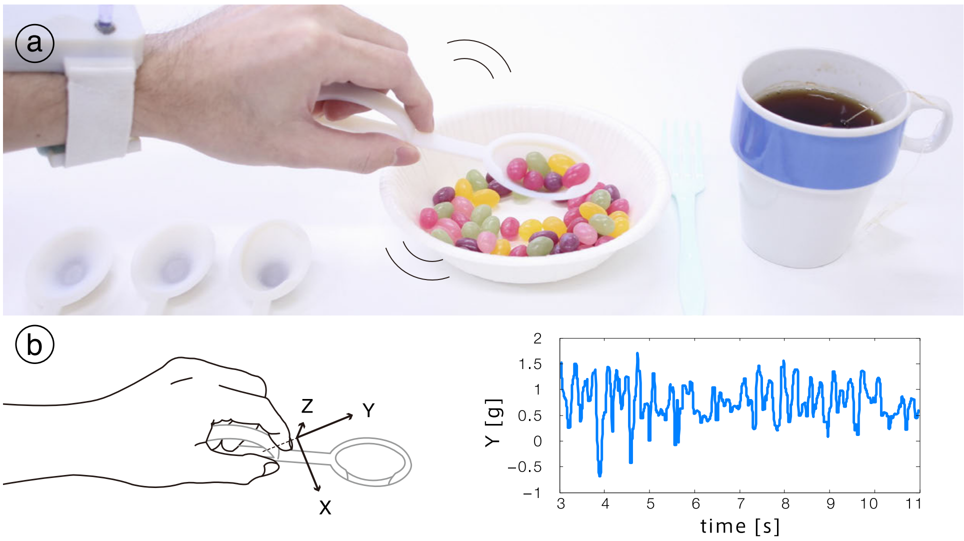


FIGURE 6.28: Experiment Setup and Result: Impairment Experience

hard to control my smartphone using my fingers", "It's scary! stop!", "Now I feel relieved..." (after the device was turned off). We also acquired comments after we demonstrated the synchronization interaction "I feel very weird because it is like someone is inside my arm and manipulating muscles..".

Chapter 7

Discussion

7.1 Smaller-person Experience

7.1.1 Wearer's Perception

Eye level affected the personal space

From the result, the eye level of the participant affected the perception of interpersonal distance because there is a significant difference between (3)HC_STA and (5)WC_STA conditions. The difference in eye level would create an oppressive feeling toward the approaching experimenter. In addition, the large neck angle in pitch axis also affected the perception of social relationship with the experimenter, because the nursing teachers usually interact with 5-years-old children. One participant reported that he/she has a frustrating feeling rather than an oppressive or scary feeling, because the participant could not move the perspective higher although their legs were fully extended. It is also presumed that their internal body representation also contributed to the change of personal space.

WC STA and HC SIT condition

When the participant observed an approaching experimenter from a lower POV while standing, they reported the largest amount of personal space as compared with the other conditions, although their eye level was equal when the participant was sitting on a chair. This result cannot be explained by only the lower viewpoint, but suggests that the participant had a strong feeling of being a child, owing to the change in their body representation through a combination of visual feedback by the lower perspective and somatosensory feedback from the standing posture. It is presumed that such visual and somatosensory feedback allowed an enhanced sense of de-magnified height because the participants could recognize that the presented lower perspective was at the highest level of their body because their legs were fully extended. It may be that the distance reported when the participant was sitting on the chair with the device ((4)HC_SIT) was smaller than under the (5)WC_STA condition because the participants knew that they could move their eye level up to a higher position by extending their legs. In this respect, it was also inferred

FIGURE 7.1: Horizontal error was also observed in 8 participants, which would suggest their perceived arm length was shortened

that such availability in changing their eye level is associated with a feeling of oppression in this experiment.

Comparison in standing and sitting conditions

When the participants were sitting on the chair during the experiment, they reported a slightly larger distance in personal space than when they were standing. This could be caused by an over-estimation of the experimenter's height through the visual stimuli because the participants also had to look up. In addition to this, several actions, such as standing up, are required to react toward the approaching experimenter while sitting on a chair. Such expectation of future interaction also contributed to enlarging personal space.

EY and HC conditions

The results indicated that the reported distance became larger when seeing the experimenter through the HMD and the camera (EY_STA and HC_STA; EY_SIT and HC_SIT), compared with EY conditions. This would be caused by the settings when converting the spherical image into the rectified image. Since the angle of view of the fish lens is 180 degree, it is necessary to increase the magnification coefficient of the cropped image in order to secure the range for the wearer's head orientation. Using a wider fisheye lens is one of solutions.

7.1.2 Wearer's Action

The results showed that the physical relationship between the wearer and the surroundings have been changed by the smaller person experience, by observing the hand adjustment actions.

Perceived arm length and distance

As shown in Fig. 7.1, it was observed that when the participants tried to shake hands with the experimenter, they extended their arm

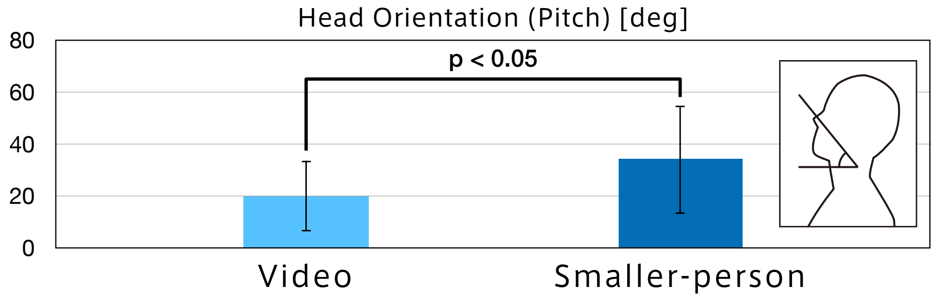


FIGURE 7.2: 13 participants looked up higher under (2) smaller person condition than under (1) video condition

longer and missed the experimenter's hand. This could have occurred because the participants thought their arm length had become shorter, as had their height, resulting in an increase in the perceived distance between hands. A similar phenomenon was also reported in which the arm length changed the perceived distance in a virtual environment [62]. It is noted that seeing an environment through HMD could affect the perception of distance at the same time.

Familiar objects as a reference

Several participants stated that they realized the change in eye level only after they saw the experimenter facing them, although they had visited the experiment room several times before and saw the desks positioned 2 m away from the standing location during the experiment. From such comments, it is assumed that the participants used more familiar objects as a reference to recognize the physical relationship between their body and space. It should be noted that the participants knew the height of the experimenter and had sufficient experience with each other through conversations because they are from the same local organization. The recorded head orientations also showed that the participants looked up higher under (2) smaller person condition than under (1) video condition (a paired T test was performed as $p < 0.05$, as shown in Fig. 7.2). From the result and observations, many participants looked at the experimenter's face before the handshake, suggesting that the level of face could be used as a reference. Such existing knowledge based on motor and social experience could help the wearers recognize their space and physical relationship.

Hand Adjustment in the Air

We found that the adjustment action has a unique and practical aspect in that the timing for observing its effect can be initiated by the experimenter, and its strength can be exposed by the participant's voluntary action, which is measurable in a visual and quantitative manner when using the tracking systems. This measurement method can also be used to evaluate a different type of change in body representation, such as an increasing height.

7.1.3 Wearer's Interaction

From the observation at the demo and experiment space, most of the participants found it easy to become familiar with the visual translator. The latency of the developed visual translator (117.6ms) is smaller than the latency of 125ms in which the wearer′s feeling of agency decreased [28][112].

Some wearers behaved like a child and the surrounding people also behaved like a taller or authoritative person. It appears that proposed experience allowed not only the wearer but also the surrounding people to perceive as the wearer become a smaller person. These new social contextual cues including an oppressive conversation, protective posture, a haughty look, and longer interpersonal distance could contribute to shaping the body representation repeatedly.

7.2 Blending Kinesthetic Experiences

7.2.1 System Evaluation, Latency, and Performance

From the performance experiment, we observed that the measured contractions decreased when the applied pulse increased. This linear trend can be attributed to the electrical characteristics of the I/O circuit. The changes could be fitted linearly, hence it is possible to compensate by a linear function. In the future, we plan to conduct another perceptual experiment to investigate the reduction in a bioSync device wearer's voluntary contractions with reproduced contractions, and assess the effects of both the electrical and perceptual characteristics.

7.2.2 Subjective Perceptual Experiment

In the perceptual experiment, the participants could recognize reproduced muscle contractions and rate them on a five-point scale accurately, while they were contracting their own muscles. A similar result was obtained in the previous work [88], where the participants could recognize their wrist angle accurately using EMS based on their kinesthetic feedback. Hence, we confirm that the kinesthetic feedback mechanism in our setup also works correctly. We also observe that the standard deviation increased when the pulse width increased. This might be the effect of the wearer's voluntary contractions on the perception of the reproduced contractions.

Another perceptual experiment would be required to study this phenomenon in detail and to assess the relevance of the signal-dependency noise theory [113]. According to this, neural control signals are corrupted by noise that increases in variance as with the size of the motor control signal increases.

7.2.3 Joint Stiffness Measurement

In the first condition (EMS to stiffness), large standard deviation was observed when the stimulus become stronger. This could be caused by the personal variation in the skin condition, electrode placement, and the musculoskeletal construction, creating different muscle contraction patterns. A machine learning system with an array of EMS electrodes has been employed to adapt personal difference [89][114]. Such techniques also could be applied to this scenario in the same manner.

In the second condition (stiffness to EMG), certain standard deviations were observed. In addition to the personal difference as mentioned before, during this condition, the participant had to keep their wrist stiffness for 5 seconds at the level of five different target values by looking at the stiffness value displayed on a screen. This procedure could be a difficult task for the participants, thereby increasing standard deviation values.

