Chairable Computing

by

Patrick Alexander Carrington

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Thesis Committee:

Dr. Amy Hurst (Chair/Advisor), UMBC, Department of Information Systems

Dr. Helena Mentis, UMBC, Department of Information Systems

Dr. Ravi Kuber, UMBC, Department of Information Systems

Dr. Nilanjan Banerjee, UMBC, Department of CSEE

Dr. Gregory Abowd, Georgia Institute of Technology

Approval Sheet

Title of Dissertation: Chairable Computing

Name of Candidate: Patrick Alexander Carrington
Doctor of Philosophy, 2017

Dissertation and Abstract Approved: ______________________

Amy Hurst
Associate Professor
Department of Information Systems
University of Maryland, Baltimore County

Date Approved: 9/7/17

Curriculum Vitae

Name: Patrick Alexander Carrington

Degree and Date to be Conferred: Doctor of Philosophy, 2017.

Secondary Education:

John F. Kennedy High School, Silver Spring, Maryland 2003-2007

Collegiate Institutions Attended:

University of Maryland, Baltimore County, Baltimore, MD, 2007-2017,

Doctor of Philosophy, Human-Centered Computing, August, 2017.

Master of Science, Human-Centered Computing, December, 2012.

Bachelor of Science, Information Systems, May 2011.

Professional Publications:

1. **Carrington, P.**, Ketter, D., and Hurst, A. (2017, To appear). Understanding Fatigue and Stamina Management Opportunities and Challenges in Wheelchair Basketball. Proceedings of ACM SIGACCESS Conference on Computers and Accessibility (ASSETS 2017). ACM.

2. **Carrington, P.**, Chang, J-M., Chang, K., Hornback, C., Hurst, A., and Kane, S.K. (2016). The Gest-Rest Family: Exploring input possibilities for Wheelchair armrests. ACM Transactions on Accessible Computing. ACM.

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4. **Carrington, P.**, Hosmer, S., Yeh, T., Hurst, A., and Kane, S.K. (2015). Like

This, But Better: Supporting Novices Design and Fabrication of 3D Models Using Existing Objects. In Proceedings of iConference 2015.

5. **Carrington, P.**, Hurst, A., and Kane, S.K. (2014). The Gest-Rest: A Pressure-Sensitive Chairable Input Pad for Power Wheelchair Armrests. In Proceedings of ACM SIGACCESS Conference on Computers and Accessibility (ASSETS 2014). ACM.

6. **Carrington, P.**, Hurst, A., and Kane, S.K. (2014). Wearables and Chairables: Inclusive Design of Mobile Input and Output Techniques for Power Wheelchair Users. In Proceedings of ACM Conference on Human Factors in Computing Systems (CHI 2014).

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8. **Carrington, P.**, Kuber, R., Anthony, L., Hurst, A. and Prasad, S. (2012). Developing an Interface to Support Procedural Memory Training using a Participatory-Based Approach. In Proceedings of BCS HCI 2012, 333-338.

Professional Positions Held:

- Department of Information Systems, UMBC
  Research Assistant, Supervisor: Dr. Amy Hurst
- New Devices Group, Intel Corporation
  Human Factors Engineering Intern, User Experience Research
- New Devices Group, Intel Corporation
  Human Factors Engineering Intern, User Experience Research
- Int'l. Center for Spinal Cord Injury, Kennedy Krieger Institute
  Rehabilitation Aide

- CMU/University of Pittsburgh NSF ERC: Quality of Life Technology Center,
  QoLT Bridge Researcher, Supervisor: Dr. Seung-Jun Kim
- Department of Information Systems, UMBC
  Research Assistant, Supervisor: Dr. Lisa Anthony
- Department of Information Systems, UMBC
  Web Developer
- IS & T Global Sustainment, Lockheed Martin Aeronautics
  Business Analysis Intern
- Department of Information Systems, UMBC
  Research Assistant, Supervisor: Dr. Andrew Sears

Abstract

Title of Dissertation: Chairable Computing

Patrick Alexander Carrington, Doctor of Philosophy, 2017

Dissertation directed by: Amy Hurst

Associate Professor

Department of Information Systems

University of Maryland, Baltimore County

Wheelchairs provide a means to independent mobility for people with motor impairments that impact their legs. For people who also experience upper-body mobility impairments, interacting with computing devices can be challenging due to the nature of hand-held devices and physical interaction requirements. Using a wheelchair can present additional challenges due to the frame obstructing movement or limiting the users ability to reach objects in their periphery. Assistive technologies (AT) may be used to overcome physical challenges presented by both devices and the wheelchair. However, complex individual differences can make designing AT uniquely challenging as solutions are often designed for one individual and may not generalize. In addition, designing AT for wheelchair users requires a constant consideration of the users needs, social factors, technological constraints, and the context in which the technology will be used. Many current Assistive technology solutions involving wheelchairs or wheelchair users take on a function-specific approach which ignores much of the social and sometimes contextual factors.

This dissertation contributes to the inclusive design of technology through an ability-based approach by developing solutions that expand the perception and expressive capabilities of technology for wheelchair users. This work seeks to improve technology solutions for people with MI who use wheelchairs by leveraging the wheelchairs existing features and benefits. Prior research on assistive technologies for wheelchair users does not fully address real world challenges or the mobile experience of using a wheelchair and computing devices. This dissertation introduces the research area of Chairable Computing, supported by an understanding of wheelchair users needs. Findings from the design of a wheelchair-based gesture-input device, as well as an exploration of activity monitoring for wheelchair athletes are presented. Our work contributes to the development of appropriate solutions that integrate with existing assistive technologies and wheelchair users lifestyles.

Dedication

This dissertation is dedicated to my wife, my parents, my sisters, and my daughter. Their love and continued support have made me who I am today. I am eternally grateful for their positivity and faith in me.

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Chapter 1

Introduction

1.1 Context of Studies

Over 35 million people in the United States are living with a motor impairment (CDC, 2012). Of those, about half (17.2 million), have difficulty walking or climbing stairs independently. Often these people will use some kind of mobility aid, such as a wheelchair, to support independent mobility. The physical characteristics of computers and mobile devices, and the motor skills required to effectively use them, can make interacting with devices difficult for individuals with motor impairments. The environment in which a device is to be used can also present challenges for a person using a wheelchair. Specifically, the wheelchair's frame can limit a persons ability to reach stationary devices or to access mobile devices that have been placed in a bag or storage compartment (Carrington et al., 2014b). This can be especially challenging while the user is mobile.

Despite the development assistive technologies for people with motor impairments, the myriad of causes for motor impairments often makes choosing the right solution to fit an individual's needs non-trivial. There is a complex negotiation between the physical characteristics of a device and the function it provides to the user that contributes to the selection of a device that is useful (Carrington et al., 2014b). In some cases, a solution that may address a functional need for the person might not be used because the it does not fit well with their life and use of the wheelchair. This lack of fit makes the AT(device) unusable.

I conducted my research in many different settings. A majority of the data collection was done in the field. I collected data in the physical therapy clinic of a rehab hospital, I visited people's homes, interviewed people and conducted observations at large and small sporting events, and had numerous video and phone calls with participants. For this research it was important for me to collect data and work with participants in their familiar environments. This allowed participants to more readily describe challenges they might face in their everyday routines. This also afforded me a perspective on the everyday situations participants may encounter by experiencing their environment for myself. Next, I will provide an overview of common causes of motor impairments, describe the population I worked with for this research , and introduce the different types of wheelchairs discussed in this dissertation.

1.1.1 Overview of Motor Impairments

Motor impairments may result from a number of causes including traumatic injury as well as congenital conditions or diseases. There are several different congenital conditions or diseases that cause motor impairment. They range in severity and complexity. Cerebral Palsy (CP) is an injury to the brain that results in decreased muscle control. Cerebral Palsey can cause muscle tightness, spasm, involuntary movement, and impaired speech (Rosenbaum et al., 2007). In severe cases, some paralysis is also common. Muscular Dystrophy (MD) is a genetic disorder that is characterized by a progressive degeneration of muscles and results in a loss of motor function(Koenig et al., 1989). Amyotrophic Lateral Sclerosis (ALS) is another degenerative disease that prevents neurons from sending signals to muscles which causes them to degrade and weaken over time. Slowness and partial to complete paralysis are common with this disease. Also, as ALS is a progressive condition it changes over time and some cases can eventually affect the muscles that control breathing which can be fatal (Rowland and Shneider, 2001).

In addition to genetics and diseases, motor impairment can also be caused by traumatic injury such as a spinal cord injury or amputation. Spinal Cord injury (SCI) can result in paralysis of the limbs. Impairment that only affects the legs is called paraplegia, while paralysis that affects both the arms and legs is called quadriplegia. Spinal Cord injury is a very common cause of motor impairment and will be discussed throughout the proposal. About 80% of people with spinal cord injuries are male (Center et al., 2016) and these injuries can be caused by a number of events including car accidents, acts of violence, falls, and sports.

Given these different causes of impairments, the resulting physical abilities of users can vary greatly. If one considers disability as a continuum, at one end you have people with minimal disabilities where a person may experience little to no limitation in their abilities. At the other end of the continuum, you have more severe disabilities where a person may require the regular use of a wheelchair for mobility or may be reliant on other assistive technologies (or caregivers) to complete daily tasks. In the next section, I will provide an overview of the different types of wheelchairs and characteristics of typical users of each type.

1.1.2 Overview of Wheelchairs

Any of the injuries or medical conditions described in the above section can result in paraplegia or quadriplegia. In these cases, a wheelchair may be used to assist with transportation and independent mobility. The ADA defines a wheelchair as a manually operated or power-driven device designed primarily for use by an individual with a mobility disability for the main purpose of indoor, or of both indoor and outdoor, locomotion. (ADA, nd). There are many different types of wheelchairs but they can be separated into two main classifications: Manual wheelchairs and Power wheelchairs.

A manual wheelchair is propelled by pushing on the hand rims to turn the individual wheels (Figure 1.1). This type of chair would most often be used by someone who either only has MI that affects their legs or someone with enough strength and motor control to propel themselves in the wheelchair. Athletic wheelchairs, such as basketball wheelchairs are specially designed to support movements associated with sports. For instance, a basketball wheelchair, is a manual wheelchair but has a lower center of gravity, lightweight wheels, and is designed for improved maneuverability. Specialized athletic wheelchairs are typically only used while playing a sport or during athletic activities.

A power wheelchair is propelled through the use of electric motors. These wheelchairs typically consist of an electric base, usually with 6 wheels, which houses the drive motors and batteries. In addition, the seat may also have motors assist with functions such as tilt, recline, or elevation (Figure 1.1). This type of chair would be used when someone has an MI that affects their upper body as well as their legs. A person with limited strength or motor control may use a power wheelchair, due to a reduced ability to effectively propel themselves using a manual wheelchair. The power wheelchair

Figure 1.1: (a) A traditional lightweight manual wheelchair for everyday use. (b) A basketball wheelchair is a variant of the lightweight manual wheelchair. It typicaly has a lower center of gravity and is more maneuverable. The wheels are set at an angle to improve the turning and maneuverability. (c) A power wheelchair uses a powered base with electric motors to propel the wheels. The user can then use different types of controllers, such as a joystick, to navigate the wheelchair.

is controlled most often using a joystick mounted on the armrest of the wheelchair. However, in situations where the user is unable to operate the wheelchair using the joystick alternative controls might be used. For example, someone who is paralyzed below the chest may still have full control and range of motion in their neck and head. In this case, a head array or an array of switches mounted around the head can be used to control the wheelchair. Someone who has reduced control of their neck and head may still be able to control the wheelchair using a sip and puff interface. This control mechanism allows the user to operate their wheelchair simply by blowing into a straw. Many other options exist for controlling the wheelchair including subtle variations in the number of switches, types of joysticks, and how they are placed or mounted.

1.2 Thesis Contributions

This dissertation contributes to both assistive technology design and mobile computing through an understanding of user perceptions toward mobile computing devices, wearable technology, and the experience of using a wheelchair. My research builds on principles of embodiment and perception to understand and describe the role that the wheelchair and technology plays in the lives of individual wheelchair users. This research also highlights opportunities for technology designers to make better use of emerging technology resources to support people with different abilities. In doing so, we can improve the universal design of such emerging technologies by offering insight into how they may be effectively utilized by people with differing physical abilities.

The two projects described in this dissertation highlight issues for two subgroups among wheelchair users. The first is people with severe physical limitations who may use a power wheelchair and benefit most from support for everyday computing tasks. The second subgroup is for more physically active wheelchair users who play adaptive sports. As mentioned in section 1.1.1, these two groups represent extremes on a continuum. In the practice of Universal Design by understanding these extremes, my goal is to contribute to understanding the space between them. In this dissertation I introduce Carrington's Starting Five, five priorities for chairables identified through my research may be used to guide future development in the area of chairable computing.