Using the mapping function (Eq. 6.3), the maximum contraction level which can be reproduced within a range of applicable EMS strength can be calculated as 25.5% where x_{stim} is 100% (1.0). This indicates that, in the current system, muscle contractions on one person within a range from 0%MVC to 25.5%MVC by one person can be transmitted and reproduced on another person. Further improvements include an enhancement of this range by optimizing electrode position, reducing the tickling sensation by the stimulus, and adapting the skin condition for creating stronger muscle contraction by EMS.

7.2.4 Joint Stiffness Perception

From the user study, EMG values on one person to EMS on another can be mapped by a linear function in the perceptual layer. It is presumed that the participants' perceptual function also followed the physical phenomenon which was observed in the previous study.

In this study, there was no instruction regarding voluntary actions by the participant. Combining both voluntary and involuntary muscle contractions could affect the perception of one's wrist joint activity, as a previous work [59] showed that standard deviation of the perceived EMS strength became larger when the participant simultaneously perform stronger voluntary muscle contraction on one side of the forearm. Further investigation on the blending of voluntary and involuntary joint stiffness control will be conducted to achieve the simultaneous operation of the monitoring and intervention in a peg rehabilitation.

Another factor which should be investigated is the relationship between the EMS strength and the sense of agency so that the patients can feel that they initiated their hand actions by themselves while receiving EMS, while the previous work [115] revealed that a user's finger action can be preempted by EMS 80 ms earlier without compromising the sense of agency.

7.2.5 Rhythmic Activity Synchronization

In the user study of the synchronization of rhythmic action, subject 1 reported that excessive involuntary contractions affected the performance of the synchronization. This could have been caused by the electrode positioning and personal muscular characteristics. This indicates that a prior adjustment is required for each subject to normalize the perceptual and kinesthetic experience among users.

We discuss the positional optimization issue in the limitations section. In future work, we plan to investigate the relationship between kinesthetic communication latency and synchronization performance. Another aspect we would like to address is the learning effect, which we could not verify in the current experiment since the number of trials for each participant was small. However, we found that synchronization time is always shorter when the experimenter who had longer prior training and participated in the entire experiment, follows the participant's rhythmic action. Some participants also stated that, at the beginning of the experiment, they did not have enough confidence to recognize and report the time when sync was accomplished.

These results suggest that several trials are required to understand new interpersonal kinesthetic communication. Another preliminary experiment showed that the rhythmic actions of two persons could be synchronized even if they are not assigned as an experimenter or a follower, and are treated equally.

7.2.6 Faster Kinesthetic Reaction

In this experiment, 38.6 % of the participants chose 3.0 or higher score in the likert questionnaire regarding the sense of agency. It is expected that these participants recognized that the entire action of the pen grab was initiated or achieved by themselves in the end although the action was performed by the intervention from the device. This result could support a hypothesis that the participants established by themselves the reasonable consensus between the reality in which they tried to do and the real achieved by the EMS intervention. In this regard, their voluntary to grab the pen have modified perceived reality, allowing to augment their sense of egocentricity beyond the time and space.

Such phenomena is often called post-diction [116] in psychology field and it is under investigation. In the scenario, the purpose of action and the result of success or failure in the task is clear to perceive, fostering the post-diction that increases his/her sense of agency. As mentioned in a neuroscience literature [117], such explicit rule could create a strong context which would play an important role in enhancing the judgement of agency and the post-diction recognition. Further investigations and discussions regarding intervention timings and the sense of agency have been investigated by a collaboration research with Dr. Shunichi Kasahara and Dr. Pedro Lopes [115].

7.2.7 Embodied Impairment Experience

In the pilot study on the simulated embodied Parkinson's experience, we received considerable feedback comments that indicated

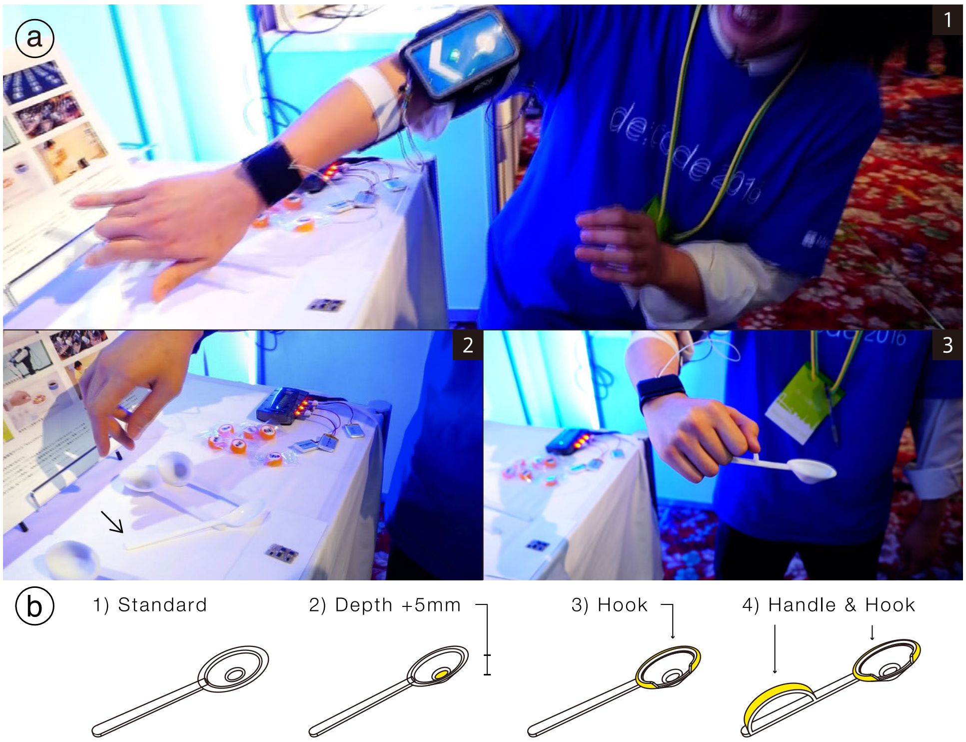


FIGURE 7.3: Demonstration at Exhibition: Impairment Experience

the existence of kinesthetic memory after the experiment. This suggests that reproduced kinesthetic impairment experience may be more effective in learning the neurological characteristics of the impairment than learning through some other modality. We would like to verify the practicality of this approach in a future study.

Some visitors also reported experiencing the existence of a remote user's presence through the kinesthetic channel, while synchronizing muscle activity between two persons. Thus, interpersonal kinesthetic communication is capable of enhancing the feeling of togetherness and reality of existence, in a manner similar to that of interpersonal haptic communication [76, 78, 81].

Chapter 8

Future Works

8.1 Smaller-person Experience

8.1.1 Another Form of Changing Body Representation

Because the change of eye level created significant differences in a wearer's perception, action, and interaction, changing the body representation larger or higher would be another form factor to investigate. The measurement of personal space and hand adjustment action could be used for evaluating the changes in social and physical relationship in this scenario as well. An appropriate range for inducing the sense of being a smaller or taller could be investigated to reveal the relationship between the eye level and the strength of ownership toward modified body representation. As we tested several posture conditions in study 1, further studies include more investigation into how the somatosensory feedback provided by various postures and leg conditions affects the visual perception, and likewise research suggesting that the perceived size and distance are affected by an inversion of the body orientation, and not by the retinal image orientation [118].

8.1.2 Peripheral Visual Field

In the developed visual translator, the wearer's head orientation and the line of sight in a spherical image are synchronized. However, the rotational centers of the human eyes and the developed visual translator are not matched. During the experiments, the participants did not report an unusual feeling when they rotated their head to the maximum angle. Previous work in the field of telepresence uses an omnidirectional multi-stereo camera system to match the rotational center [52]. In addition, recent feature tracking techniques enable reconstructing three-dimensional views from monoscopic 360°videos, and to observe through rotational and translational motions of the viewpoint [119]. These techniques can be applied to the system to provide a more accurate peripheral visual field on the HMD.

8.1.3 Central Visual Field

Approximately two or three in ten participants stated that they felt dizzy while or after using the device for 3-5 minutes. From their comments, this could be caused by not only the rendering latency but also fluctuations in the camera module at their waist induced by walking. Using a small camera gimbal for stabilizing the camera module, and using a wireless HMD with a high-performance desktop computer for reducing the latency could be possible solutions.

FIGURE 8.1: Possible Scenarios: (a) Educational tool for medical staff and nursing teachers (b) Design tool for spatial and product designers

8.1.4 Possible Scenarios

Educational Tool

Figure 8.1 (a) represents a pilot study in a hospital and a nursing school. Because the developed device is capable of providing subjective and emotional experiences of being a child, it can be used as an education tool for adults, who often stay with children. In this pilot study, medical doctors are asked to wear the device and to walk around in a children's ward in a hospital, and they noticed that it is difficult to talk with receptionists face to face since monitors placed on a desk prevented the doctors to see a receptionist's face. They also stated that we should keep the same level with their eye, and secure certain distance when we try to talk to them for avoiding an oppressive impression. From this observation, it is suggested that the proposed experience can encourage adults to change their attitude and awareness towards children. Our future plans include installing the developed devices into new employee training programs in amusement park, public transportation, and hotel companies. In addition, we plan to combine the developed system with other simulator such as augmented reality based autism simulator [67]. This work is solely based on the visual perception without changing the body representation. The experience of the embodied interaction of a autism child in an existing environment would provide new perspectives to caregivers such as parents.

Design Tool

As another practical scenario, the device could also be used as an assistive design tool (Fig. 8.1 (b)). During the pilot study in the hospital, some medical staff noted that a bracing strut in a floor looked much bigger and it gave them a strong oppressive feeling. Such new discoveries in affective experience would improve space design in a manner that is visually friendly for children. Creating a hazardous map for children in existing environments, such as schools and hospitals, is also an important activity when considering an evacuation route. We also observed during the exhibition that some of the demonstration visitors tried to hold a plastic bottle with a tiny hand, and noticed that they needed to use both their hands. Then, the visitors proposed some attachments to facilitate grasping the bottle with one tiny hand. Another pilot study in a grocery market showed that the reproduction of limited ROM of the upper limb allows sales staffs to check whether products are placed within a range of a child's hand. From these observations, the developed device can be used for design assessment based on more emotional and empathic experiences, with conventional quantitative methodologies.

Amusement Tool

Since the smaller person experience changes interactions of the wearer and the surrounding people, the device can be used as an amusement tool to enhance the play among parents and their children. Parents can explore a maze or treasure hunting game from the same perspective as their children to find the exit, as an example. A lower perspective can give us new inspiration, allowing us to find an object under a structure, and enabling parents and their children to cooperate and play together.

8.2 Blending Kinesthetic Experience

8.2.1 Electrode Placement

In the bioSync device proposed in this study, one set of electrodes is used for both stimulation and measurement. This limits the bandwidth of the kinesthetic information exchanged. By placing more electrodes encircling the forearm, it would be possible to transmit expressive cues through kinesthetic channels in a manner similar to that of haptic manipulators [79]. Placing more electrodes on muscles would require positional optimization. This is a common issue in EMS research field because the perceived strength and involuntary contraction level depend on the stimulated muscle. In the proposed system, the electrode position is established empirically based on several trials. Hence, the positional optimization of the common electrodes is required in the developed system as well. There have been several studies on placement optimization for EMG or EMS using array electrodes and machine learning systems [89, 114]. These techniques can be applied to the bioSync system. The discharging effect in a multi-electrode environment should be investigated as well.

8.2.2 Blending of Contraction Strength

In this study, we focused mainly on the implementation of bidirectional communication and the temporal characteristics of blended kinesthetic interaction rather than on contraction strength. Although we have reported the results of a perceptual study involving the blended muscle activity and contraction strength of two users, the further qualitative evaluation of the proposed interaction is required. The difference between muscle activity and the perception of it will also be investigated in a future study.

8.2.3 Possible Scenarios

Figure 8.2 illustrates three potential scenarios proposed as promising applications of the bioSync system.

(a) Shared Embodied Experience

It is very difficult for people to understand the characteristics of a patient's experience of physical impairment. For instance, product and architectural designers should fully understand how the symptoms affect physical interactions in a daily life, in order to be able to apply this knowledge in improving tools and residential buildings. Checklists and guidelines such as housing enabler models [5] or field evaluations involving patients have typically been used as tools in design. In addition to these, we propose a virtualized Parkinson's embodiment using the bioSync devices so that people who do not have Parkinson's, including caregivers, can easily experience and understand the tremors and challenges that Parkinson's sufferers face in the daily life (Fig. 8.2(a)). This can provide empirical and embodied knowledge of the impairments, which are usually difficult to explain using words. The amplitude, frequency and target body are variable; as a consequence, designers can perform a number of different experimental trials and evaluate the usability of products and spaces under various conditions. Compared with a conventional tremor desktop-type simulator [57], transforming the wearer's embodiment into that of another would provide more realistic and persuasive experience, likewise transforming visual and haptic sensation [120].

(b) Interactive Rehabilitation and Sports Training

Gait training with a power-assist exoskeletal robot is increasingly becoming popular. The Hybrid Assistive Limb (HAL) developed by Sankai et al. [26], which consists of EMG sensors and lower-limb exoskeletons, was developed for intention-based walking support for paraplegia patients. It is important to learn the timing of each gate phase, such as backward kick-out, during gait training. However, the motors in the exoskeletons are limited in that they can not produce instantaneous actions to the user. bioSync can enable a patient and a therapist to share and learn the timings for such quick exertions, thereby creating the possibility for enhanced monitoring and interactive teaching. In sports training, it is important for coaches to perceive not only players' form and motions but also player's muscle activities. The timing of muscle exertion is important in running and swimming training, for instance, and the flow of muscle exertion is important in pitching and gymnastics motion training, for instance. Interactive kinesthetic feedback between players and coaches would allow players to perceive the correct forms and motions.

(c) Visio-kinesthetic Transmission

To achieve an effective training procedure with immersive and realistic feedback for sports spectating and skill transmission, we propose the use of a visio-kinesthetic experience transmission system using the bioSync device with a HMD system. The user can record and replay not only physical bodily movements but also muscle activities simultaneously. Combining these modalities would help in gaining body ownership and togetherness for a remote user, in the similar manner to the related work [58] that shares visual and tactile sensation to be another.

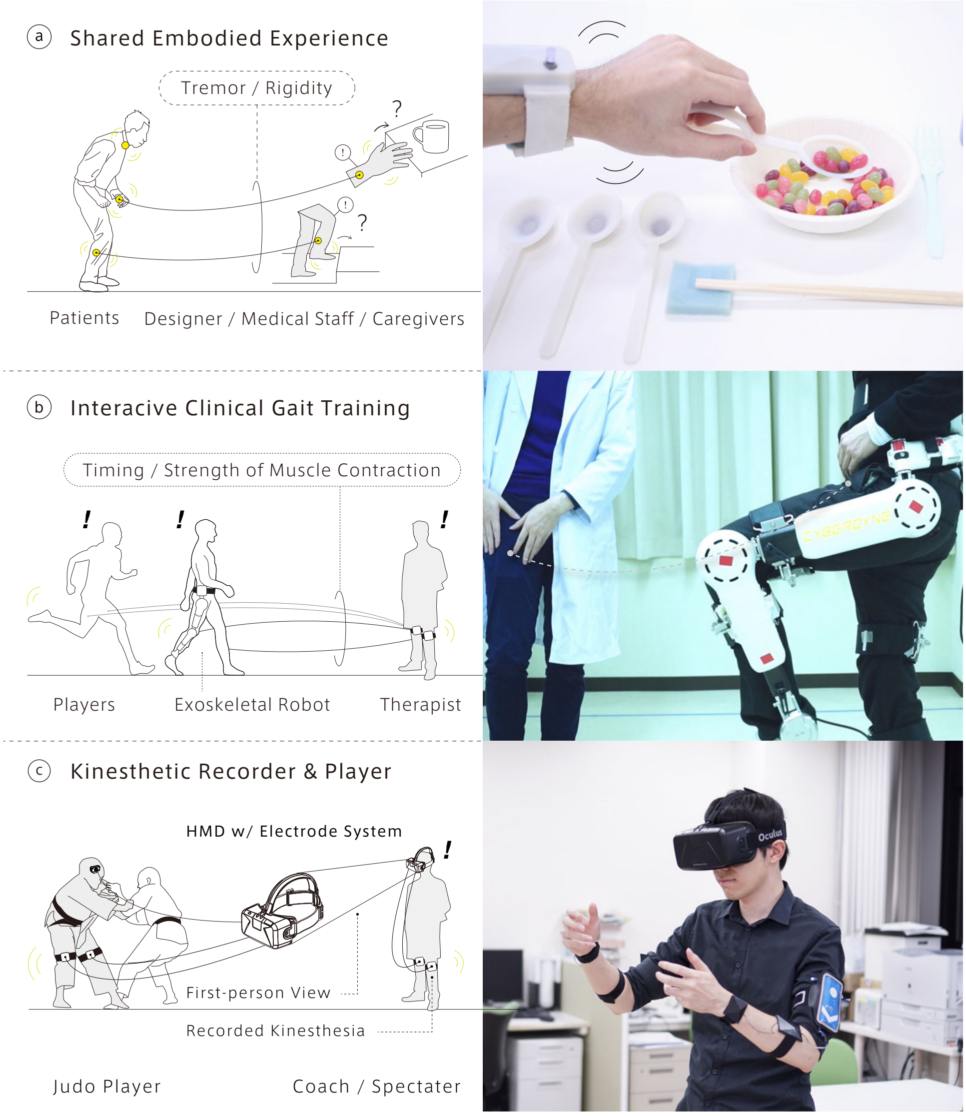


FIGURE 8.2: Possible Scenarios: (a) Neuromuscular symptoms such as those of Parkinson's impairment can be recorded and reproduced for evaluating product and spatial design. (b) Interactive gait training with a power-assist exoskeletal robot accomplished by sharing the timing of the backward kick-out, and sports training by sharing muscle tensions with trainers. (c) Reviewing physical body motions by experiencing recorded kinesthetic feedback with a first-person view through a HMD system.

Chapter 9

Conclusions

9.1 Smaller-person Experience

In this paper, we explored how human perceptions and actions can be changed through the experience of a smaller person in a real world environment. To achieve this, we have developed a wearable visual translator and a pair of passive hand exoskeletons that change the wearer's body representation into that of a small-person. The visual translator allows to shift the wearer's eyesight level down to their waist level by using a HMD and a stereo camera module, while allowing for FOV control through head movements, while the passive hand exoskeletons are capable of miniaturizing grabbing motion and constraining ROM of the upper-limb to reproduce a smaller-person's haptic perspective.

Four user studies were conducted to investigate the wearer's changes in their social and physical relationships, and to observe a feedback experience. From study 1, which was a personal space evaluation, when the participant felt smaller using the developed device, the largest personal distance was observed. This could have been caused by an oppressive feeling toward the approaching experimenter induced by the feeling of being small. In study 2, it was observed that the participants raised their hands higher than usual when trying to shake hands with the experimenter because they perceived their own body representation as being smaller. It was confirmed that the experience of being a smaller person changed the physical relationship of the wearer and the surroundings. In addition to this, using a rehabilitation peg board, it was observed that the developed exoskeleton decreased the user's chronological hand function which would reproduce a smaller-person's physical capability, while preserving the wearer's developmental hand function. In study 3, I observed the wearer's interactions during demonstrations at conferences and exhibitions. It was often observed that the visitors behaved like a child, such as performing a protective pose when surrounded by adults, or talking like a baby. Interestingly, surrounding people such as young students also treated the wearers like a child, and behaved as teachers or parents by acting in an overbearing manner.

These findings, challenges, and design considerations will benefit further studies on the design of user experiences based on changes in body representation while preserving active and embodied interactions in a real-world environment.