1.3 Contributing Papers

This thesis is based on contributions from the following papers:

I. Carrington, P., Hurst, A., and Kane, S. K. (2014b). Wearables and chairables: inclusive design of mobile input and output techniques for power wheelchair users. In *CHI '14: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3103–3112, New York, New York, USA. ACM Request Permissions

II. Carrington, P., Hurst, A., and Kane, S. K. (2014a). The gest-rest: a pressure-sensitive chairable input pad for power wheelchair armrests. In *ASSETS '14: Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility*, pages 201–208, New York, New York, USA. ACM Request Permissions

III. Carrington, P., Chang, J.-M., Chang, K., Hornback, C., Hurst, A., and Kane, S. K. (2016). The Gest-Rest Family: Exploring Input Possibilities for Wheelchair Armrests. *ACM Transactions on Accessible Computing*, 8(3):12:1–12:24

IV. Carrington, P., Chang, K., Mentis, H., and Hurst, A. (2015). But, I don't take steps: Examining the Inaccessibility of Fitness Trackers for Wheelchair Athletes. In *ASSETS '15 Proceedings of the 17th International ACM SIGACCESS Conference on Computers Accessibility*, pages 193–201. ACM

V. Carrington, P., Ketter, D., and Hurst, A. (2017). Understanding Fatigue and Stamina Management Opportunities and Challenges in Wheelchair Basketball. In *ASSETS '17 Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM

1.4 Organization and Structure

Chapter 2 discusses the concepts of embodiment and perception as they relate to the use of a mobility aid. I discuss relevant literature in assistive technology and wheelchair-based computing to highlight current design practices and describe limitations of these approaches.

Chapter 3 describes a research project involving power wheelchair users to understand device and interaction preferences. This chapter also documents the development of the Gest-Rest Family and describes lessons learned regarding input types. Design considerations for power wheelchair users are discussed.

Chapter 4 documents and describes a research project to understand device and interaction preferences of wheelchair athletes for monitoring physical activities. Two studies are presented, one involving general wheelchair athletes and the other involving wheelchair basketball players and coaches, specifically. Design considerations for wheelchair athletes are discussed.

Chapter 5 describes Carrington's Starting Five, priorities for chairable computing, by highlighting commonalities and distinctions between the examples in Chapters 3 and 4. This chapter will also provide an overview of lessons learned and implications for design.

Chapter 6 concludes this dissertation by providing a summary of the contributions and describes future directions for this research.

Chapter 2

Literature Review and Background

This dissertation builds on elements from multiple areas including, embodied interaction, accessibility, and mobile and wearable technology. In this chapter, I discuss related literature in four sections. The first section describes the concepts of embodiment and perception as they relate to the use of assistive technologies and specifically, a mobility aid. The second section describes related work in the design of wheelchair-based technologies, particularly those in robotics, communication, and physical activity. In the third section, I describe accessibility and assistive technology research in HCI. Finally, in section 2.4 I discuss wearable technology and the concept of designing for the body.

2.1 Embodiment and Perception

Martin Heideggar proposed in his work, Being and Time (2010) two concepts that have helped to shape what is considered embodied interaction in HCI. In particular, the difference between ready-to-hand (zuhanden) and present-at-hand (vorhanden). According to Dourish (2001) this distinction helped to shape other foundational work in understanding human cognition by Winograd and Flores (1986). These phenomenological concepts deal with how we encounter things in the world and act through them. The example he describes is of interacting with a computer through a mouse. Dourish describes that the majority of the time the mouse is considered ready-to-hand as the user is interacting through the mouse with the objects on the screen and her focus is on the interaction and the work. This readiness-to-hand shifts to present-at-hand when the mouse reaches the edge of the mousepad and the user is forced to lift the mouse and move it back to center. The shift occurs because in that instance the user must shift their attention to act on the tool instead of through it. Other phenomenologists like Maurice Merleau-Ponty have discussed the meaning of the body and its relation to tools, such as assistive technologies. In Phenomenology of Perception (Merleau-Ponty, 1996, Chap. 3) Merleau-Ponty talks about the white cane that a blind person uses as an extension of the user or the body in that the cane becomes a part of the body which experiences the world.

One could consider the wheelchair as part of the users body and essential to consider how they experience the world. When considering how to design computing technologies for people who regularly use wheelchairs we should not only consider the user and their needs. Fundamentally, an understanding of how the wheelchair and the user act together when interacting with the world is important to ensuring that additional devices and assistive technologies will not interfere in a negative way with the user. The aim of this dissertation is to shed light on how to consider the wheelchair and the user together when designing technology. I contend that abandonment becomes more likely when a device transitions from ready-to-hand to present-at-hand and the user becomes aware that new technology may interfere with other aspects of their lives.

2.2 Accessibility and Assistive Technology

Assistive Technology (AT) is a term used to refer to a broad range of devices, services, strategies, and practices that are conceived and applied to ameliorate the problems faced by individuals who have disabilities (Cook and Polgar, 2008). For the purposes of this research we focus mainly on devices and strategies. Design and research in assistive technology is often complex and although some solutions may be straightforward functionally, there are other issues that can impact the successful development and implementation of assistive technologies. One very important issue in Assistive Technology research is how to address the issue of abandonment where solutions are functionally useful but users discontinue use of the technology for many reasons. Another important issue is that of stigma, primarily due to its impact on AT abandonment, but also due to its relationship to the perception of both users and devices.

2.2.1 Abandonment

One major issue is the abandonment of assistive technology solutions despite the potential benefits they provide. This issue has been explored and several factors that lead to abandonment have been identified. Starting with Phillips and Zhao (1993), researchers have determined that factors relating to the manufacturers, ease of acquisition, device performance, and changes in user needs are significantly related to abandonment. Pape et al. (2002) review of AT abandonment literature revealed that social and psychological factors including perception of the devices and self-perception were also primary factors in determining the likelihood of using an assistive device. Finally, Riemer-Reiss and Wacker (2000) discovered that participation in the selection process and relative advantages were helpful in predicting use or abandonment. Each of these studies provide evidence that the users perception of themselves, the device, and their environment contribute to predicting whether it will be used or abandoned.

2.2.2 Stigma

People with disabilities choose not to use, or choose to discard, technologies for many reasons. Even when a technology is usable and accessible, users might avoid the technology if they feel it will make them stand out or feel abnormal. Elliott et al. (2010) use the term stigma to describe the social interactions created when people are thought not to meet expectations of normal. Bispo and Branco (2008) note that assistive technologies such as wheelchairs often act as symbols of stigma. Parette and Scherer (2004) noted that stigma may be affected by the design of an assistive technology, such as its aesthetics, or whether it has been universally designed. Shinohara and Wobbrock (2011) explored perceptions and misperceptions of assistive technology and disability with visually impaired users, and found that individuals had fewer concerns about stigma when using mass-market computing devices. They propose that issues of perception and social acceptance might be mitigated using mass-market devices that support assistive functions. While an assistive technology users perception of stigma appears to vary across contexts, it is clear that people with disabilities consider the form factor of a device, and its visibility, when considering using that device.

Other research has explored design guidelines for accessible mobile technologies on the go. Kane et al. (2009) explored how people with visual or motor impairments used mobile devices on the go, and recommended that accessible mobile devices be configurable, context-aware, and integrated with accessibility features. Kim and Smith (2008) explored the accessibility challenges faced by wheelchair users when using laptop and desktop computers. They found that many of the accessibility problems related to storage, positioning, and physical access to the device.

2.3 Wheelchair-Based Computing

2.3.1 Robotics and Smart Wheelchairs for Mobility

Advancements in robotics have allowed the creation of intelligent wheelchairs to meet the needs of individuals who use wheelchairs by assisting in a number of ways. In particular, some have been developed to support mobility and navigation of indoor and outdoor spaces Lin et al. (2012). These solutions have been implemented either by providing the wheelchair with autonomous control. For example, Lin et al. (2012) equipped a wheelchair with a camera-based system to allow the wheelchair to adjust control in different indoor and outdoor environments.

Braga et al. (2011) created IntellWheels which was a modular platform for developing intelligent wheelchairs. While not a specific solution this platform allowed developers to select appropriate inputs and outputs based on the needs of the user and could be used either autonomously or semi-autonomously to drive the wheelchair. Other control methods that have been implemented include control of the wheelchair using gaze (Wästlund et al., 2010), body motions (Gulrez et al., 2011), and voice commands (Hockey and Miller, 2007). These projects offer a variety of control mechanisms and offer the user a variety of shared control situations. At the moment the majority of these projects are technically drive and each considers a particular use case where the given control mechanism might be useful. However, many of these do not consider personal preference in their adaptation process.

Simpson (2005) describe several smart wheelchair projects, many of which, rely on rebuilding a wheelchair or modifying a robot and thus create a fundamentally new wheelchair. They described the characteristics of 46 different smart wheelchair projects. Each of these projects had the goal of furthering the independent mobility of their users. One example in particular the Hephaestus Smart Wheelchair by Simpson et al. (2002) describes a system that could be attached to any standard power wheelchair. This idea is consistent with the goal of chairable computing. However, the components described focus on mobility, which extends the capability of the wheelchair. This dissertation focuses on the addition of computing components to peoples existing wheelchairs in order to improve their independent interaction with technology.

2.3.2 Adaptations for Device Access

There are few examples in the HCI literature of designing wheelchair-based information technologies. However, Nischelwitzer et al. (2006) created MediaWheelie, which enables a wheelchair user to control computing devices using their wheelchairs joystick or a sip-and-puff device. Wobbrock et al. (2004) enabled text entry in power wheelchairs using the EdgeWrite alphabet. Kim and Smith (2008) conducted a survey about challenges faced using a laptop while in a wheelchair, and users desired design features for a wheelchair-based wearable computing system. These findings were applied to a concept design (Kim et al., 2008) for a wheelchair-based computing system using an interactive tray. Despite these efforts, further research is needed to understand how such systems would perform and whether these concept designs would be acceptable in practice.

2.3.3 Measuring Physical Activity

A number of studies in medicine and rehab science have begun to explore the measurement and monitoring of physical activities of wheelchair users. One common approach is the use of a Miniature Data Logger (MDL). This approach has been used to quantify the activities of children using manual and power wheelchairs (Cooper et al., 2008), manual wheelchair use among veterans (Tolerico et al., 2007), and even quantifying activity during wheelchair basketball and rugby games (Sporner et al., 2009). Researchers have seen limited success in this approach perhaps because these studies were not aimed at widespread adoption of the technology and rather to understand more about the movements and actions of the wheelchair users. Sporner et al. (2009) suggest that wheelchair basketball and rugby coaches may be able to use the datasets generated during their pilot study to recreate game-like conditions during practice and training. However, the MDL's used in their studies require post-processing of the data after the activity which would not provide the real-time feedback necessary to make immediate adjustments. While this quantification of physical activity has been explored briefly more research is needed to understand the implications such a technology may have in the long term and for continued use.

2.4 Wearable Technology

In 1999, in his thesis, Thad Starner described the characteristics he believed an ideal wearable should have, including that they should persist and provide constant access by allowing continuous use and being mobile and physically unobtrusive (Starner, 1999). He also describes how the wearable should adapt its input and output modes to those that are most appropriate at the time of use. The device should also take a minimal amount of the users attention when in use and especially when not in use. This temporal component of access is can be overlooked by accessibility researchers in favor of more function-oriented goals. However, this constant and on-demand access can have a profound effect on the perceived usefulness of a technology.

Morris et al. (2011) describe several promising types of sensors, interfaces, and techniques that allow always-available mobile interactions. Their review of different technologies focuses on things that are placed on the body (Morris et al., 2011, p.249). This supports the ideas presented by Starner (1999) regarding the design of wearables for the body to provide a truly mobile experience. However, in contrast, Starner uses the term "cyborg" which he references from Clynes and Kline (1960) to mean "a combination of human and machine in which the interface becomes a 'natural' extension that does not require much conscious attention, such as when a person rides a bike." Morris et al. (2011) present requirements for always-available technologies. In either case, these examples focus on a view of the user that does not consider users with different physical abilities and hold a narrow view of the body composed of the physical human body. With regard to chairable computing we consider the relationship between man and machine(wheelchair) to extend the body in the sense that it changes the user's perception of their environment. Thus, in this same environment we must consider the wheelchair a part of the body, which has not been adequately considered by wearable technology design. In doing so, we move toward more universal design of wearable technologies and mobile interaction. However, a set of guidelines for designing technologies to meet the needs of this user group is not present in the literature. By combining knowledge from these different areas, this dissertation contributes a set of guidelines for designing new systems and evaluating existing solutions for people who use wheelchairs to support mobile interactions.

2.5 Chapter Summary

Prior work has not properly considered the embodied relationship between wheelchair users and their mobility aids. We have learned from studies in assistive technology literature that improper consideration, or lack of understanding, of the role of person's mobility aid can lead to misperception and misguided development of future technology solutions (e.g. solutions that make incorrect assumptions about how people perceive and interact with the world). While the design and development of wheelchair-based technologies has been explored previously, much of the existing work has focused on addressing a functional limitation and does not account for the holistic experience of using the new devices as part of the users' lives. There is also a lack of guidelines for the design of technologies specifically for wheelchair users.

This dissertation aims to change the perception when designing for wheelchairs by bringing in aspects of how people have approached designing wearable technologies for the body. I envision shifting the conceptualization of treating the wheelchair as only a medical mobility aid toward a more embodied perception; considering it as part of the user's body. This dissertation aims to provide a set of guidelines or priorities for designers and developers to consider when developing solutions for people who use wheelchairs.

Chapter 3

Designing Technologies for Power Wheelchair Users

3.1 Introduction

In this chapter, I describe research to understand the needs of power wheelchair users with regard to mobile technologies. Two major research studies are presented. First, a multi-part user study involving power wheelchair users and clinicians to understand user needs and preferences with regard to mobile inputs and outputs. Prototype designs, accessibility challenges and opportunities are discussed. Second, based on the findings from the first study, I developed a set of prototypes to further explore the requirements and important considerations for input devices for power wheelchairs. Finally, I discuss five important considerations for chairable computing regarding power wheelchair users.

3.2 Developing an Understanding of User Needs

This study began with interviews to explore the accessibility challenges faced by power wheelchair users when using their current mobile devices. These interviews focused on common activities that participants performed with their devices, the accessibility challenges they encountered, and the accessibility and usability tradeoffs between mobile devices and traditional PCs. Six interviews involved discussion only, while three included a design activity in which the participants created medium-fidelity prototypes of alternative input devices.

3.2.1 Participants in Technology Use Interviews

I interviewed nine power wheelchair users about their technology use habits. Participants were recruited through mailing lists and snowball sampling. Our participants were between the ages of 24 and 89, and had motor impairments that caused fatigue, tremor, or paralysis. The first six of these interviews were conducted remotely via phone or Skype. The final three interviews and design activities were conducted at the participants homes and at a spinal cord injury rehabilitation clinic. Participant profiles can be found in Table 3.1.

3.2.2 Procedure for Technology Use Interviews

I conducted nine semi-structured interviews (four in-person and five via phone and video chat). Participants were asked to describe how they interacted with mobile devices and PCs during work, school, and leisure activities. Since our interviews focused on computing tasks using mobile devices, we did not ask directly about activities of daily living (ADL). Participants did discuss ADLs in relation to the

Table 3.1: Profiles for wheelchair users in the study.

PID	Sex/Age	Description of Abilities
P1	M, 89	Tremor and reduced hand strength
P2*	F, 30	Upper body mobility limited to one finger on her right hand. Easily fatigued.
P3+*	F, 41	Has difficulty with fine motor movements due to numbness, pain, and fatigue.
P4+*	M, 52	Able to raise and lower left arm, move left index finger. Left arm is contracted.
P5	F, 25	Limited strength and gross motor ability.
P6	F, 45	Did not disclose.
P7*	M, 24	Complete paralysis from the neck down. Uses sip-and-puff to control wheelchair.
P8+*	M, 26	Paralysis from neck down. Able to move right shoulder and slightly lift left arm. Uses head switch array to control wheelchair.
P9*	F, 18	Able to move arms and torso. Difficulty with fine motor functions in wrists and hands. Operates devices with loosely clenched fists.
P10+	M, DNS	Paralysis and difficulty with gross motor movements. Favors left side.
P11+	M, 20	Severely limited hand control. Able to move arms, but arms are contracted and bent.
P12+	M, 39	Paralysis from the neck down. Uses micro joystick with his chin to operate wheelchair.
P13+	M, 31	Able to move both arms below shoulder. Difficulty with fine motor functions. Operates devices with loosely clenched fists.

devices they used to assist in completing those activities. Participants were asked to identify mobile and personal computing devices that they interacted with on a regular basis, and to describe challenges they encountered while interacting with those devices. Finally, I asked participants about the challenges they faced when using computing devices. We discussed device characteristics that they would find useful or desirable for users with mobility impairments who use wheelchairs.

Participants identified applications that they used or were interested in using, based on a list of application categories derived from popular online app stores: iOS App Store, the Mac App Store, and the Google Play store. Each store listed apps in 20-25 categories, which were condensed into five high-level categories. The resulting classifications were media consumption, media creation, communication, access to information, and tasks/organization. These categories and descriptions are shown in table 3.2. Using these categories allowed me to systematically identify desirable computing tasks based on users goals rather than specific technological constraints.

Prototyping Activity

During three of the interviews, I worked collaboratively with the participant on a medium-fidelity prototyping activity. We used a MaKey MaKey micro-controller board (Figure 3.1) to demonstrate how a wheelchair might be augmented with additional inputs for controlling common mobile device and media functions, without altering the existing control of the wheelchair. The MaKey MaKey enables its users to quickly prototype button-based interfaces using various materials, such as metal, conductive plastic, or clay, which can be activated using touch. I demonstrated how the MaKey MaKey can be used to create controls using household objects such as screws, aluminum foil, and Play-Doh.

Table 3.2: Mobile app classifications, based on popular app categories, used to focus discussions in formative interviews.

Classification	Description	App Categories
Consumption	One of the major activities performed using mobile technology is media consumption. This category refers to how we view or use digital media.	Books and Magazines, Music, Video, Games
Creation	A growing category of applications for mobile devices and personal electronics is creation. These applications allow users to create their own digital and print media at low cost.	Photography, Music, Video, Books and Magazines, Graphics and Design
Communication	The category where mobile devices really excel is in their capability to support communication.	Email, phone, chat, text, Social Networking
Access to Information	This category is similar to consumption, however in this category we focus on more factual content and knowledge rather than creative media.	Education, Finance, Health and Fitness, News, Sports, Shopping, Travel, Utilities, Weather
Tasks and Organization	This category is all about applications that help to achieve a certain goal or complete activities on the go. This includes questions specifically about finance, shopping, navigation, and productivity.	Finance, Shopping, Navigation, Productivity (Reminders, Organization, Automation, etc.)

After the demonstration, I asked participants to consider how they might use the MaKey MaKey to design a user interface for their own wheelchair to support any of the five application categories from Table 3.2, e.g., to design a digital music player. Participants were encouraged to think about and comment on the size, shape, color, material, and location of these inputs, in addition to their function.

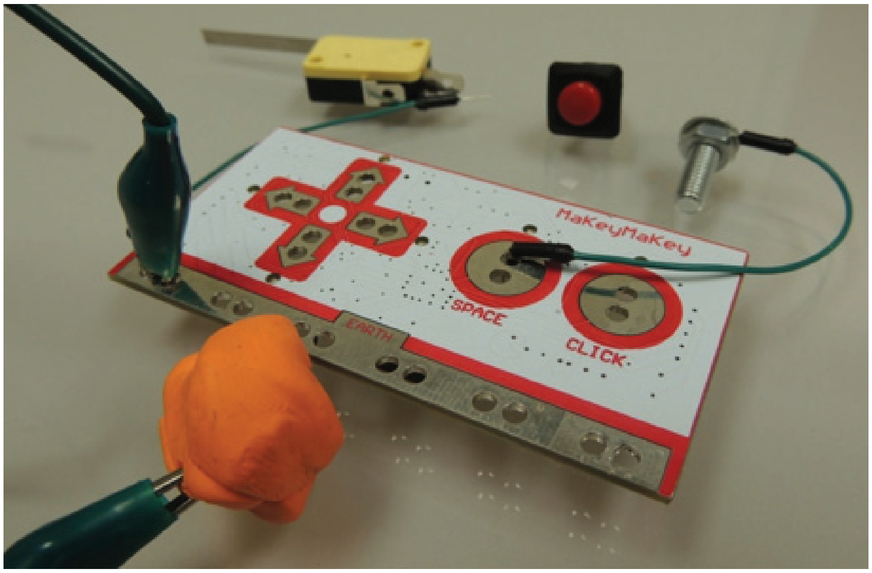


Figure 3.1: Medium-fidelity prototype created with the MaKey MaKey microcontroller board and various button materials.

3.2.3 Findings from Technology Use Interviews

Field notes from the interviews were coded to identify themes related to the devices used and the reasons given for choosing one device over another. All participants identified their favorite and least favorite attributes of existing mobile devices that they had used; three of the participants also provided feedback on the prototype designs that they created.

Accessibility of Current Devices

All participants described some difficulties when using their existing devices due to their limited arm and finger strength. Participants also found devices difficult to reach, and often required assistance from a caregiver when stowing, retrieving, or re-positioning a device. Participants also had difficulty managing multiple devices.

Three important design guidelines were identified for creating mobile devices that would be more accessible to our user group. First, size and weight are important.

Devices should be lightweight whenever possible so that they can be manipulated by individuals with limited arm and finger strength. Second, since participants often had difficulty using the device touch screen or buttons, devices could be made more accessible by allowing alternative input, such as speech recognition or head movements, as an alternative to hand- and finger-based interaction. Third, participants were concerned about how devices would add to the profile of their wheelchair, as any increase in the size of the wheelchair could make it more difficult for the wheelchair user to navigate. Participants were therefore interested in low-profile add-ons, and in using existing empty space on their wheelchair, such as under the seat or behind the seat back, to carry technology.

Prototype Designs

Using a case-based approach combined with the rapid prototyping toolset of the MaKey MaKey allowed me to look closely at each participant and their choices, while maintaining consideration for their individual abilities.

Each of the participants who completed the design activity (P7–P9; see Table 3.1) exhibited differing levels of mobility, and each designed distinct user interfaces. Both P7 and P8 have very limited mobility, which requires them to use their heads to operate their wheelchairs. P7 uses a sip and puff interface to control his wheelchair, which allows him to operate the drive and mode functions of his chair by breathing into a straw. P8 uses a head array, which features directional controls around his head allowing him to operate his wheelchair by hitting three different switches around his head using head movements. P9 has much more range of motion. She has difficulty primarily with fine motor, grip, and strength activities, but is able to move her arms.

Perhaps due to their limited mobility, P7 and P8 gravitated toward single-button

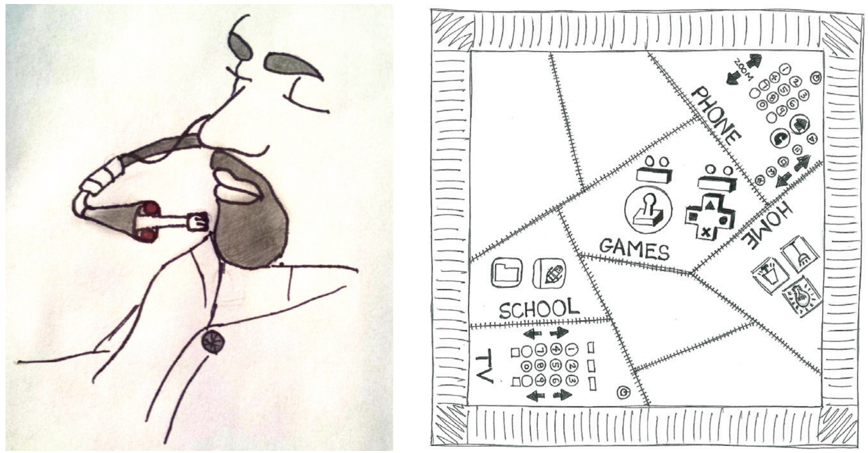


Figure 3.2: New input devices proposed by participants. (Left) P7, who is paralyzed below the neck, designed extra inputs around the straw of his sip and puff control. (Right) P9 designed a wearable quilt, containing conductive fabric controls for devices and applications at school and home.

interfaces during the design activity. These designs used a single button to move a cursor through a list of options (Figure 3.2). They preferred these designs due to their limited range of motion, and their familiarity with controlling their wheelchair using switches. When asked whether they would use a more complex user interface, both P7 and P8 stated that they were concerned about the reliability of the motions required to activate a larger number of switches.

P9, who had a much higher range of motion than her peers, preferred designs that involved multiple controls spread out around her wheelchair: one button near the wheelchairs joystick, two buttons on the armrest, and one button on the base of the wheelchair below the seat. P9 also suggested creating a blanket that could be draped over her body, and which could be used to control different devices that could be plugged into the blanket (Figure 3.2).

An individuals abilities strongly influence their preferred control layout. Participants with less motor control (P7, P8) wanted to control multiple tasks using a single, multi-function button, while the participant with better motor control (P9) designed an interface with more controls. However, in all three cases, participants were willing to use multi-function buttons if appropriate visual feedback was available.

3.3 Designing Prototype Natural User Interfaces for Wheelchair Users

Doctors, therapists, and family members are frequently involved in the process of choosing a wheelchair that is suitable for an individuals needs, and ensuring that the wheelchair has the appropriate accessibility features. Additionally, therapists and rehabilitation technicians often have knowledge and experience regarding multiple types of motor impairments, while wheelchair users are likely to be most familiar with their own condition. These therapists and caregivers are important secondary stakeholders because they are deeply involved in the selection and maintenance of the technology. I conducted a series of focus group design sessions with clinical staff at a local spinal cord rehabilitation center. Problems, opportunities, and designs from the formative interviews were used to guide focus group discussion.

3.3.1 Focus Groups: Participants and Procedures

Thirty physical therapists, occupational therapists, and rehabilitation technicians participated in the focus groups. Focus group participants were invited to attend multiple sessions, although not all participants were able to. Table 3.3 summarizes the participants and session topics.

There were four focus group sessions, each focusing on a specific design activity. Wheelchair users at the clinic could not typically attend focus groups due to schedule conflicts with their rehab appointments. Personas based on our interview participants

Table 3.3: Discussion topics, participants, and repeat participants for each focus group session.