9.2 Blending Kinesthetic Experience

In this research, I proposed and modeled a novel style of interpersonal kinesthetic communication, called the blended kinesthetic interaction that allows people to mutually perceive and interrupt each other's muscle activity. To achieve this interaction, I developed paired wearable kinesthetic I/O devices that are equipped with a specially designed electrodes system for simultaneous EMG measurement and stimulation at 100Hz via low-latency wireless communication (approx. 20ms). I also proposed dynamically adjustable frequency stimulation over a wide range of frequencies (1-100Hz), which allows the bioSync device to be adapted to various skin conditions and purposes.

Through the perceptual experiment, it was verified that the bioSync users were able to recognize reproduced muscle contractions and rate them on a five-point scale while they were contracting their own muscles. It was also verified that the kinesthetic interpersonal communication allows people to synchronize the rhythmic action without visual and audio feedback. I also conducted a pilot study on providing a simulated embodied impairment experience. The results suggested that reproducing the neurological action of Parkinson's tremors could enhance the understanding of the disease.

The pilot study regarding faster kinesthetic reaction and the sense of agency not only demonstrated that the human's responsive action can be accelerated by wiring the two persons but also suggested that their stiff voluntary to perform actions with reward at the right timing allows their sense of egocentricity, the subjective feeling of producing a desired consequence or performance initiated by their own voluntary, to be generated.

These findings would provide design ideas for the kinesthetic interaction, and contribute to potential applications such as education, design, and medical activities, that reveals new aspects of human behaviors for embodied and social experiences.

9.3 Shaping Egocentric Experiences

The general conclusion regarding shaping egocentric experiences with wearable cybernic interfaces derived from design, development, and evaluation were described. In contrast to the related works that attempted to append or extend physical body functions, the proposed experience have successfully amplified the participants' knowledge, and particularly embodied the knowledge of one's embodied and social experiences. Hence, I proposed the conceptual representation of shaping a body representation in a real-world environment based on active interactions to reproduce one's embodied and social experiences.

A major attribute of the proposed experiences was that the interaction could be initiated by the participant's voluntary action. The participant must create, interpret, and review narratives of the experience by themselves through reaching, seeing, touching, and speaking, thus increasing their participation level toward the experience.

As another attribute, the interaction styles involved the surrounding people, thereby allowing the participants to increase their awareness of other people. This situation allowed for the surrounding people, apart from the wearer, to perceive as the wearer became a smaller person or a Parkinson's patient. These new social and physical contexts including an oppressive conversation, protective posture, conceited look, longer interpersonal distance, and more supportive behavior contributed to shaping the body representation repeatedly.

9.4 General Conclusion

Based on the research experience of this topic, the 1) definitions of the newly established academic categories of human informatics and empowerment informatics, and 2) contributions to these fields are outlined below.

Definitions

My definition of human informatics is

> Computational understanding of and intervention in a human

Beyond the existing engineering and informatics field, the category of human informatics involves neuroscience and psychology because it involves the investigation of humans. The major attribute of this field is that it is possible to measure, analyze, and intervene in humans with computational methodologies.

It has now become possible to quantify a human's physical and physiological parameters, such as joint angle, head orientation, locomotion phase, heart rate, and biosignals from muscles and a brain, using wearable sensors. These personal big data allowed for the pattern revelation and computational model construction of one's perceptions, actions, and interactions. To understand and interpret these patterns, knowledge from psychology would be exploited. Neuroscience studies are key to understand the fundamental phenomena to explain one's perceptual and behavioral patterns.

Furthermore, interventions in humans have now become possible in a wearable form factor through light emission, sonification, exoskeletons, and EMS. These interventions can be designed and presented to a human based on a computational model. In particular, these technologies require studies on human agency to preserve the sense of egocentricity in his/her interactions; therefore, knowledge in neuroscience will be beneficial.

The simultaneous combination of these measurement and intervention methodologies allows for a new loop of human motor command and sensory feedback to be created. The wearable cybernic robot, named HAL [26, 27, 121] created a new proprioceptive loop using biosignal measurements and an exoskeletal robot. The developed pair of wearable kinesthetic devices have created the proprioceptive loop beyond an individual by wiring muscles [111]. Changing the relationship between the efferent active signal and the afferent signal of consequential sensation of the intended motion changes human perceptions, actions, and even interactions in an environment, apart from bodily sensation, thereby allowing new aspects of humans to be revealed [28, 122]. This technology can enhance a human's well-being and quality of life.

Hence, the definition of empowerment informatics would be

> The enhancement of one's mind, i.e., his/her intention to initiate and perform actions with the support of human informatics technology.

Conventionally, the term empowerment has been used in psychology, sociology, and nursing as "a process of increasing personal, interpersonal, or political power such that individuals can take action to improve their life situations." [123] This topic has been highlighted recently in a technological community; for instance, one of the largest academic conferences on human–computer interaction, ACM SIGCHI, has chosen their conference topic as "Empowering People" in 1990. With the latest human informatics technologies, "computational empowerment" in which information technology can create, complement, or enhance a user's intention to take action, has now become possible. Apart from hacking the human body function, these technologies can also hack the mind to enhance one's subjective agency [18, 124].

Contributions

The contributions to the fields of human informatics and empowerment informatics are outlined below. These contributions arose from the research outcomes based on interaction design, engineering activities, and numerous opportunities for demonstrations.

- Proposed, developed, and evaluated wearable cybernic devices that allow for changing one's bodily sensation and representation based on his/her active interactions by measuring and intervening in human body functionalities
- Proposed and verified design considerations for the interfaces to achieve the proposed shaping egocentric experience without compromising the wearer's intention to reach objects and people, and to initiate and perform interactions
- Proposed and verified a new methodology that allows for the change in one's body representation to be measured using a handshake action quantitatively
- Proposed and verified a new methodology that allows for the change in one's hand function to be measured with a exoskeleton using a peg board that is typically used in a rehabilitation scenario quantitatively
- Proposed and verified a new interaction style for acquiring the embodied knowledge of one's embodied and social experiences, allowing for the empowerment of people who has voluntarily understand, communicate, and cooperate with different people
- Demonstrated that the developed wearable devices designed with human informatics are effective for gaining empathy toward different people and also for enhancing a wearer's inclination toward interacting for learning through demonstrations at museums, exhibitions, and field studies

Bibliography

[1] Matthew R Longo, Friederike Schüür, Marjolein P M Kammers, Manos Tsakiris, and Patrick Haggard. "What is embodiment? A psychometric approach". English. In: *Cognition* 107.3 (June 2008), pp. 978–998. DOI: `10.1016/j.cognition.2007.12.004`. URL: `http://linkinghub.elsevier.com/retrieve/pii/S0010027708000061`.

[2] Björn Hartmann Leila Takayama Scott R Klemmer. "How Bodies Matter: Five Themes for Interaction Design". In: (May 2006), pp. 1–10.

[3] Koichi Furukawa, Ken Ueno, Tomonobu Ozaki, Shihoko Kamisato, Ryuji Kawamoto, Koji Shibuya, Naruhiko Shiratori, Masaki Suwa, Masato Soga, Hirokazu Taki, Tsutomu Fujinami, Satoshi Hori, Yoichi Motomura, and Souhei Morita. "Research Trend of Physical Skill Science –Towards Elucidation of Physical Skill–". Japanese. In: *Transactions of the Japanese Society for Artificial Intelligence* 20.2 (2005), pp. 117–128. DOI: `10.1527/tjsai.20.117`. URL: `http://joi.jlc.jst.go.jp/JST.JSTAGE/tjsai/20.117?from=CrossRef`.

[4] *HQL Database Site*. URL: `http://www.hql.jp/database/children/index.html`.

[5] Susanne Iwarsson. "The Housing Enabler: An Objective Tool for Assessing Accessibility". English. In: *British Journal of Occupational Therapy* 62.11 (Nov. 2016), pp. 491–497. DOI: `10.1177/030802269906201104`. URL: `http://journals.sagepub.com/doi/10.1177/030802269906201104`.

[6] *JISX8341*. URL: `http://www.jisc.go.jp/app/pager?id=143026`.

[7] Google. *Google Cardboard*. URL: `https://vr.google.com/cardboard/`.

[8] Oculus. *Oculus Rift*. Jan. 2019. URL: `https://www.oculus.com`.

[9] GoPro. *Go Pro*. URL: `https://gopro.com`.

[10] RICOH. *THETA*. URL: `https://theta360.com/en/`.

[11] Youtube. *Youtube*. URL: `https://www.youtube.com/`.

[12] Shunichi Kasahara, Mitsuhito Ando, Kiyoshi Suganuma, and Jun Rekimoto. "Parallel Eyes". In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems - CHI '16*. 2016. DOI: `10.1145/2858036.2858495`.

[13] Hiroyuki Iizuka, Daisuke Kondo, Hiroki Kawasaki, Hideyuki Ando, and Taro Maeda. “Coordinated behavior between visually coupled dyads”. In: *the 2nd Augmented Human International Conference*. New York, New York, USA: ACM Press, 2011, pp. 1–4. ISBN: 9781450304269. DOI: `10.1145/1959826.1959849`. URL: `http://portal.acm.org/citation.cfm?doid=1959826.1959849`.

[14] Autodesk. *Autodesk AutoCAD Architecture*. 2019. URL: `https://www.autodesk.com/products/autocad-architecture/overview`.

[15] Emilie Loup-Escande, Jean-Marie Burkhardt, Hervé Christofol, and Simon Richir. “A Decision-making Help Tool in Innovative Product Design”. English. In: *Journal of Decision Systems* 19.1 (Apr. 2012), pp. 9–31. DOI: `10.3166/jds.19.9-31`. URL: `http://www.tandfonline.com/doi/abs/10.3166/jds.19.9-31`.

[16] Lara Maister, Mel Slater, Maria V Sanchez-Vives, and Manos Tsakiris. “Changing bodies changes minds: owning another body affects social cognition”. English. In: *Trends in Cognitive Sciences* 19.1 (Jan. 2015), pp. 6–12. DOI: `10.1016/j.tics.2014.11.001`. URL: `http://dx.doi.org/10.1016/j.tics.2014.11.001`.