Topic	Number of Occupational Therapists	Number of Physical Therapists	Number of Rehab Technicians	Number of Repeat Participants
Phone	3	7	1	
Game Controller	3	7	5	
Input Modes	3	4	5	10
Output Modes	3	4	5	9

(see Table 3.1) were created for use during the focus groups in lieu of actual wheelchair users. Focus group participants designed solutions to meet the needs and abilities of these personas (Figure 3.3). During the early sessions, participants were conservative with their designs. To promote creativity, technology probes were included in a subset of sessions, to show participants a real emerging technology that may be relevant to their interests. The four sessions covered the following topics:

Focus Group 1: Phone Design

Participants were asked to design inputs for a mobile phone application for two different personas, one with head movement only, and one with limited arm and head movement. Eleven rehab therapists participated in this session, and worked as a single design group.

Focus Group 2: Game Controller

Participants designed a game controller, forcing them to design for the multiple inputs that could be needed to play different games. Seventeen participants attended this session; participants were separated into three groups.

Figure 3.3: Focus groups with therapists and rehabilitation technicians regarding possible layouts and functionality for chairable interfaces. Participants used sticky notes to indicate the location, size, and type of inputs.

Focus Group 3: Input Modes

In this session, participants discussed different input modalities. Participants were shown a video of the Worldkit system (Xiao et al., 2013) as an example of an anywhere interface, and were encouraged to think about a variety of input modes. Twelve people participated in this session; participants were divided into two groups, each with a different persona.

Focus Group 4: Output Modes

Participants explored different visual output modalities for a wheelchair-based computing interface. Participants were shown videos of Skinput (Harrison et al., 2010) and Google Glass to help generate ideas of non-traditional feedback modes. Twelve people participated in this session; nine had participated in at least one previous session. For this session, participants were divided into three groups, each receiving one persona.

3.3.2 Findings from Prototyping Focus Groups

The focus group sessions provided insight about the placement and usefulness of various input and output devices. Each group identified unique design concerns relating to their topic.

Focus Group 1: Phone Design

This group designed a traditional switch-based interface with very few buttons (three or fewer), for both personas. These buttons were assigned to menu navigation and selection only. While the designs created in this session were conservative, participants provided useful insight about button design. Specifically, the focus group members designed the button layouts and sizing to match the personas motor capabilities: larger buttons were placed near the shoulders and elbows on the seat back, where people tend to have less fine motor control, while smaller buttons were placed near the fingers and on the arm rests, since fine motor actions would be more likely there.

Focus Group 2: Game Controller

Participants in the second focus group created more varied designs. For example, one design added buttons to a head array to provide 4-way navigation, while other designs included using a trackball or the wheelchairs joystick. Some participants raised concerns about the complexity of these interfaces, and others raised concerns about accidentally activating these controls.

Focus Group 3: Input Modes

The Worldkit (Xiao et al., 2013) demonstration helped participants to think about designing interactions within the system, rather than focusing only on button layout.

In this session, participants created solutions to enable the user to interact with multiple kinds of applications or games. One group attempted to place inputs in every area that the user could reach. This group chose input types based on the users mobility in that location: for example, the team placed a trackball under the users left arm, because that user had sufficient gross motor function to move the trackball. This group also placed pressure switches behind the users shoulder to take advantage of the reliable but imprecise movement in that body region.

Focus Group 4: Output Modes

Members of this focus group were introduced to wearable projection, via Skinput (Harrison et al., 2010), and head-mounted displays, via Google Glass. Focus group participants were most excited about projected output, and each group created at least one design featuring projection. The design groups considered the privacy implications of a projected display, and took different design stances to address this concern: two groups used projection on nearby, semi-private surfaces such as the users body or a lap tray, while the third group designed a shareable projection that could be aimed at nearby surfaces. All three groups were interested in a head-mounted display for presenting private information. One group designed an output system that combined a head-mounted display for personal use with a pico-projector for sharing information with others.

Focus group members discussed using the existing display on a power wheelchair to present information from the users phone or tablet. This design raised concerns about whether the user would have to deactivate the wheelchairs drive or seat controls to interact with the mobile devices, which might be too complicated. After discussing this topic, the group chose to add an extra screen that was separate from the wheelchairs controls.

Participants expressed several concerns about the safety, usefulness, and visibility of the proposed output devices. Specifically, there were concerns about distraction caused by using the displays while driving the wheelchair and concerns about unusual devices such as Google Glass causing unwanted attention and encouraging device theft. Participants also questioned whether each of the output devices would be bright enough in outdoor environments.

Focus Group Summary

Overall, focus group participants generated a variety of input and output form factors. As in the initial interviews, focus group participants agreed that input and output could be placed around the wheelchair, as long as the size and type of the input matched both its location and the users range of motion in that body area. Focus group members were excited about new display technologies, but raised concerns about potential distraction and conspicuousness.

3.4 Evaluating End-User Configuration Preferences

While the focus groups generated many unique ideas, the design groups were primarily made up of clinical workers, rather than wheelchair users. Ideas generated during the focus group sessions were presented to seven power wheelchair users to verify the feedback received from clinicians. Of these participants, one had previously participated in a focus group meeting, and three had participated in formative interviews; the remaining participants were new to this research.

3.4.1 Procedures for Configuration Interviews

The interview discussion focused on four key design issues that arose during the formative interviews and focus groups: choosing form factors for a computing device, identifying potential input areas on and around their wheelchairs, choosing input and output modes, and assembling a complete design from their chosen inputs and outputs.

Chairable Form Factors

Participants were shown design sketches for four possible chairable technologies, based on design ideas from previous sessions, and were asked to compare them:

1. Integrated controls: buttons, switches, or touch pads that are permanently installed on the wheelchair;

2. Gestures: functions are controlled primarily by gestures, including hand gestures on a surface or in the air, body gestures, facial expressions, and eye gaze;

3. Removable controls: control panels, trays, or textiles that can be added to or removed from the wheelchair;

4. Wearables: clothing or accessories with embedded computing capabilities that could be worn on the body.

Reachable Areas

Previous design sessions identified various reachable regions for placing controls. However, which areas are possible or comfortable to reach might vary by individual. To identify reachable areas, participants were shown an illustration of potentially reachable areas on a power wheelchair (those areas are highlighted in Figure 3.4). Participants were asked to rate their ability to reach each labeled area on their own wheelchairs using the following scale: excellent, good, possible but difficult, or not possible.

Output Modes

Participants were asked to rank their preferences between three output modes, derived from our prior sessions:

1. Projector: A pico projector can display images on the body, on the wheelchair, or on surfaces in the area surrounding the wheelchair.

2. Add-on screens: Flat panel display screens may be attached or removed from the wheelchair frame.

3. Head-mounted display: Visual feedback can be presented on a micro display in the users field of vision.

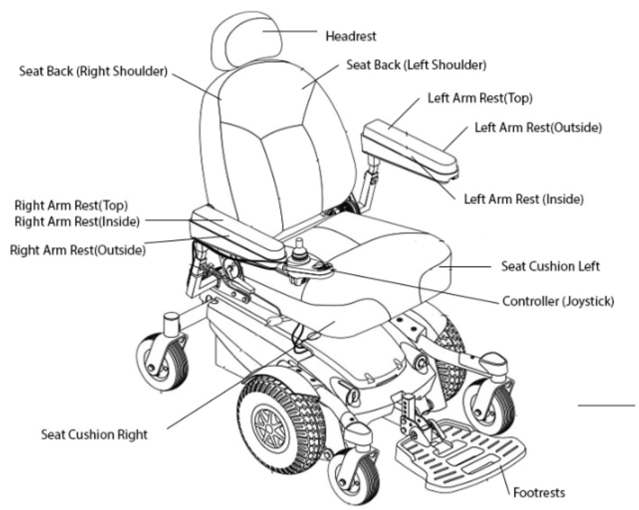
Ideal Wheelchair Layout

After participants finished ranking input and output options, they were asked to select appropriate locations for their preferred input and outputs using a sample diagram (Figure 3.4) in order to create their ideal configuration. Participants were allowed to place multiple input and output devices at the same location, or to place duplicate devices in multiple locations.

Inputs

Outputs

Locations



Head Rest	____________	**Controller (Joystick)**	____________
Seat Back Left Shoulder	____________	**Footrests**	____________
Seat Back Right Shoulder	____________		
Left Arm Rest (top)	____________		
Left Arm Rest (inside)	____________		
Left Arm Rest (outside)	____________		
Right Arm Rest (top)	____________		
Right Arm Rest(inside)	____________		
Right Arm Ret (outside)	____________		
Seat Cushion Left	____________		
Seat Cushion Right	____________		

Figure 3.4: Sample Ideal Configuration Worksheet

3.4.2 Findings from Configuration Interviews

Findings from the configuration interviews are presented in four subsections, based on the interview format: chairable input form-factors, reachable areas around the wheelchair, output modes, and ideal configurations.

Chairable Form Factors

Overall, participants preferred the integrated and wearable input options. Integrated controls were chosen as the first or second choice by four participants. Participants felt that integrated inputs would be easy to use because they could be placed in areas that were accessible to them without adding an additional device. Three participants chose wearable inputs as their top choice, but wanted them to be inconspicuous. Two participants wanted inputs placed on their chest, which would be easy for them to reach.

Removable controls, such as interactive wheelchair trays, were less popular, but appealed to users who used trays previously. For example, one participant requested a removable tray to hold his laptop. Participants were also interested in the idea of interactive textiles or blankets, as they would be easy to carry, easy to add or remove, and unobtrusive (similar to Figure 3.2). One participant preferred the idea of an interactive fabric surface on her lap instead of an interactive tray, which might be too rigid or get in her way.

Two participants chose gesture input as their top choice because they felt it was the most interesting of the options and might be fun to use. One of these participants was interested in using gestures to play games, and was especially interested in gesture interfaces that could be operated with only one hand. However, four participants ranked gestures as their least favorite option: two were simply uninterested, while the other two felt that they lacked the fine motor control necessary to perform gestures.

Reachable Areas

Unsurprisingly, reachable areas depended on individual ability. However, several areas were consistently rated as being reachable, including the areas around the wheelchair armrests and around the wheelchair joystick.

Output Modes

Six of the seven participants ranked the head-mounted display as their first or second choice. They believed that a head-mounted display would be easy to see, unobtrusive, and always available. However, participants were concerned that a head-mounted display would be conspicuous, or that it could be stolen or fall off. Two participants liked the functionality of the head-mounted display, but were unwilling to wear a device on their head.

Add-on screens were popular, likely because most participants either had a small screen embedded in their wheelchair controller or had previously seen a smartphone or tablet mounted on a wheelchair.

Several participants were skeptical about using a projected interface with their wheelchair, and four of the seven participants said that projected output was their least favorite choice. These participants had concerns about the brightness of the display, especially while outside. However, participants thought that projection could be useful when indoors, or when another screen or surface was not available (i.e., projecting onto their lap). Participants felt that a projected display would be lightweight, and liked the idea of a movable display. However, few participants indicated they would use projected output exclusively.

Ideal Wheelchair Layout

Each participant chose their preferred user interface components and arranged them on the wheelchair diagram. Participants tended to place inputs and outputs around the armrests of the chair regardless of other reachable areas. Most participants placed output devices directly adjacent to input devices, as these areas were easily reachable and visible. All participants added multiple outputs to their designs. Many participants used a head-mounted display in combination with a projector. All seven participants added integrated controls to at least one area of their wheelchair.

3.5 Developing the Gest-Rest Family

Using the feedback from the technology use interviews, focus groups, and configuration interviews, I developed the Gest-Rest Family, a set of prototype input devices for the armrest of a power wheelchair. The ideal wheelchair layout described by power wheelchair users involved integrated inputs on the armrest of the wheelchair. The Gest-Rest family was designed to also keep in mind the accessibility challenges described during the technology interviews. As such, these prototype devices offer options for interaction through mechanical switch, touch, and pressure-based inputs. A Gest-Rest enables users to perform hand and finger gestures directly on the armrest of their power wheelchair. All Gest-Rest prototypes are meant to attach to or replace the existing armrest of wheelchair. As indicated in the previous section, power wheelchair users stated that integrating technology into form factors that could be worn on the body or integrated with the wheelchair, especially the armrests, was desirable.

3.5.1 Gest-Rest Hardware

The Gest-Rest family includes 5 prototype devices (Figure 3.5). I used a combination of mechanical momentary switches, Force Sensitive Resistors (FSRs), and capacitive touch sensors to create these prototypes. Each Gest-Rest uses a different number or type of sensor. We created the single button, D-pad, FSR-12, FSR-16, and Touchscreen Gest-Rests to represent the different input types available for power wheelchair users. Each of the Gest-Rests have a similar interaction area of approximately 6cm x 6cm. This information is also summarized in Table 3.4. More detailed descriptions of these prototypes can be found in the original journal article (Carrington et al., 2016).