[17] Domna Banakou, Raphaela Groten, and Mel Slater. “Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes.” English. In: *Proceedings of the National Academy of Sciences of the United States of America* 110.31 (July 2013), pp. 12846–12851. DOI: `10.1073/pnas.1306779110`. URL: `http://www.pnas.org/content/110/31/12846.full`.

[18] Patrick Gruneberg, Hideki Kadone, and Kenji Suzuki. “Voluntary initiation of movement: multifunctional integration of subjective agency”. In: *Frontiers in Psychology* 6.320 (May 2015), pp. 3–14. DOI: `10.3389/fpsyg.2015.00688`. URL: `http://www.frontiersin.org/Cognition/10.3389/fpsyg.2015.00688/abstract`.

[19] Angelo Maravita and Atsushi Iriki. “Tools for the body (schema)”. English. In: *Trends in Cognitive Sciences* 8.2 (Feb. 2004), pp. 79–86. DOI: `10.1016/j.tics.2003.12.008`. URL: `http://linkinghub.elsevier.com/retrieve/pii/S1364661303003450`.

[20] Marie Martel, Lucilla Cardinali, Alice C Roy, and Alessandro Farnè. “Tool-use: An open window into body representation and its plasticity”. English. In: *Cognitive neuropsychology* 33.1-2 (June 2016), pp. 82–101. DOI: `10.1080/02643294.2016.1167678`. URL: `http://www.tandfonline.com/doi/full/10.1080/02643294.2016.1167678`.

[21] Mariella Pazzaglia and Marco Molinari. "The embodiment of assistive devices—from wheelchair to exoskeleton". English. In: *Physics of life reviews* 16 (Mar. 2016), pp. 163–175. DOI: `10.1016/j.plrev.2015.11.006`. URL: `http://linkinghub.elsevier.com/retrieve/pii/S1571064515002110`.

[22] Alessandro Farnè, Atsushi Iriki, and Elisabetta Làdavas. "Shaping multisensory action–space with tools: evidence from patients with cross-modal extinction". English. In: *Neuropsychologia* 43.2 (Jan. 2005), pp. 238–248. DOI: `10.1016/j.neuropsychologia.2004.11.010`. URL: `http://linkinghub.elsevier.com/retrieve/pii/S0028393204002866`.

[23] Patrick Grüneberg, Hideki Kadone, Naomi Kuramoto, Tomoyuki Ueno, Yasushi Hada, Masashi Yamazaki, Yoshiyuki Sankai, and Kenji Suzuki. "Robot-assisted voluntary initiation reduces control-related difficulties of initiating joint movement: A phenomenal questionnaire study on shaping and compensation of forward gait". English. In: *PLoS ONE* 13.3 (Mar. 2018), e0194214–15. DOI: `10.1371/journal.pone.0194214`. URL: `http://dx.plos.org/10.1371/journal.pone.0194214`.

[24] Mel Slater, Martin Usoh, and Anthony Steed. "Taking steps: the influence of a walking technique on presence in virtual reality". In: *ACM Transactions on Computer-Human Interaction (TOCHI)* 2.3 (Sept. 1995), pp. 201–219. DOI: `10.1145/210079.210084`. URL: `http://portal.acm.org/citation.cfm?doid=210079.210084`.

[25] Katrin Wolf, Markus Funk, Rami Khalil, and Pascal Knierim. "Using virtual reality for prototyping interactive architecture". In: *the 16th International Conference*. New York, New York, USA: ACM Press, 2017, pp. 457–464. ISBN: 9781450353786. DOI: `10.1145/3152832.3156625`. URL: `http://dl.acm.org/citation.cfm?doid=3152832.3156625`.

[26] Kenta Suzuki, Gouji Mito, Hiroaki Kawamoto, Yasuhisa Hasegawa, and Yoshiyuki Sankai. "Intention-based walking support for paraplegia patients with Robot Suit HAL". In: *Advanced Robotics* 21.12 (2007), pp. 1441–1469. DOI: `10.1163/156855307781746061`. URL: `https://www.tandfonline.com/doi/abs/10.1163/156855307781746061`.

[27] H Kawamoto and Y Sankai. "Comfortable power assist control method for walking aid by HAL-3". In: *IEEE International Conference on Systems, Man and Cybernetics*. IEEE, 2002, p. 6. ISBN: 0-7803-7437-1. DOI: `10.1109/icsmc.2002.1173328`. URL: `http://ieeexplore.ieee.org/document/1173328/`.

[28] Shunichi Kasahara, Keina Konno, Richi Owaki, Tsubasa Nishi, Akiko Takeshita, Takayuki Ito, Shoko Kasuga, and Junichi Ushiba. “Malleable Embodiment”. In: *the 2017 CHI Conference*. New York, New York, USA: ACM Press, 2017, pp. 6438–6448. ISBN: 9781450346559. DOI: `10.1145/3025453.3025962`. URL: `http://dl.acm.org/citation.cfm?doid=3025453.3025962`.

[29] J R Lackner. “Some proprioceptive influences on the perceptual representation of body shape and orientation.” English. In: *Brain* 111 (Pt 2) (Apr. 1988), pp. 281–297. URL: `http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?dbfrom=pubmed&id=3378137&retmode=ref&cmd=prlinks`.

[30] M R Longo and P Haggard. “What Is It Like to Have a Body?” English. In: *Current Directions in Psychological Science* 21.2 (Mar. 2012), pp. 140–145. DOI: `10.1177/0963721411434982`. URL: `http://cdp.sagepub.com/lookup/doi/10.1177/0963721411434982`.

[31] Lucilla Cardinali, Francesca Frassinetti, Claudio Brozzoli, Christian Urquizar, Alice C Roy, and Alessandro Farnè. “Tool-use induces morphological updating of the body schema”. English. In: *Current Biology* 19.12 (June 2009), R478–R479. DOI: `10.1016/j.cub.2009.05.009`. URL: `https://linkinghub.elsevier.com/retrieve/pii/S0960982209011099`.

[32] Giulia Galli, Jean Paul Noel, Elisa Canzoneri, Olaf Blanke, and Andrea Serino. “The wheelchair as a full-body tool extending the peripersonal space”. English. In: *Frontiers in Psychology* 6 (May 2015), pp. 1–11. DOI: `10.3389/fpsyg.2015.00639`. URL: `http://journal.frontiersin.org/Article/10.3389/fpsyg.2015.00639/abstract`.

[33] Luke E Miller, Luca Montroni, Eric Koun, Romeo Salemme, Vincent Hayward, and Alessandro Farnè. “Sensing with tools extends somatosensory processing beyond the body”. English. In: *Nature* 561.7722 (Sept. 2018), pp. 1–19. DOI: `10.1038/s41586-018-0460-0`. URL: `http://dx.doi.org/10.1038/s41586-018-0460-0`.

[34] Andrea Serino, Michela Bassolino, Alessandro Farnè, and Elisabetta Làdavas. “Extended multisensory space in blind cane users.” English. In: *Psychological Science* 18.7 (July 2007), pp. 642–648. DOI: `10.1111/j.1467-9280.2007.01952.x`. URL: `http://journals.sagepub.com/doi/10.1111/j.1467-9280.2007.01952.x`.

[35] Elisa Canzoneri, Marilena Marzolla, Amedeo Amoresano, Gennaro Verni, and Andrea Serino. "Amputation and prosthesis implantation shape body and peripersonal space representations". English. In: *Scientific Reports* 3.1 (2013), p. 389. DOI: `10.1038/srep02844`. URL: `http://www.nature.com/articles/srep02844`.

[36] Jumpei Arata, Masashi Hattori, Shohei Ichikawa, and Masamichi Sakaguchi. "Robotically enhanced rubber hand illusion." English. In: *IEEE Transactions on Haptics* 7.4 (Oct. 2014), pp. 526–532. DOI: `10.1109/TOH.2014.2304722`. URL: `http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?dbfrom=pubmed&id=25532152&retmode=ref&cmd=prlinks`.

[37] Matthew Botvinick and Jonathan Cohen. "Rubber hands 'feel' touch that eyes see". English. In: *Nature* 391.6669 (Feb. 1998), pp. 756–756. DOI: `10.1038/35784`. URL: `https://www.nature.com/articles/35784`.

[38] Arvid Guterstam, Valeria I Petkova, and H Henrik Ehrsson. "The Illusion of Owning a Third Arm". English. In: *PLoS ONE* 6.2 (Feb. 2011), e17208–11. DOI: `10.1371/journal.pone.0017208`. URL: `http://dx.plos.org/10.1371/journal.pone.0017208`.

[39] Jaron Lanier. *You Are Not A Gadget*. English. A Manifesto. Penguin UK, Jan. 2010. ISBN: 0141960884. URL: `http://books.google.co.jp/books?id=LNan8BNXQjYC&printsec=frontcover&dq=intitle:You+are+not+a+Gadget+A+Manifesto&hl=&cd=1&source=gbs_api`.

[40] Björn van der Hoort, Arvid Guterstam, and H Henrik Ehrsson. "Being Barbie: The Size of One's Own Body Determines the Perceived Size of the World". English. In: *PLoS ONE* 6.5 (May 2011), e20195–10. DOI: `10.1371/journal.pone.0020195`. URL: `http://dx.plos.org/10.1371/journal.pone.0020195`.

[41] Björn van der Hoort and H Henrik Ehrsson. "Body ownership affects visual perception of object size by rescaling the visual representation of external space". English. In: *Attention, Perception, & Psychophysics* 76.5 (May 2014), pp. 1414–1428. DOI: `10.3758/s13414-014-0664-9`. URL: `http://link.springer.com/10.3758/s13414-014-0664-9`.

[42] Ana Tajadura-Jimamp x000E9 nez, Domna Banakou, Nadia Bianchi-Berthouze, and Mel Slater. "Embodiment in a Child-Like Talking Virtual Body Influences Object Size Perception, Self-Identification, and Subsequent Real Speaking". English. In: *Nature Publishing Group* 7.1 (Aug. 2017), pp. 1–12. DOI: `10.`

1038/s41598-017-09497-3. URL: http://dx.doi.org/10.1038/s41598-017-09497-3.

[43] Tabitha C Peck, Sofia Seinfeld, Salvatore M Aglioti, and Mel Slater. "Putting yourself in the skin of a black avatar reduces implicit racial bias". English. In: *Consciousness and Cognition* 22.3 (Sept. 2013), pp. 779–787. DOI: 10.1016/j.concog.2013.04.016. URL: http://dx.doi.org/10.1016/j.concog.2013.04.016.

[44] Domna Banakou, Parasuram D Hanumanthu, and Mel Slater. "Virtual Embodiment of White People in a Black Virtual Body Leads to a Sustained Reduction in Their Implicit Racial Bias". In: *Frontiers in Human Neuroscience* 10 (Nov. 2016), pp. 642–12. DOI: 10.3389/fnhum.2016.00601. URL: http://journal.frontiersin.org/article/10.3389/fnhum.2016.00601/full.

[45] Lara Maister, Natalie Sebanz, Günther Knoblich, and Manos Tsakiris. "Experiencing ownership over a dark-skinned body reduces implicit racial bias". English. In: *Cognition* 128.2 (Aug. 2013), pp. 170–178. DOI: 10.1016/j.cognition.2013.04.002. URL: http://dx.doi.org/10.1016/j.cognition.2013.04.002.

[46] Kevin Fan, Jochen Huber, Suranga Nanayakkara, and Masahiko Inami. "SpiderVision". In: *the 5th Augmented Human International Conference*. New York, New York, USA: ACM Press, 2014, pp. 1–8. ISBN: 9781450327619. DOI: 10.1145/2582051.2582100. URL: http://dl.acm.org/citation.cfm?doid=2582051.2582100.

[47] Faye Y Wu and H Harry Asada. "Bio-Artificial Synergies for Grasp Posture Control of Supernumerary Robotic Fingers." In: *Robotics - Science and Systems* (2014). URL: https://dspace.mit.edu/handle/1721.1/88457.

[48] Yuhan Hu, Sang-won Leigh, and Pattie Maes. "Hand Development Kit". In: *the 30th Annual ACM Symposium*. New York, New York, USA: ACM Press, 2017, pp. 27–29. ISBN: 9781450354196. DOI: 10.1145/3131785.3131805. URL: http://dl.acm.org/citation.cfm?doid=3131785.3131805.

[49] Sang-won Leigh, Timothy Denton, Kush Parekh, William Peebles, Magnus Johnson, and Pattie Maes. "Morphology Extension Kit". In: *the Twelfth International Conference*. New York, New York, USA: ACM Press, 2018, pp. 11–18. ISBN: 9781450355681. DOI: 10.1145/3173225.3173239. URL: http://dl.acm.org/citation.cfm?doid=3173225.3173239.

[50] Yoshio Ishiguro, Adiyan Mujibiya, Takashi Miyaki, and Jun Rekimoto. "Aided eyes - eye activity sensing for daily life." In: *AH* (2010), pp. 1–7. DOI: `10.1145/1785455.1785480`. URL: `http://portal.acm.org/citation.cfm?doid=1785455.1785480`.

[51] Shunichi Kasahara and Jun Rekimoto. "JackIn - integrating first-person view with out-of-body vision generation for human-human augmentation." In: *AH* (2014), pp. 1–8. DOI: `10.1145/2582051.2582097`. URL: `http://dl.acm.org/citation.cfm?doid=2582051.2582097`.

[52] Susumu Tachi, Kouichi Watanabe, Keisuke Takeshita, Kouta Minamizawa, Takumi Yoshida, and Katsunari Sato. "Mutual Telexistence Surrogate System - TELESAR4 - telexistence in real environments using autostereoscopic immersive display." In: *IROS* (2011), pp. 157–162. DOI: `10.1109/IROS.2011.6094543`. URL: `http://ieeexplore.ieee.org/document/6094543/`.

[53] MHD Yamen Saraiji, Tomoya Sasaki, Reo Matsumura, Kouta Minamizawa, and Masahiko Inami. "Fusion". In: *ACM SIGGRAPH 2018 Emerging Technologies*. New York, New York, USA: ACM Press, 2018, pp. 1–2. ISBN: 9781450358101. DOI: `10.1145/3214907.3214912`. URL: `http://dl.acm.org/citation.cfm?doid=3214907.3214912`.

[54] Kana Misawa and Jun Rekimoto. "Wearing another's personality". In: *the 2015 ACM International Symposium*. New York, New York, USA: ACM Press, 2015, pp. 125–132. ISBN: 9781450335782. DOI: `10.1145/2802083.2808392`. URL: `http://dl.acm.org/citation.cfm?doid=2802083.2808392`.

[55] Carlos Cardoso and P John Clarkson. "Simulation in user-centred design: helping designers to empathise with atypical users". English. In: *Journal of Engineering Design* 23.1 (Apr. 2010), pp. 1–4. DOI: `10.1080/09544821003742650`. URL: `http://www.tandfonline.com/doi/abs/10.1080/09544821003742650`.

[56] Honda Motor. *Honda Child Vision*. Jan. 2019. URL: `https://www.honda.co.jp/safetyinfo/kyt/partner/childvision.pdf`.

[57] Gastone Pietro Rosati Papini, Marco Fontana, and Massimo Bergamasco. "Desktop Haptic Interface for Simulation of Hand-Tremor." English. In: *IEEE Transactions on Haptics* 9.1 (Jan. 2016), pp. 33–42. DOI: `10.1109/TOH.2015.2504971`. URL: `http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?dbfrom=pubmed&id=26642457&retmode=ref&cmd=prlinks`.

[58] B Philippe, D Gonzalez-Franco, A Pointeau, C Cherene Prix Ars Electronica, and 2014. *The Machine to be Another-Embodied Telepresence using human performers*. URL: `http://scholar.google.comjavascript:void(0)`.

[59] Jun Nishida and Kenji Suzuki. "bioSync". In: *the 2017 CHI Conference*. New York, New York, USA: ACM Press, 2017, pp. 3316–3327. ISBN: 9781450346559. DOI: `10.1145/3025453.3025829`. URL: `http://dl.acm.org/citation.cfm?doid=3025453.3025829`.

[60] Ida Shino and Yamanaka Toshimasa. "A study on the usability of environment objects by the difference in eye level (In Japanese)". In: *Japan Society of the Science of Design*. 2000.

[61] Nicola Bruno and Marco Bertamini. "Haptic perception after a change in hand size". English. In: *Neuropsychologia* 48.6 (May 2010), pp. 1853–1856. DOI: `10.1016/j.neuropsychologia.2010.01.006`. URL: `http://dx.doi.org/10.1016/j.neuropsychologia.2010.01.006`.

[62] Sally A Linkenauger, Heinrich H Bülthoff, and Betty J Mohler. "Virtual armŒşs reach influences perceived distances but only after experience reaching". English. In: *Neuropsychologia* 70.C (Apr. 2015), pp. 393–401. DOI: `10.1016/j.neuropsychologia.2014.10.034`. URL: `http://dx.doi.org/10.1016/j.neuropsychologia.2014.10.034`.

[63] H Henrik Ehrsson. "The experimental induction of out-of-body experiences." English. In: *Science (New York, N.Y.)* 317.5841 (Aug. 2007), pp. 1048–1048. DOI: `10.1126/science.1142175`. URL: `http://www.sciencemag.org/cgi/doi/10.1126/science.1142175`.

[64] Sally A Linkenauger, Markus Leyrer, Heinrich H Bülthoff, and Betty J Mohler. "Welcome to Wonderland: The Influence of the Size and Shape of a Virtual Hand On the Perceived Size and Shape of Virtual Objects". English. In: *PLoS ONE* 8.7 (July 2013), e68594–16. DOI: `10.1371/journal.pone.0068594`. URL: `http://dx.plos.org/10.1371/journal.pone.0068594`.

[65] Daniel Freeman, Nicole Evans, Rachel Lister, Angus Antley, Graham Dunn, and Mel Slater. "Height, social comparison, and paranoia$_{A}immersivevirtualrealityexperimentalstudy$". English. In: *Psychiatry Research* 218.3 (Aug. 2014), pp. 348–352. DOI: `10.1016/j.psychres.2013.12.014`. URL: `http://dx.doi.org/10.1016/j.psychres.2013.12.014`.

[66] Nick Yee and Jeremy Bailenson. “The Proteus Effect: The Effect of Transformed Self-Representation on Behavior”. English. In: *Human Communication Research* 33.3 (July 2007), pp. 271–290. DOI: `10.1111/j.1468-2958.2007.00299.x`. URL: `https://academic.oup.com/hcr/article/33/3/271-290/4210718`.

[67] Shibo Qin, Yukie Nagai, Shinichiro Kumagaya, Satsuki Ayaya, and Minoru Asada. “Autism simulator employing augmented reality - A prototype.” In: *2014 Joint IEEE International Conferences on Development and Learning and Epigenetic Robotics (ICDL-Epirob)* (2014), pp. 155–156. DOI: `10.1109/DEVLRN.2014.6982972`. URL: `http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6982972`.

[68] H Mori and Y Gogi. “The change of students’ perceptions toward the elderly by simulated experience of the elderly (In Japanese)”. In: *The Research Bulletin of Shujitsu University and Shujitsu Junior College* 43 (2014), pp. 263–272.

[69] Jun Nishida, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki. “CHILDHOOD”. In: *the 2015 Virtual Reality International Conference*. New York, New York, USA: ACM Press, 2015, pp. 1–4. ISBN: 9781450333139. DOI: `10.1145/2806173.2806190`. URL: `http://dl.acm.org/citation.cfm?doid=2806173.2806190`.

[70] Jun Nishida, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki. “CHILDHOOD”. In: *ACM SIGGRAPH 2015 Emerging Technologies*. New York, New York, USA: ACM Press, 2015, pp. 1–1. ISBN: 9781450336352. DOI: `10.1145/2782782.2792501`. URL: `http://dl.acm.org/citation.cfm?doid=2782782.2792501`.