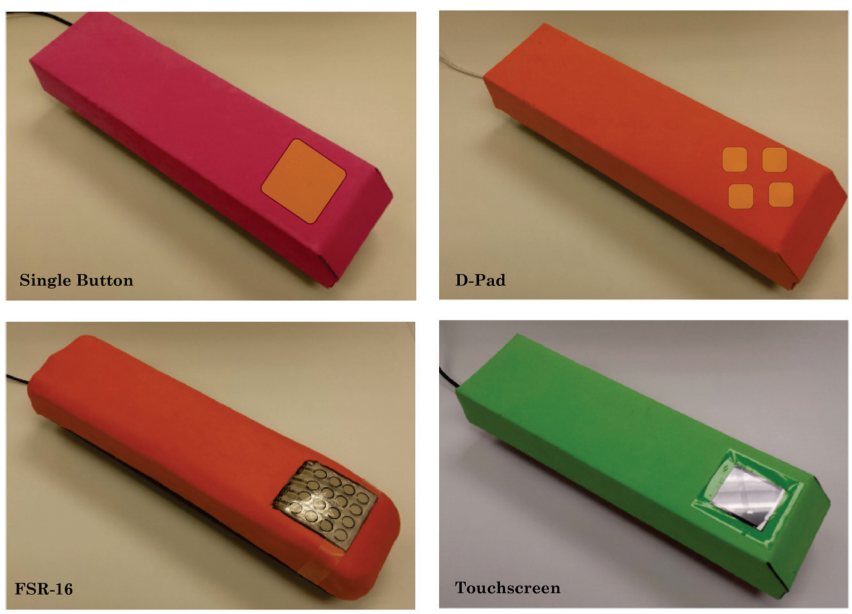


Figure 3.5: The Gest-Rest Family. Top left - Single Button using one mechanical switch. Top Right - D-pad which offers 4 mechanical switches arranged in a diamond shape. Bottom Left - FSR-16 which offers a 4 x 4 array of force sensitive resistors which act as a single touch surface. The FSR-12 is not shown but uses a 3 x 4 array of force sensitive resistors. Bottom Right - Touchscreen which offers a capacitive input surface.

Table 3.4: Summary of Gest-Rest Family Hardware.

Device	Input Type	Arduino	Size
Single Button	6cm x 6cm Momentary Switch	Nano	6cm x 6cm
D-Pad	4 1.26cm Momentary switches	Nano	6cm x 6cm
FSR-12	3 x 4 grid of Flexiforce FSRs	Mega	6cm x 8cm
FSR-16	4 x 4 grid of Flexiforce FSRs	Nano	6cm x 6cm
Touchscreen	Adafruit 2.8in TFT touchscreen	Uno	4.5cm x 5.7cm

Testing Mounts

Each of the prototypes constructed after the Gest-Rest FSR-12, included a mount for an 8020 aluminum extrusion, testing frame. The testing frame allowed testing of the prototype armrests without removing participants armrests for the study session. These mounts were laser cut from Masonite using a ULS VLS 6.0 system. Each of these mounts was created to provide options during data collection so that the armrest could be properly positioned. Additionally, each prototype was covered with a 1/16 thick sheet of EVA foam for user comfort. Each of the prototypes and mounts are shown in Figure 3.5 and Figure 3.6.

3.5.2 Controller and Visualization Software

The Gest-Rest prototype hardware is controlled by an Arduino application. This application measures the state of each sensor and passes it to the computer via a serial port. For the Single Button and D-pad the input had X and Y coordinates for each button. For the FSR-12, FSR-16, and touchscreen the Arduino application

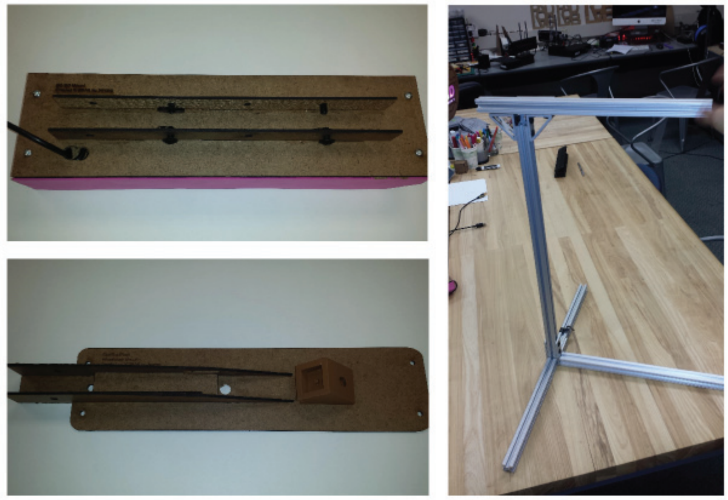


Figure 3.6: Gest-Rest Mounting Hardware. Top left Freestanding armrest mount, Bottom Left Wheelchair armrest mount, Right Freestanding armrest structure. For the experiments each Gest-Rest was attached to the armrest mount positioned directly next to their existing armrest.

handles all of the calculations needed to determine the center of mass for the gesture across the surface as well as formatting the raw data values from the sensors. The center point is calculated using the geometric center of mass of the touches. I used the center of mass rather than individual touch points in order to support different hand poses. Using the center point allows users to interact with their whole hand or arm instead of requiring a finger or small pointing tool. For this visualization, pressure input from the FSR-12 and FSR-16 was used to weight the touch points so that the center point also represented the center of force for interactions involving multiple touch points.

I created a second application in the Processing programming language to visualize the pressure applied to each sensor and to log the sensor values and timestamp every 30ms. This visualization software was the same for each of the hardware implementations (Figure 3.7).

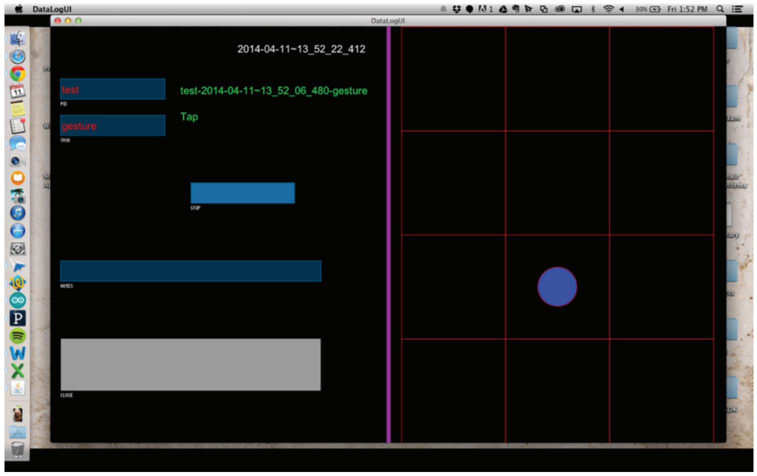


Figure 3.7: Visualization interface. Center of mass for a touch shown at the right (Blue Dot) This interface was presented to users via a 13 laptop screen and positioned so that the user could comfortably see the visual feedback and read the large text.

3.5.3 Gesture Set Design

The array of pressure sensors enables additional gestures beyond standard touch screen gestures, such as soft and hard presses. Furthermore, the shape of the armrest may afford different interactions than a touch screen, such as squeezing the edge of the armrest. I identified a set of 21 gestures, based on existing gesture sets for touch screen devices (Wu and Balakrishnan, 2003), which could be used on an interactive armrest. These gestures include standard tap or press gestures and directional swipes. I tested an additional five, force-sensitive, gestures designed specifically for an armrest interface. These gestures are all location and pressure independent and may be performed anywhere on the surface.

The set was divided into three categories 1) Tap or Press Gestures, 2) Directional Gestures, and 3) Pressure-Based Gestures. Multi-finger gestures were not included in this set, as they are often difficult to perform for individuals with motor impairments (Trewin et al., 2013). This gesture set is represents the intended gestures to be used with the Gest-Rest Family. Table 3.5 shows supported gestures for each Gest-Rest.

Table 3.5: Supported gestures for each Gest-Rest Device.

Gesture	Single	D-Pad	FSR-12	FSR-16	Touchscreen
Tap	✓	✓	✓	✓	✓
Double-Tap	✓	✓	✓	✓	✓
Triple-Tap	✓	✓	✓	✓	✓
Short-hold (1sec)	✓	✓	✓	✓	✓
Med-hold (3 sec)	✓	✓	✓	✓	✓
Long-hold (6 sec)	✓	✓	✓	✓	✓
Up, Down, Left, Right	–	✓	–	–	–
Flick (Up, Down, Left, Right)	–	–	✓	✓	✓
Swipe (Up, Down, Left, Right)	–	–	✓	✓	✓
Drag (Up, Down, Left, Right)	–	–	✓	✓	✓
Lift	✓	✓	✓	✓	✓
Roll	–	✓	✓	✓	✓
Rock	–	✓	✓	✓	✓
Squeeze	–	–	✓	✓	–
Punch	–	–	✓	✓	–

✓= Supported, – = Not-Supported

Tap or Press Gestures

Tap or press gestures can be performed anywhere on the surface and do not require the user to move their hand once they press down on the surface. There were three different types of taps and three different durations for holds, making a total of six gestures in this category.

- **Single Tap or Press.** This gesture was defined as a tap or press once on the surface. Taps and presses were treated similarly across the surface of the device.
- **Double Tap or Press.** This gesture was defined as tapping or pressing twice on the surface in succession.
- **Triple Tap or Press.** This gesture was defined as tapping or pressing three times on the surface in succession.
- **Short Press and Hold.** This gesture was defined as a press and hold for approximately one second.
- **Medium Press and Hold.** This gesture was defined as a press and hold for approximately three seconds.
- **Long Press and Hold.** This gesture was defined as a press and hold for approximately ten seconds.

Directional Gestures

Directional gestures were based on traditional touchscreen directional gestures (e.g., swipe and flick), but participants were able to use any part of their hand or arm to perform this gesture. I specified different gesture types based on the duration of the gesture. These gestures can be performed in four of the relative directions (e.g. up, down, left, and right). For directional gestures, users were allowed to define the speed at which they performed each type of gesture relative to the others. This meant a flick was faster than a swipe and a swipe was faster than a drag, however no specific duration was enforced.

- **Flick.** This gesture was defined as a quick sharp motion in the given direction after pressing down on the surface.
- **Swipe.** Sliding the hand or finger across the surface in the given direction.
- **Drag.** The drag gestures were similar to swipes however they were performed slower across the surface in the given directions.

Pressure-Based Gestures

These gestures were designed to use the pressure sensing capability of the Gest-Rest. They involved pressure applied by the whole hand, arm, or wrist. There were five gestures in this category.

- **Lift.** To perform this gesture the user would just lift their hand or arm from a rest position.
- **Roll.** To perform this gesture the user places the hand or wrist on the surface and rolling left or right then lift off.
- **Rock.** This gesture was similar to the roll gesture; however, in this case, a user is expected to roll the hand or arm left and right multiple times before lifting off of the surface.
- **Squeeze.** To perform this gesture the user needed to grip the outside edges of the armrest and squeeze, then release.
- **Punch.** To perform this gesture the user punched the surface.

3.6 Evaluation of the Gest-Rest Family

The evaluation of the Gest-Rest Family took place in two stages. The first was a formative evaluation of the first prototype, the Gest-Rest FSR-12. The second stage consisted of the development and comparative evaluation of the four additional prototypes. The details for each of these evaluations can be found in greater detail in the original journal article (Carrington et al., 2016). In the following sections, I will summarize the methods and lessons learned from this proof of concept development and evaluation process as they pertain to Chairable Computing.

3.6.1 Participant Procedures for Formative Evaluation

I followed slightly different protocols for participants using wheelchairs compared to therapists. The tasks and procedures used for each user group are described below.

Procedure for Wheelchair Users

Participants first completed a brief questionnaire about their background and their use of technology. Next, participants were given a brief introduction to the Gest-Rest and were able to try it out. The armrest was attached to a mount and positioned beside participants wheelchairs in the position of their existing armrest. Participants performed three tasks using the Gest-Rest FSR-12, a gesture rating task, menu selection task, and gesture invention task. The session took approximately one hour.

Procedure for Therapists

Therapists did not complete the full gesture rating and menu selection tasks. Instead they were introduced to the tasks and given an opportunity to attempt each gesture. They were asked to provide feedback about various gestures in the gesture set, and discuss potential benefits and obstacles that might occur when using this device. Participants also provided feedback about the usefulness of this Gest-Rest for participants with varying levels of motor ability.

3.6.2 Participant Procedures for Comparative Evaluation of the Gest-Rest Family

For the comparative study the same gesture-rating task from the formative study was performed with each of the Gest-Rests. Again slightly different protocols were used for participants using wheelchairs and therapists. The task and procedures used for each user group below.

Procedure for Wheelchair Users

Participants first completed a brief questionnaire about their background and their use of technology. Next, participants were given a brief introduction to the protocol. Each armrest was attached to a stand and positioned beside participants wheelchairs in the position of their existing armrest. Participants performed a gesture-rating task for each of the armrests. The same visualization software was used throughout for each of the prototypes. Each participant attempted each gesture at least three times. The study session took approximately 90 minutes. The gesture set for each of the Gest-Rest prototypes is described below:

- **Single-Button:** Participants were asked to perform the taps and hold gestures using this armrest. Participants were also asked to perform the lift gesture.
- **Directional-Pad (D-Pad):** Participants were asked to perform the taps and hold gestures as well as directional presses using the buttons (e.g. pressing the

left button for a left gesture) using this armrest. Participants were also asked to perform the rock, roll, and lift gestures.