[71] Michael S A Graziano and Dylan F Cooke. “Parieto-frontal interactions, personal space, and defensive behavior”. English. In: *Neuropsychologia* 44.6 (Jan. 2006), pp. 845–859. DOI: `10.1016/j.neuropsychologia.2005.09.009`. URL: `http://linkinghub.elsevier.com/retrieve/pii/S0028393205003131`.

[72] Giacomo Rizzolatti, Luciano Fadiga, Leonardo Fogassi, and Vittorio Gallese. “The Space Around Us”. In: *Science (New York, N.Y.)* 277.5323 (1997), pp. 190–191. DOI: `10.1126/science.277.5323.190`. URL: `http://science.sciencemag.org/content/277/5323/190`.

[73] Jun Nishida, Kanako Takahashi, and Kenji Suzuki. “A wearable stimulation device for sharing and augmenting kinesthetic feedback”. In: *the 6th Augmented Human International Conference*. New York, New York, USA: ACM Press, 2015, pp. 211–212. ISBN: 9781450333498. DOI: `10.1145/2735711.2735775`.

URL: `http://dl.acm.org/citation.cfm?doid=2735711.2735775`.

[74] Jun Nishida and Kenji Suzuki. "bioSync - Wearable haptic I/O device for synchronous kinesthetic interaction." In: *IEEE Virtual Reality Conference 2016* (2016), pp. 243–244. DOI: `10.1109/VR.2016.7504744`. URL: `http://ieeexplore.ieee.org/document/7504744/`.

[75] Hiroki Kawasaki, Shin Okamoto, Hideyuki Ando, and Taro Maeda. "Collaboration and skill transmission by first-person perspective view sharing system." In: *RO-MAN* (2010), pp. 125–131. DOI: `10.1109/ROMAN.2010.5598668`. URL: `http://ieeexplore.ieee.org/document/5598668/`.

[76] Scott Brave and Andrew Dahley. "inTouch". In: *CHI '97 extended abstracts*. New York, New York, USA: ACM Press, 1997, p. 363. ISBN: 0897919262. DOI: `10.1145/1120212.1120435`. URL: `http://portal.acm.org/citation.cfm?doid=1120212.1120435`.

[77] Ken Nakagaki, Chikara Inamura, Pasquale Totaro, Thariq Shihipar, Yin Shuang, and Hiroshi Ishii. "Linked-Stick". In: *the 33rd Annual ACM Conference Extended Abstracts*. New York, New York, USA: ACM Press, 2015, pp. 1609–1614. ISBN: 9781450331463. DOI: `10.1145/2702613.2732712`. URL: `http://dl.acm.org/citation.cfm?doid=2702613.2732712`.

[78] Hideyuki Nakanishi, Kazuaki Tanaka, and Yuya Wada. "Remote handshaking". In: *the 32nd annual ACM conference*. New York, New York, USA: ACM Press, 2014, pp. 2143–2152. ISBN: 9781450324731. DOI: `10.1145/2556288.2557169`. URL: `http://dl.acm.org/citation.cfm?doid=2556288.2557169`.

[79] Jeremy N Bailenson, Nick Yee, Scott Brave, Dan Merget, and David Koslow. "Virtual interpersonal touch: Expressing and recognizing emotions through haptic devices". In: *Human-Computer Interaction* 22.3 (2007), pp. 325–353. DOI: `10.1080/07370020701493509`. URL: `http://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=mekentosj&SrcApp=Papers&DestLinkType=FullRecord&DestApp=WOS&KeyUT=000249943800003`.

[80] Shannon O'Brien and Florian Mueller. "Holding hands over a distance - technology probes in an intimate, mobile context." In: *OZCHI* (2006), p. 293. DOI: `10.1145/1228175.1228226`. URL: `http://portal.acm.org/citation.cfm?doid=1228175.1228226`.

[81] Scott Brave, Clifford Nass, and Erenee Sirinian. "Force-Feedback in computer-mediated communication." In: *HCI* (2001). URL: `https://dblp.org/rec/conf/hci/BraveNS01`.

[82] E Aiello, D H Gates, B L Patritti, K D Cairns, M Meister, E A Clancy, and P Bonato. "Visual EMG Biofeedback to Improve Ankle Function in Hemiparetic Gait". English. In: *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*. Department of Physical Medicine, Rehabilitation, University of Messina, Messina, Italy. Department of Physical Medicine, and Rehabilitation, Harvard Medical School, Spaulding Rehabilitation Hospital, Boston, MA, USA. IEEE, 2005, pp. 7703–7706. ISBN: 0-7803-8741-4. DOI: `10.1109/IEMBS.2005.1616297`. URL: `http://ieeexplore.ieee.org/document/1616297/`.

[83] Naoto Igarashi, Kenji Suzuki, Hiroaki Kawamoto, and Yoshiyuki Sankai. "bioLights: light emitting wear for visualizing lower-limb muscle activity." English. In: *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference* 2010 (2010), pp. 6393–6396. DOI: `10.1109/IEMBS.2010.5627306`. URL: `http://ieeexplore.ieee.org/document/5627306/`.

[84] Guillermo Bernal, Dishaan Ahuja, and Federico Casalegno. "EMG-based biofeedback tool for augmenting manual fabrication and improved exchange of empirical knowledge". In: *the XVI International Conference*. New York, New York, USA: ACM Press, 2015, pp. 1–8. ISBN: 9781450334631. DOI: `10.1145/2829875.2829932`. URL: `http://dl.acm.org/citation.cfm?doid=2829875.2829932`.

[85] Yasunori Tsubouchi and Kenji Suzuki. "BioTones: A wearable device for EMG auditory biofeedback". In: *Annual International Conference of the IEEE Engineering in Medicine and Biology* (July 2010), pp. 6543–6546. DOI: `10.1109/IEMBS.2010.5627097`. URL: `http://ieeexplore.ieee.org/document/5627097/`.

[86] Marco Dozza, Fay B Horak, and Lorenzo Chiari. "Auditory biofeedback substitutes for loss of sensory information in maintaining stance". English. In: *Experimental Brain Research* 178.1 (Oct. 2006), pp. 37–48. DOI: `10.1007/s00221-006-0709-y`. URL: `http://link.springer.com/10.1007/s00221-006-0709-y`.

[87] Raafat Shalaby, Thomas Schauer, Wolfgang Liedecke, and Jörg Raisch. "Amplifier design for EMG recording from stimulation electrodes during functional electrical stimulation leg cycling ergometry". In: *Biomedizinische Technik/Biomedical Engineering* 56.1 (Feb. 2011), pp. 23–33. DOI: `10.1515/bmt.2010.055`. URL: `http://www.degruyter.com/view/`

j/bmte.2011.56.issue-1/bmt.2010.055/bmt.2010.055.xml.

[88] Pedro Lopes, Alexandra Ion, Willi Mueller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. "Proprioceptive Interaction". In: *the 33rd Annual ACM Conference*. New York, New York, USA: ACM Press, 2015, pp. 939–948. ISBN: 9781450331456. DOI: 10.1145/2702123.2702461. URL: http://dl.acm.org/citation.cfm?doid=2702123.2702461.

[89] Emi Tamaki, Takashi Miyaki, and Jun Rekimoto. "PossessedHand - techniques for controlling human hands using electrical muscles stimuli." In: *CHI Conference on Human Factors in Computing Systems* (2011), p. 543. DOI: 10.1145/1978942.1979018. URL: http://dl.acm.org/citation.cfm?doid=1978942.1979018.

[90] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. "Affordance++". In: *the 33rd Annual ACM Conference*. New York, New York, USA: ACM Press, 2015, pp. 2515–2524. ISBN: 9781450331456. DOI: 10.1145/2702123.2702128. URL: http://dl.acm.org/citation.cfm?doid=2702123.2702128.

[91] Pedro Lopes, Doăa Yüksel, François Guimbretière, and Patrick Baudisch. "Muscle-plotter". In: *the 29th Annual Symposium*. New York, New York, USA: ACM Press, 2016, pp. 207–217. ISBN: 9781450341899. DOI: 10.1145/2984511.2984530. URL: http://dl.acm.org/citation.cfm?doid=2984511.2984530.

[92] Pedro Lopes and Patrick Baudisch. "Muscle-propelled force feedback". In: *the SIGCHI conference*. New York, New York, USA: ACM Press, 2013, p. 2577. ISBN: 9781450318990. DOI: 10.1145/2470654.2481355. URL: http://dl.acm.org/citation.cfm?doid=2470654.2481355.

[93] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. "Impacto". In: *the 28th Annual ACM Symposium*. New York, New York, USA: ACM Press, 2015, pp. 11–19. ISBN: 9781450337793. DOI: 10.1145/2807442.2807443. URL: http://dl.acm.org/citation.cfm?doid=2807442.2807443.

[94] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. "Dexmo". In: *the 2016 CHI Conference*. New York, New York, USA: ACM Press, 2016, pp. 1991–1995. ISBN: 9781450333627. DOI: 10.1145/2858036.2858487. URL: http://dl.acm.org/citation.cfm?doid=2858036.2858487.

[95] "An Encounter-Type Multi-Fingered Master Hand Using Circuitous Joints". In: (Feb. 2005), pp. 1–6.

[96] Yoshihiro Muraoka. “Development of an EMG recording device from stimulation electrodes for functional electrical stimulation.” English. In: *Frontiers of medical and biological engineering : the international journal of the Japan Society of Medical Electronics and Biological Engineering* 11.4 (2002), pp. 323–333. URL: `http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?dbfrom=pubmed&id=12735431&retmode=ref&cmd=prlinks`.

[97] Edward T Hall. *The Hidden Dimension*. English. 1969. URL: `http://books.google.co.jp/books?id=Yf27OgAACAAJ&dq=intitle:The+Hidden+Dimension&hl=&cd=1&source=gbs_api`.

[98] Tina Iachini, Yann Coello, Francesca Frassinetti, and Gennaro Ruggiero. “Body Space in Social Interactions: A Comparison of Reaching and Comfort Distance in Immersive Virtual Reality”. English. In: *PLoS ONE* 9.11 (Nov. 2014), e111511–7. DOI: `10.1371/journal.pone.0111511`. URL: `http://dx.plos.org/10.1371/journal.pone.0111511`.