- **Touchscreen:** Participants were asked to perform the full gesture set from the formative study using this armrest. This included taps and holds, directional, and special gestures (excluding squeeze and punch).

- **FSR-16:** Participants were asked to perform the full gesture set from the formative study using this armrest. This included all taps and holds, directional, and special gestures.

Procedure for Therapists

Therapists were first introduced to the Gest-Rest prototype and given a description of the gesture set. Next, they had an opportunity to test gestures using the prototype, but did not complete the full gesture rating activity. The therapists discussed and provided feedback about various gestures in the gesture set, and discussed potential benefits and obstacles that might occur when using this device. Participants also provided feedback about the usefulness of this Gest-Rest for participants with varying levels of motor ability.

3.7 Lessons Learned from the Gest-Rest Family

The results from both the formative and comparative evaluations are condensed here to illustrate the main findings from this exploration.

3.7.1 Acceptance of Wheelchair-based Form Factor

Taking into consideration both the formative and comparative studies several important considerations emerge regarding the form factor of integrated armrest controls for chairable interfaces. Across all of these interaction types both wheelchair users and therapists discussed the benefits of having the input device integrated into the armrest. All participants described an increased sense of independence since there would be no need for assistance in positioning the device for use (e.g. a caregiver setting up a laptop or a phone). During the interviews wheelchair users described accidents such as dropping a phone or losing a button, which would be far less likely with the integrated form factor. In addition to comparisons between the traditional removable switches or touchscreens, participants also identified some unique benefits the armrest has to offer regarding physical support while interacting with devices. Therapists described how a wheelchair user who might have difficulty with precise targeting could use the armrest to stabilize themselves while interacting with the surface. Finally, consistent with our previous findings for Chairable Computing (Carrington et al., 2014b), participants (therapists and wheelchair users) were pleased by the always-available nature an integrated form factor provides.

3.7.2 Potential Applications

User-Invented Gestures

One strong point of having the form-factor of the arm rest was that people could invent gestures that would work specifically for them when attempting to accomplish tasks. For instance, one participant wanted a gesture along the edge of the device to activate his smartphone as pressing the power button on the device was difficult. Another simply wanted to be able to swipe using his palm instead of having to use one finger. These user-invented gestures that were generated for the Gest-Rest prototypes do not need to be limited to just that device. It is conceivable that these gestures could work on other gesture-based input devices.

Applications of the Gest-Rest

Participants identified potential uses for the Gest-Rest. Power wheelchair users were especially interested in using this device as a command center to operate environmental controls (lights, fans, doors, etc.) around the home. Wheelchair users also mentioned using this device as an alternative for speech input as it would be always available to them without needing someone to set up the software.

Therapists also suggested that an input device of this type would be useful for access to many remote controlled appliances around the house. One therapist suggested it as an alternative to speech software solutions to provide access to keyboard and mouse functions on a PC. Therapists appreciated that the Gest-Rest could be used in addition to the traditional wheelchair joystick, as it would enable users to perform additional functions without having to switch modes on the device.

3.7.3 Lessons Learned About Input Types

The first input prototype that was tested was the FSR-12, which was used in the formative study to learn more about interacting with and armrest-based input. I observed the way that people wanted to interact with that device and the interaction styles people compared it to. Through the comparative evaluations, I wanted to gauge the perception of what could be done using a differing number of sensor resolution in this case representing one, four, sixteen, and hundreds. In addition to the gesture set, the characteristics and tradeoffs participants perceived while interacting with the different resolution devices are presented.

Comparing the different input types offered by the Gest-Rest prototypes lessons revealed findings in four areas: 1) the tactile or haptic experience, 2) sensor resolution, 3) force-sensitive input, and 4) customization and personalization. These findings are described briefly below. More details can be found in (Carrington et al., 2016).

Tactile or Haptic Experience. Different prototypes offered a different tactile experience while interacting with the input. In particular, the difference between the flat single-button and the raised D-Pad. Different participants had reacted differently to raised buttons one participant found it easier to use while another stated they required more effort. Neither the touchscreen or FSR-16 provides the haptic feedback of pressing a physical button, however both participants preferred the FSR-16. Discussions with the therapists revealed that patients with sensory deficits may have increased difficulty feeling whether either the single-button or the D-Pad buttons were pressed. Therapists suggested providing additional feedback on the device such as audio or visual feedback. These concerns were not raised for the FSR-16 or the touchscreen as it was assumed that these were sensitive enough that the person would not need to concentrate on how hard they were pressing down.

Sensor Resolution. The number of sensors and the resolution of the sensors seemed to significantly influence how participants perceived the inputs. First, during the sessions with wheelchair users, I observed a preference for the more continuous inputs (FSR and Touchscreen). A button affords to be pushed and in general people only think to push one at a time. This concept of discreet buttons/sensors came up during the session with P2. He stated that it might be difficult to push just one of the FSR-16 circles, however, interacting with the full surface all at once would be fine. This was confirmed by a similar comment during a session with the therapists.

Although they were informed that the FSR-16 was essentially one big sensor, they perceived it as a set of buttons. Two therapists asked if some of the sensors on the FSR-16 could be grouped together to make it easier to press certain areas. They were interested in how the sensor pad could be reconfigured. For the touchscreen, participants were asked if they would want to reconfigure it in a similar way but the reply was that it seemed unnecessary. The higher the resolution of the input the more likely it was to be perceived as one continuous input surface rather than discreet buttons.

Force Sensitive Input. The FSR-16 performed very well with regard to versatility. Wheelchair users found it to be very similar to a touchscreen and it ranked highly in ease of use and responsiveness. For therapists, it was ranked highest in terms of versatility while remaining very responsive and easy to use. The FSR Gest-Rest can be used with any part of the hand or arm, via tools, and through various materials. Although the touchscreen was the most familiar input type for participants given previous experience with smartphones, the same challenges associated with using capacitive touchscreens with different parts of the hand, or using tools, persist in this form factor. The versatility of the FSR-16 was especially appealing to occupational therapists since they felt that they could now customize other surfaces or tools on top of this Gest-Rest, if needed, to support their patients (e.g. a brace on the hand would not interfere with the input).

Customization/Personalization. Customization is a very important consideration especially given the individual differences of this user population. One of the limitations of the single button and D-pad Gest-Rests was that these two Gest-Rests are static in that once the buttons are placed they must be manually removed to reconfigure. The FSR and Touchscreen Gest-Rests can be reconfigured using software without modifying the hardware. Each of these devices has their strengths, which have been identified by the comparative evaluation. Force sensitive input does reduce some of the limitations of capacitive touch, however familiarity was very important and the higher resolution of the capacitive touchscreen should be acknowledged. Thus, a family of devices may be used to support the need for both static and dynamic interactions.

3.8 Considerations for Power Wheelchair Users

Most current power wheelchair interfaces are similar, providing a small set of buttons, and possibly a joystick, at the end of one armrest. Research and development described in this chapter asked participants to envision wheelchair user interfaces that were substantially different. While participants came up with many different ideas, several themes reappeared repeatedly throughout this research.

The following are five priorities to consider when designing chairable devices for power wheelchair users:

1) **Always-on and Always Available.** In order to provide the most utility to users, the chairable device should be independently accessible and always available to the user. Activation and set up of devices often required assistance and therefore could not easily be used independently. In the case of the Gest-Rest, the device's positioning was chosen to maximize the availability of the device for wheelchair users to access independently.

2) **Maintain wheelchair form factor.** Choosing an appropriate power wheelchair is a complex process that involves detailed assessments of the intended users abilities, medical factors, and environment. This choice often involves trade-offs between the dimensions of the chair: if the chair is too wide, it wont fit through doorways, or may not properly support the user. If the seat is too high, the user may risk falling or may have difficulty using dining tables and desks. Participants main concern when adding technology to wheelchairs was changing the chairs shape. The armrest form factor of the Gest-Rest was well-received by both wheelchair users and therapists as it would not stand out or get in the way of other tasks any more than their usual armrest would.

3) **Different controls for different body regions.** Participants varied significantly in their range of motion: some were limited to minor movements, while others could reach many areas on or around the wheelchair. However, participants commonly noted that controls should match the area within the users range of motion and the body part that will actuate it. Controls near the users fingertips can be small, while controls near the users shoulders must be larger. The com-

parison of different input types also revealed that certain sensory deficits are also important to consider when choosing controls. The customization that certain input types offer can lead to more universal input designs to meet the needs of multiple users with the same (base) device.

4) **Familiarity to existing solutions.** While some participants were excited about new input and output modes, participants (and especially therapists) tended to favor simple interfaces similar to existing switch interfaces. While such controls may be less efficient, participants considered them to be more reliable and thus desirable. Simple switch controls may be provided as backup to these new interfaces. In addition, the touchscreen Gest-Rest was ranked highly primarily due to it's familliarity to mobile touchscreen devices.

5) **Robustness.** Robustness to diverse locations, weather conditions, and contexts was important to our participants. For example, participants were intrigued by the flexibility of a projected display, but doubtful that such a display would be useful in all lighting or weather conditions. This consideration is also evident from the perspective of always-available inputs (Morris et al., 2011). In order for inputs to be always available they need to be able to operate in changing environmental conditions. In much the same way body-worn devices travel with the user, designers should consider that the wheelchair also travels with the user as their primary means of mobility.

3.9 Chapter Summary

This chapter described research to understand power wheelchair users needs and preferences regarding current and new mobile computing devices and techniques. The results of a multi-part user study were presented demonstrating accessibility challenges and prototyping opportunities for future solutions. THe Gest-Rest family was developed as a prototype instantiation of power wheelchair users' preferences. The Gest-Rest prototypes were then utilized in a comparative evaluation aimed at understanding more about different input techniques. Finally, a set of five considerations for designing mobile solutions for power wheelchair users was discussed. Those considerations focus on maximizing independent access and availability despite more severe motor limitations. Those considerations are best realized through power wheelchair-attached devices.

Chapter 4

Understanding Opportunities for Wheelchair Athletes

4.1 Introduction

In the previous chapter, we identified five priorities for designing chairable interactions and devices. Those findings were based on a multi-part user study with power wheelchair users. In this chapter, I discuss research conducted with wheelchair athletes and wheelchair basketball players. In contrast to the previous chapter, this chapter focuses primarily on manual wheelchair users and explores a different application, wheelchair sports and physical activity. While the population and application are different the focus of this dissertation is on designing for people who use wheelchairs. The following sections will describe research aimed at understanding the needs and challenges of manual wheelchair users regarding technology use for fitness and physical activity.

This chapter begins with a discussion of fitness and the concept referred to as the quantified self. I provide a discussion of related literature regarding fitness technologies for people with disabilities. Next, I describe exploratory research on the accessibility of consumer available fitness tracking solutions and describe my exploration into wheelchair basketball. I will conclude the chapter with a discussion of the five priorities for designing *chairables*, identified in the previous chapter, as they apply to this population of wheelchair users and manual wheelchairs for sports.

4.2 Fitness and Quantified Self

There has been a rising popularity in wearable devices for fitness over the past few years which has led to fitness devices accounting for almost half of consumer wearable devices (Carrington et al., 2015). This emphasis on fitness devices has also led to more discussions of the role that technology can play in people's everyday lives. Wearable fitness devices have been at the center of many of these conversations as they provide a means for people to monitor, review, and manage their own data regarding their health and fitness. This practice of self-tracking and quantification is referred to as the Quantified Self.

To begin my exploration of this space for wheelchair users I conducted a small interview study to learn more about the landscape of wearable fitness technologies for people who use wheelchairs. Before I discuss the results of that study, I will briefly describe related work in the areas of wearable fitness technologies and quantified self.

4.2.1 Wearable Fitness Technology

There is a wide range of wearable devices that are being used to track fitness. One of the most common examples is a wearable pedometer. Pedometers are used to record a step count and have been used to improve participation in physical activities (Bravata et al., 2007; Chan et al., 2004). Wearable fitness devices often capture this information and more. Many of the commercially available wearable fitness devices such as the Fitbit Flex and Nike+ Fuelband, are able to track information such as step count, calorie expenditure, and overall physical activity by tracking motion.

These devices are well suited to activities such as running and walking. However, other types of exercises have been tracked using wearable systems. The Recofit system, created by Morris et al. (2014), uses an armband capture the repetitive motions inherent to strength training. This makes it possible to count repetitions when lifting weights or doing stretches.

Many types of fitness-related information can be captured either using a single device or through multiple devices. The Microsoft Band is able to measure many details such as distance, calories burned, motion activity, sleep activity, heart rate, steps taken, and skin temperature from a single device. In contrast, people also may use multiple devices to track these features. See Section 5.3 for an examination of current trends in wearable fitness technology which represents the landscape of available sensing and applications.