[99] Michael A Dosey and Murray Meisels. “Personal space and self-protection.” English. In: *Journal of Personality and Social Psychology* 11.2 (1969), pp. 93–97. DOI: `10.1037/h0027040`. URL: `http://doi.apa.org/getdoi.cfm?doi=10.1037/h0027040`.

[100] Gay H Tennis and James M Dabbs join(". “Sex, Setting and Personal Space: First Grade Through College”. In: *Sociometry* 38.3 (Sept. 1975), p. 385. DOI: `10.2307/2786172`. URL: `https://www.jstor.org/stable/2786172?origin=crossref`.

[101] Erica Gessaroli, Erica Santelli, Giuseppe di Pellegrino, and Francesca Frassinetti. “Personal Space Regulation in Childhood Autism Spectrum Disorders”. English. In: *PLoS ONE* 8.9 (Sept. 2013), e74959–8. DOI: `10.1371/journal.pone.0074959`. URL: `http://dx.plos.org/10.1371/journal.pone.0074959`.

[102] T V Perneger. “What’s wrong with Bonferroni adjustments”. English. In: *BMJ* 316.7139 (1998), pp. 1236–1238. DOI: `10.1136/bmj.316.7139.1236`. URL: `http://www.bmj.com/cgi/doi/10.1136/bmj.316.7139.1236`.

[103] Yoav Benjamini and Yosef Hochberg. “Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing”. English. In: *Journal of the Royal Statistical Society: Series B (Methodological)* 57.1 (Jan. 1995), pp. 289–300. DOI: `10.1111/j.2517-6161.1995.tb02031.x`. URL: `https://rss.onlinelibrary.wiley.com/doi/full/10.1111/j.2517-6161.1995.tb02031.x`.

[104] Keisuke Yagi, Kenji Suzuki, and Hiromi Mochiyama. "Human Joint Impedance Estimation With a New Wearable Device Utilizing Snap-Through Buckling of Closed-Elastica". In: *IEEE Robotics and Automation Letters* 3.3 (July 2018), pp. 1506–1513. DOI: `10.1109/LRA.2018.2800114`. URL: `http://ieeexplore.ieee.org/document/8276258/`.

[105] Modar Hassan, Keisuke Yagi, Kaiwen Hsiao, Hiromi Mochiyama, and Kenji Suzuki. "Tarsusmeter: Development of a wearable device for ankle joint impedance estimation." English. In: *Conference proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference* 2017 (July 2017), pp. 3293–3296. DOI: `10.1109/EMBC.2017.8037560`. URL: `https://ieeexplore.ieee.org/document/8037560/`.

[106] Antônio Padilha Lanari Bo, Christine Azevedo-Coste, Philippe Poignet, Christian Geny, and Charles Fattal. "On the use of FES to attenuate tremor by modulating joint impedance". In: *CDC-ECE* (2011). DOI: `10.1163/156855307781746061`. URL: `https://dblp.org/rec/conf/cdc/BoAPGF11`.

[107] Antônio Padilha Lanari Bo and Philippe Poignet. "Tremor attenuation using FES-based joint stiffness control". In: *2010 IEEE International Conference on Robotics and Automation* (May 2010), pp. 2928–2933. DOI: `10.1109/ROBOT.2010.5509560`. URL: `http://ieeexplore.ieee.org/document/5509560/`.

[108] Antônio Padilha Lanari Bo, Philippe Poignet, Dingguo Zhang, and Wei Tech Ang. "FES-controlled co-contraction strategies for pathological tremor compensation". In: *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, Sept. 2009, pp. 1633–1638. ISBN: 978-1-4244-3803-7. DOI: `10.1109/IROS.2009.5354397`. URL: `http://ieeexplore.ieee.org/document/5354397/`.

[109] Yohei Ariga, Daisuke Maeda, Hang T T Pham, Mitsunori Uemura, Hiroaki Hirai, and Fumio Miyazaki. "Novel equilibrium-point control of agonist-antagonist system with pneumatic artificial muscles - II. Application to EMG-based human-machine interface for an elbow-joint system." In: *IROS*. IEEE, 2012, pp. 4380–4385. ISBN: 978-1-4673-1737-5. DOI: `10.1109/IROS.2012.6385790`. URL: `http://ieeexplore.ieee.org/document/6385790/`.

[110] Jun Nishida and Kenji Suzuki. "Wearable Kinesthetic I/O Device for Sharing Muscle Compliance". In: *The 31st Annual ACM Symposium*. New York, New York, USA: ACM Press, 2018, pp. 57–59. ISBN: 9781450359498. DOI: `10.1145/3266037.3266100`. URL: `http://dl.acm.org/citation.cfm?doid=3266037.3266100`.

[111] Jun Nishida, Shunichi Kasahara, and Kenji Suzuki. "Wired muscle". In: *ACM SIGGRAPH 2017 Emerging Technologies*. New York, New York, USA: ACM Press, 2017, pp. 1–2. ISBN: 9781450350129. DOI: `10.1145/3084822.3084844`. URL: `http://dl.acm.org/citation.cfm?doid=3084822.3084844`.

[112] Thomas Waltemate, Irene Senna, Felix Hülsmann, Marieke Rohde, Stefan Kopp, Marc Ernst, and Mario Botsch. "The impact of latency on perceptual judgments and motor performance in closed-loop interaction in virtual reality". In: *the 22nd ACM Conference*. New York, New York, USA: ACM Press, 2016, pp. 27–35. ISBN: 9781450344913. DOI: `10.1145/2993369.2993381`. URL: `http://dl.acm.org/citation.cfm?doid=2993369.2993381`.

[113] C M Harris and D M Wolpert. "Signal-dependent noise determines motor planning." English. In: *Nature* 394.6695 (Aug. 1998), pp. 780–784. DOI: `10.1038/29528`. URL: `http://www.nature.com/articles/29528`.

[114] Manami Katoh, Narihiro Nishimura, Maki Yokoyama, Taku Hachisu, Michi Sato, Shogo Fukushima, and Hiroyuki Kajimoto. "Optimal selection of electrodes for muscle electrical stimulation using twitching motion measurement." In: *AH* (2013), p. 543. DOI: `10.1145/1978942.1979018`. URL: `http://dl.acm.org/citation.cfm?doid=1978942.1979018`.

[115] Shunichi Kasahara, Jun Nishida, and Pedro Lopes. "Preemptive Action: Accelerating Human Reaction using Electrical Muscle Stimulation Without Compromising Agency". In: *CHI Conference on Human Factors in Computing Systems Proceedings CHI*. 2019. DOI: `https://doi.org/10.1145/3290605.3300873`.

[116] Matthis Synofzik, Gottfried Vosgerau, and Martin Voss. "The experience of agency: an interplay between prediction and postdiction." English. In: *Frontiers in Psychology* 4 (2013), p. 127. DOI: `10.3389/fpsyg.2013.00127`. URL: `http://journal.frontiersin.org/article/10.3389/fpsyg.2013.00127/abstract`.

[117] Matthis Synofzik, Gottfried Vosgerau, and Albert Newen. "Beyond the comparator model: A multifactorial two-step account of agency". English. In: *Consciousness and Cognition* 17.1 (Mar. 2008), pp. 219–239. DOI: `10.1016/j.concog.2007.03.010`. URL: `http://linkinghub.elsevier.com/retrieve/pii/S1053810007000268`.

[118] "Perceived size and perceived distance of targets viewed from between the legs: Evidence for proprioceptive theory". In: (Sept. 2006), pp. 1–16. DOI: `10.1016/j.visres.2006.04.002`. URL: `http://linkinghub.elsevier.com/retrieve/pii/S0042698906002112`.

[119] Zhili Chen Duygu Ceylan Jingwei Huang and Hailin Jin. "6-DOF VR Videos with a Single 360-Camera". In: (Feb. 2017), pp. 1–8.

[120] Jun Nishida, Soichiro Matsuda, Mika Oki, Hikaru Takatori, Kosuke Sato, and Kenji Suzuki. "Egocentric Small-person Experience by Changing a Visual Perspective". In: *In Proceedings of the CHI Conference on Human Factors in Computing Systems CHI . ACM, New York, NY, USA.* 2019. DOI: `https://doi.org/10.1145/3290605.3300926`.

[121] Yoshiyuki Sankai. "HAL: Hybrid Assistive Limb Based on Cybernics". In: *Robotics Research*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 25–34. ISBN: 978-3-642-14742-5. DOI: `10.1007/978-3-642-14743-2_3`. URL: `http://link.springer.com/10.1007/978-3-642-14743-2_3`.

[122] Ana Tajadura-Jiménez, Maria Basia, Ophelia Deroy, Merle Fairhurst, Nicolai Marquardt, and Nadia Bianchi-Berthouze. "As Light as your Footsteps". In: *the 33rd Annual ACM Conference*. New York, New York, USA: ACM Press, 2015, pp. 2943–2952. ISBN: 9781450331456. DOI: `10.1145/2702123.2702374`. URL: `http://dl.acm.org/citation.cfm?doid=2702123.2702374`.

[123] Lorraine M Gutierrez. "Working with Women of Color: An Empowerment Perspective". English. In: *Social Work* (1990). DOI: `10.1093/sw/35.2.149`. URL: `https://academic.oup.com/sw/article/35/2/149/1892655/Working-with-Women-of-Color-An-Empowerment`.

[124] Aneesha Singh, Ana Tajadura-Jimez, Nadia Bianchi-Berthouze, Nic Marquardt, Monica Tentori, Roberto Bresin, and Dana Kulic. "Mind the Gap". In: *the 2016 CHI Conference Extended Abstracts*. New York, New York, USA: ACM Press, 2016, pp. 1092–1095. ISBN: 9781450340823. DOI: `10.1145/2851581.2886440`. URL: `http://dl.acm.org/citation.cfm?doid=2851581.2886440`.