4.2.2 Reflecting on Fitness with Quantified Self

Inherent to self-tracking, there is also the need to view or report the data that is being collected. Reports of this data can be used for multiple purposes including understanding one's habits and influencing behavior change. The Quantified Self (QS) describes the technology movement focused around using tracked physical activity and data about one's habits to enhance an understanding of one's own habits. The notion is that, through reflection on this data, a person can improve their habits and health (Patel et al., 2015).

Participation in self-tracking and monitoring activities can have several motivations. Some of the most common reasons for self-tracking and monitoring are for behavior change, curiosity, and self-discovery. MacLeod et al. (2013) discussed motivations and opportunities for personal informatics to be used by people with chronic illnesses. They described potential disparities between the presumed motivation of behavior change and the actual motivation of users to self-track. In this instance, an understanding and control over their health data motivated users to use self-tracking devices. People wanted to understand the effectiveness of their treatments. Whooley et al. (2014) described the integration of multiple data sources to identify correlations between actions such as sleep and cognitive performance. This reflective reintegration of information from multiple sources enables the data to be used in many ways. Rooksby et al. (2014) illustrate this point by describing how people use tracking data from different sources. They stress that people interweave multiple data streams and that a single tracker may not give a full representation of a person's activity. Another important point to note is that the process of tracking is not only just to measure activity, but there are also emotional (Calvo and Peters, 2013) and social implications (Lupton, 2014) for measuring physical activity. Reviewing and sharing data with others can create new connections and provide a platform for sharing experiences (Rooksby et al., 2014).

4.3 Fitness Technology in Competitive Sports

In professional and collegiate sports, managing the health of the athletes is essential to the success of the team. Athletes are expected to perform at the peak of their ability whenever they compete and to improve they are routinely asked to perform at or beyond the edge of their abilities. Over time performance will inevitably decrease but strategies can be implemented to understand and reduce the performance impact. This constant boundary pushing puts a strain on the body and if not properly managed can lead to fatigue and/or injury.

Several strategies have been employed for stamina and fatigue management in competitive sports. The most effective methods involve detailed analytics, constant assessment, and are multi-faceted interventions including detailed exercise programs, nutrition regimens, mental training, and rest (Montgomery et al., 2008; Rampinini et al., 2009; Robson-Ansley et al., 2009). Often these programs involve a significant mental training and awareness component where athletes must learn about their own bodies and abilities. Technology has been used effectively to support this process.

4.4 Fitness Devices for People with Disabilities

Specifically, this work focuses on fitness devices for people with motor impairments. Previous research projects have begun to identify a research agenda and illuminate important implications for the design of mobile fitness technologies for people with disabilities.

Currently, the Apple Watch with watchOS 2.0 update is the only consumer-available wearable fitness device with features to specifically address wheelchair use. It offers a wheelchair mode, which enables the ability track pushes instead of steps and convert some exercises to be more appropriate for someone using a wheelchair.

Few research projects have explored fitness tracking for people with motor impairments. Carrington et al. (2015) and Malu and Findlater (2016) introduced several accessibility challenges relating to the design of fitness devices for people with motor impairments. In the following section, I will describe an interview study which provides an overview of consumer wearables and implications for the design of wearables for people with mobility impairments (Carrington et al., 2015).

4.5 Wearable Fitness Technology Use Interviews

First, this research aimed to understand current technology use, habits, and practices within the contexts of fitness and adaptive sports. I used semi-structured interviews to gather opinions of wearable technology and identify barriers to adoption for fitness purposes. The aim of this study was to answer the following questions:

1. How are wearable fitness devices currently providing benefits for adaptive sport athletes?
2. How are current technology/design assumptions creating barriers to wearable fitness device use?
3. What is the potential for wearable technology to improve sport/activity participation?

During these interviews we discussed general fitness activities, participation in sporting events and activities, and participants' opinions and experiences using wearable technologies.

4.5.1 Procedure for Fitness Technology Use Interviews

The interview consisted of four discussion areas: demographics and background, fitness routines, special equipment used for fitness, and experience with wearable technology. For the background, participants were asked demographic information as well as details about the equipment required for them to participate in their chosen sports. Next, activities related to participants' general fitness and day-to-day exercise are described. Finally, I discuss features of wearable devices and potential uses for wearable technology to integrate into participants' general fitness and sport-related activities. These interviews were conducted remotely by phone (or Skype, Google Hangouts, etc.) or in person when available. The interviews lasted approximately 30–45 minutes.

4.5.2 Participants in Fitness Technology Use Interviews

I interviewed five wheelchair athletes and three physical and occupational therapists. Five participants were power or manual wheelchair users who participated in adaptive sports such as cycling, basketball, and rugby. Participants were recruited through mailing lists and snowball sampling. Participant profiles are described in Table 4.1 and Table 4.2. The remaining three participants were physical and occupational therapists recruited from a local spinal cord injury rehabilitation center. Physical activity is often a component of rehabilitation activities. I included therapists in our study to gain a perspective on the role and impact of wearable technology from professionals who work with many wheelchair users.

Table 4.1: Participant profiles for wheelchair users. HC – Hand Cycle, R – Rugby, B – Basketball, T – Tennis * – Power Wheelchair User

P#	Age	Sex	Time using Wheelchair	Sports	Time in Primary Sport
P1	40	F	6 years	HC	2+ years
P2*	28	M	24+ years	R	<1 year
P3	57	M	37 years	B, R	35 years
P4	24	M	24 years	B, T	9 years
P5	20	M	5 years	HC	3 years

Table 4.2: Participant profiles for therapists

P#	Sex	Focus
T1	F	Physical Therapy
T2	F	Occupational Therapy
T3	F	Physical Therapy

4.5.3 Analysis of Fitness Technology Use Interviews

The features of wearable devices identified during our analysis of the wearable database to derive the original three themes. A thematic analysis using the field notes from the interviews was used to identify strengths and weaknesses across different types of devices. The combined results of these interviews with our analysis of the wearable database to develop additional themes discussed in the preliminary findings.

The preliminary results from the interview study suggest that fitness trackers are, in many ways, inaccessible for wheelchair users who participate in adaptive sports (Carrington et al., 2015). This supported my suspicion that several accessibility challenges, associated with the design of wearable systems for fitness, contributed to our observed low adoption of wearable devices among adaptive sport athletes.

I first examined the accessibility challenges disrupting adoption of wearable technology by adaptive sport athletes. Then, five thematic areas were identified to describe challenges associated with wearable systems: 1) Aesthetics, 2) Sensing Hardware, 3) Analysis, 4) Fit and 5) Feedback. The findings suggest approaches to address prominent accessibility challenges including improved analysis algorithms, instrumenting the wheelchair, and developing a more inclusive vocabulary for presenting fitness data to users. The focus of this dissertation, following the preliminary study, will be on wheelchair basketball due to availability of participants and to simplify the analysis of the results.

4.5.4 Findings from Fitness Technology Use Interviews

Accessibility Challenges

Patel et al. (2015) describe an important multi-step process of selecting and using a wearable device: 1) motivation to purchase a device, 2) the user must remember to wear it, 3) the device must accurately track the target behavior, and 4) the data must be presented to the user appropriately. Throughout this section, I discuss accessibility challenges and opportunities during different stages of this process in particular stages one, three, and four.

Many factors, including device design, functionality, cost, and marketing, can influence a user's motivation to purchase a wearable device. There may also be social issues that factor into motivation to purchase or use a device.

A large proportion of wearable fitness devices measure physical activity as steps. There are many issues that stem from this dominant unit of measurement for fitness wearable technology. The first being that step count is a measurement that is not inclusive to people who are not ambulatory; i.e. those who do not take steps. This leads to a misperception that the technology is not capable of measuring relevant activities and can lead to non-use.

Certain sensor type and body location combinations may not be feasible for this population (Figure 4.1). For instance, a movement tracker that attaches to the foot may not accurately track a wheelchair user's movements given that it was designed for someone who is walking. Another example involves people with spinal cord injury, who may not sweat below the level of their injury (Cheshire and Freeman, 2003). This makes chemical measurement such as the sweat analysis used by the Electrozyme ineffective. While the information being sensed may not inherently be inaccessible, the design of the sensors themselves can create challenges for use.

Fitness Routines

Generally, participants' fitness routines consisted of their normal daily activities with the addition of sport specific practices or events one to two times per week.

P1 is very active and trains for multiple marathons with her hand cycle. She is a teacher and also moves a lot with her students. P2 uses a power wheelchair and is physically active primarily during rugby practices once a week and stretching for therapy. He said, The only time I am able to push around in a chair is at rugby practiceother than that I have been in physical therapy. P3 is involved in several sports throughout the year but participates primarily in basketball and is currently working out with a rugby team. P4 is a university student who lives on campus so he moves around a lot to get to and from class. Also, when the weather is nice, he will go outside and do a few laps around the block. As for basketball, he plays once a week with a recreational team. P5 works at the spinal cord injury clinic and is an avid hand cyclist who participants in many races. He trains multiple times a week.

Figure 4.1: This figure highlights the accessibility challenges in two wearable fitness trackers currently on the market. The electrozyme watch (top) measures enzymes in sweat, which may not be effective for some users with spinal cord injury. The Fitbit charge (left) is used as a step counter, which is not a useful measurement for wheelchair users who don't walk. The clasp used on the Nike+ GPS Watch (right) can be difficult for users with limited hand dexterity to use independently.

Equipment Used for Fitness Activities

The primary equipment used by each of our participants were specialized wheelchairs for their primary sport. Two participants used hand bikes to participate in cycling. For both wheelchair basketball and rugby, there are specialized wheelchairs used for participating in the sport. These wheelchairs often have special purposes within the sport. For instance, in rugby, there are different chairs for offensive and defensive players. The wheelchair is designed to make it easier to perform the motions necessary to play the game. Thus, the effort required to move a certain way in one wheelchair might be different from another. Figure 4.3 shows several different types of sport wheelchairs including the two main types of wheelchairs used for rugby, a basketball wheelchair, and an adaptive hand bike. These different types of wheelchairs should be taken into consideration when choosing an appropriate fitness tracker since the physical activities will be different from sport to sport.

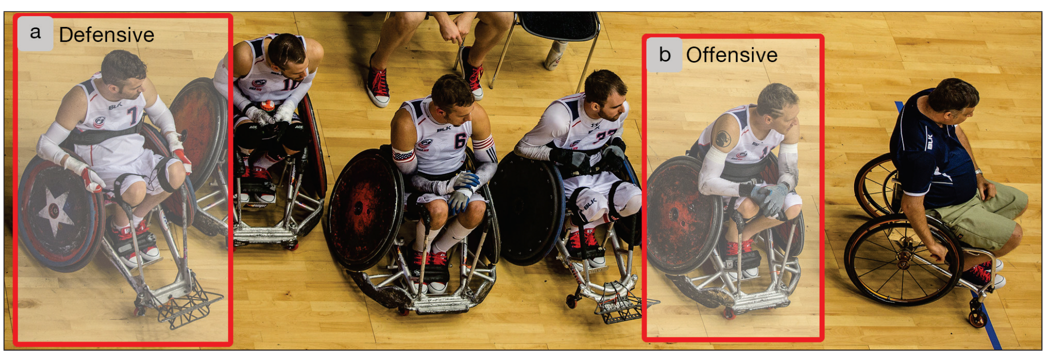


Figure 4.2: Rugby players may choose a chair that is specially suited to the different positions and duties they fulfill during the game. Defensive chairs (a) have an attachment on the front designed to hook other players and keep them from moving. While offensive chairs (b) are more streamlined with skirts to guard against defensive hooks. Both are shown above.

Figure 4.3: Specialized and often custom equipment is used by adaptive sport athletes to improve the safety and accessibility of each sport. (Left) Adaptive Hand bike (Right) Basketball Wheelchair.

Athlete Interest in Tracking Physical Activity

Four of our wheelchair users were interested in tracking their personal physical activity. P1 wanted to track her activity throughout the day for self-interest and self-reflection, and compare her activity with her family and friends who owned Fitbit devices. As a teacher, she is very active everyday with her students. In addition, she goes hiking and competes in marathons with her hand-cycle. She was interested in being able to compare data from those hikes, her daily activities, and her cycling.

> *"I'm sitting, yes, but I'm constantly rolling a round...I'm always interested to know, not steps but how much I'm actually moving around. I've got three kids...I'm never sitting around...I'm never immobile so I would love to know how much I'm burning so I could weight that against my intake."– P1*

P4 was interested in tracking information such as his heart rate, breathing, and pushing. He would use the information to learn more about how he is moving and breathing while playing basketball and tennis. Then he might be able to identify areas or activities where he can improve.

P2 was interested in using a wearable fitness tracker primarily to augment the nutrition tracking he already does for his health. He currently uses MyFitnessPal to track calorie intake from the different foods that he is eating. While working with a nutritionist, he discovered that he needs to think about more than just the food he is eating.

> *"Miles, calories burned, heart rate would be interesting. I would use it for my own personal benefit. I could pass it on to my doctors. I've been consulting with a nutritionisteven prior to rugby. Now it's getting harder*

> *and harder to lose weight. I might be gaining muscle and losing weight but we're not sure." –P2*

P3 was not interested in tracking his own physical activity or using a wearable device for himself. However, he did mention potential benefits for some rugby players.

> *"Some of them have problems with low-blood pressure when they work out. We've had to stop games because their blood pressure dropped. Something like that [wearable] might be good for them so they don't pass out." –P3*

Therapist Interest in Tracking

All three therapists were interested in having their patients use a wearable device in order to track their rehab activities. This could allow the therapists to track their patients' progress toward rehabilitation goals. The following quote summarizes the theme of the therapists' interest in their patients using wearable trackers:

> *"What would be really cool for wearable (fitness trackers) in the rehab setting would be a way to track patients' activity. At the moment, we can suggest or prescribe that the person be active or perform different exercises but we really have no way of knowing whether they did it besides their word. It might not be feasible to get at all of the different motions or exercises but even being able to track the major things like therapy, walking, propelling, sleeping, etc. would probably be very beneficial." –T1*

Only two participants (P2 and P5) mentioned therapy as a routine activity. Giving therapists tracking abilities could improve physical rehabilitation outcomes by facilitating contact when athletes are not regularly seeing a therapist.

Challenges of Wearable System Design

The data from these interviews combined with my own experience with wearable technology design were taken into consideration to identify challenges and opportunities for wearable fitness devices. The following five (5) dimensions were derived to compare across devices to highlight the strengths and weaknesses of wearable fitness devices and are described below:

1) Aesthetics and Device Visibility The physical appearance of the device and its' visual appeal. This also includes aspects that make the device visible or recognizable from afar.

2) Sensor Hardware The sensors used in wearable devices to capture information about the user. Combinations of these sensors can be used to produce more detailed information about the user.

3) Analysis of Sensor Data The method in which raw data is converted into useful information. This refers to how sensor data is actually processed as well as how users think data is processed.

4) Fit and Ergonomics The intended location and fit on the body for the wearable device. Some systems are more flexible than others with their location. Others are restricted to a certain location either by the form factor or the sensor.

5) Presentation and Feedback The way in which sensor data is presented and how the user receives and utilizes feedback from the system regarding their activities. This can be in the form of raw numbers, relative graphs, coaching feedback, etc.

With each of the five components there may be particular limitations or restrictions that may lead to misperceptions and uncertainty of the technologies' capabilities. The relationship between these five themes is described in Figure 4.4. Feedback is strongly influenced by the analysis of data, which is closely tied to the type of sensing and the ergonomics associated with each design. For a full description of these themes, see Carrington et al. (2015)

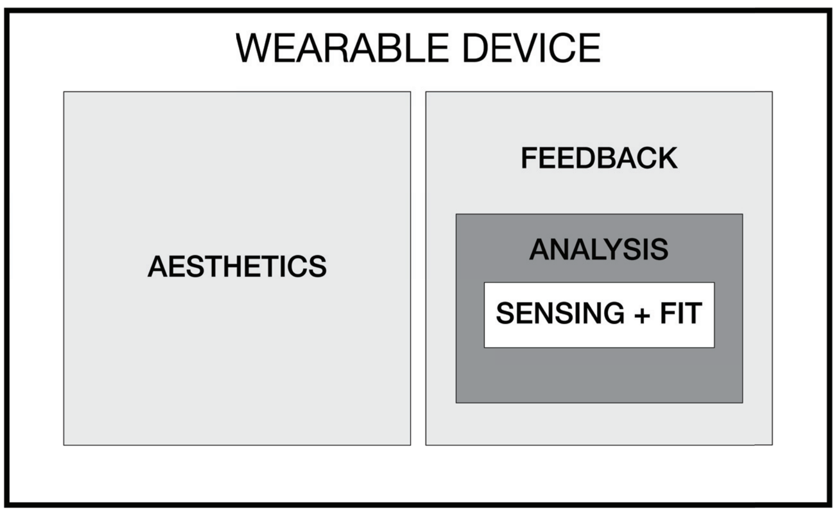


Figure 4.4: This diagram represents the relationship of the five thematic areas identified that influence wearable system design choices.

4.6 Exploring Wheelchair Basketball

This study involved three parts: observations at two National Wheelchair Basketball Tournament (2016 and 2017), interviews with wheelchair basketball players and coaches, and an online survey. From the observations and informal conversations I learned valuable information about the sport of wheelchair basketball and it's surrounding community. In a similar fashion, the interviews were conducted to learn more about people's attitudes and experiences with fitness technologies. These interviews were focused on a using devices to support athletes in their basketball related activities rather than general fitness. Finally, I conducted a an online survey to learn more about players' and coaches' interest in automatic tracking based information collected during the observations and interviews. The details of these activities and high level findings are presented in the following sections.

4.6.1 Observations at the National Tournaments

The National Wheelchair Basketball Tournament (NWBT) attracts hundreds of athletes, annually. It is managed by the National Wheelchair Basketball Association (NWBA). I conducted observations at the 2016 and 2017 tournaments to learn more about the NWBA, the community, and the rules and practices of the sport.

In 2016, I observed interactions within the community and had informal conversations with community members, players, coaches, and tournament staff. These observations informed the design of interviews observations at the 2017 tournament.

Figure 4.5: Wheelchair Basketball is one of the world's most popular adaptive sports. It is a team sport that incorporates multiple roles and is designed to be inclusive of people with differing abilities.

During the fitness technology interviews, participants mentioned that different factors of the games including game speed, scheduling, and availability of substitute players impacted their management of fatigue. Thus, during the 2017 tournament we looked for examples of these factors and recruited for the survey and future studies.

Competition Levels

At the NWBT there are 3 levels of competition for adults: Division 1, Division 2, and Division 3. All three of these divisions are co-ed. The NWBA also governs a collegiate division, with Men's and Women's teams, and manages the US National Wheelchair Basketball Team. Division 1 through three are based on the level of competition with 1 being the highest and 3 being the lowest. Players in the collegiate division may also play on a Division 1-3 team or the national team.

Game Speed and Competition Level

I observed that Division 1 level games moved at a faster pace because players tended to move at higher speeds. I also observed that Division 1 games tended to also have a lot of time when the clock is stopped for different in game events, timeouts, fouls, and short pauses. These in-game events allow the athletes to pause for a moment before resuming the high-intensity activities of the game. This also occurred in Division 2 and 3 games but with longer pauses and overall the pace of the games was slower.

Functional Classification and Inclusive Competition

The functional classification system is summarized in Table 4.3. This classification system is used to group players into categories based on their physical ability to execute fundamental basketball movements. Each player is assigned a class from 1.0 to 4.5 based on their abilities. This classification is used to ensure every player has an equal right and opportunity to be an integral member of a team. According to NWBA rules each team is allowed a maximum of 15 points total for the five active players on the court at any given time. This ensures a balance of the total functional abilities for each team.

The functional abilities of players can vary significantly and not all wheelchair basketball players used a wheelchair when they were not playing. At the end of a game some people will roll to the sideline unstrap from their chairs and walk away. It is difficult to tell what a player's functional classification might be unless you are trained to do so. For instance, one may confuse a physical limitation for fatigue or a fatigue-related response. The classification process involves watching and interviewing individual players by a panel of reviewers to receive an official classification.

Table 4.3: Description of the functional classification system.

Class	Description
1.0	No active movement of the trunk in the vertical, forward or sideways plane.
1.5	Has characteristics of a class 1.0, but more trunk stability
2.0	Has active use of upper trunk in the vertical and forward planes, able to rotate the upper trunk while upright in both directions, able to hold the ball forward with both arms extended, able to lean the trunk into the forward plane about 45 degrees with control and return to the upright sitting position, able to actively bring upper trunk off the backrest of the chair, and uses hands to return to upright of trunk if no thighs-unless knees are significantly higher than the hips.
2.5	Has characteristics of class 2.0, but able to lean forward and return to upright sitting position possibly with difficulty
3.0	Displays active use of the upper and lower trunk in the forward and vertical planes: Can lean forward 90 degrees, placing chest on thighs and return to upright with ease without knees significantly higher than hips, can hold the ball with both hands outstretched in front of face without loss of stability, can rotate upper and lower trunk as a unit not supported by wheelchair backrest, rotation of the trunk occurs at the level of the pelvis not the waist, unable to maintain stability leaning sideways, and works within a Cylinder'
3.5	Has characteristics of a class 3.0, but able to move partially out into the sideways plane and return to upright sitting, able to remain upright in hard contact situations forward, able to sit with hips higher than knees, often raises and lowers trunk with each push, able to generate some power in legs with pushing, able to retrieve a ball with two hands on the floor slightly to the side and return to upright position, can lean to the side but remains within his base of support, plays within a WIDER cylinder than a Class 3.0 player, does not have full volume of action to either side.
4.0	Displays the ability to move the trunk maximally in all planes of movement with weakness to one side, has one strong side and one weaker side, can hold the ball with outstretched hands in front or overhead without loss of stability even in contact situations, no need to counterbalance even in contact situations unless contact is forceful and directed into the weaker side.
4.5	Displays the ability to move the trunk maximally in all planes of movement with no significant weakness in any direction, full volume of action in all planes, displays ability to lean to either side during shooting, passing, contesting a shot or trying to intercept a pass.

Fatigue Related Incidents

At the tournament, there is a medical staff on site in case of injuries or other emergencies. Most of these incidents involved cuts or other physical injuries. However, there were also a few instances where people received medical treatment due to fatigue, overheating, or fainting. While we observed very few of these events it is one extreme situation relating to fatigue that could be prevented with the right prior information.

4.6.2 Fitness Technology Interviews for Basketball

We conducted semi-structured interviews with 5 wheelchair basketball players and 2 wheelchair basketball coaches. The interviews focused on understanding the opportunities for using fitness tracking technologies for wheelchair basketball.

Participants in Fitness Technology Interviews

Participant details are provided in Table 4.4. Participants were volunteers and were recruited through the NWBA, via email, and by word of mouth. All participants were compensated for their time.

Table 4.4: Demographics and background of basketball players and coaches who participated in fitness technology interviews.

ID	Age	Gender	Years Exp.	Class	Occupation
P1*	ND	Male	25	N/A	Coach
P2	26	Male	15	1.0	Academic Advisor
P3*	31	Female	3	N/A	Adaptive Sports Coordinator
P4	26	Male	14	1.0	Engineer
P5	34	Male	20+	2.5	Receptionist
P6	38	Male	7	1.0	Recreational Director
P7	23	Male	<1	3.0	Accountant

*This participant was a coach

Procedure of Fitness Technology Interviews

The semi-structured interviews were approximately 30 minutes and consisted of the following sections:

- **Background (∼5 minutes).** This section covered demographic information about the participants, their amount of experience with wheelchair basketball, and roles they have on their wheelchair basketball teams. For players, we also covered information about their basketball wheelchair and official classification.
- **Experience with Mobile Tracking (∼5 minutes).** We asked participants to describe any previous experiences they have had with mobile or wearable fitness tracking technology. We asked about their overall impressions of the devices and the experience of using them.
- **Current and Desired Tracking and Training Activities (∼15 minutes).** We asked participants about the activities that they are currently tracking with respect to their individual training, team practices, and competition. These activities included sport specific statistics, drills, metrics, performance assessments, as well as fitness related activities. We also asked about desired or potential activities that participants would like to automatically track using mobile or wearable technologies.
- **Ideal Mobile Tracking Solution (∼5 minutes).** In this section, we asked participants to describe their ideal mobile tracking solution or device and its capabilities. We asked participants to describe the potential benefits of this proposed technology. We also asked questions about any existing restrictions that might limit the use of such a technology in training, practice, or during competition.

Analysis of Interviews

Each interview was transcribed and coded. We used a thematic analysis approach to code the interview data and identify relevant themes based on the interview transcripts and field notes from observations. Resulting themes included device requirements, fatigue management, past experiences, wheelchair basketball routines, tracking behaviors, and desired information.

4.6.3 Findings from Fitness Technology Interviews

The findings from the preliminary interviews will be presented in the following subsections based on the structure of the interview provided above.

Previous Experience with Tracking

Participating in organized competitive wheelchair basketball exposed each of our participants to some aspect of tracking or quantifying their performance. However, for the purposes of this research we focused on automatic tracking using some type of mobile or wearable device. Three of the five players had experience using a mobile or wearable fitness tracker.

P2 used a Fitbit but did not have a great experience with it:

> *"I have tried a Fitbit for a little bit, for a little while...but I had troubles with it actually tracking how much activity I had. I mean like I don't take steps of course but I got to the end of the day and it had 500 steps for example. or umm the actual miles. all thecalculations seemed roughly quite off. umm I don't know it just doesn't recognize movements the same way... but it definitely wasn't correct..." "I tried it for 2...2 weeks I think.*

> *[I got it because] I liked the idea behind the accountability you could have with other people. umm to kind of push each other. for me it didn't do a whole lot for me." – P2, Player*

P4 also used a Fitbit but had a better impression and still uses the device:

> *"I have a Fitbit... um it tracks it does track my steps and heart rate and calories burned and all that sorta stuff. um I just have the simple version of the Fitbit I don't have the fancy one with the touch screen and all that...Yeah, I find it useful I like it. It does keep track of things pretty well I feel like. so I do like it...I've had it for a little over a year now..." - P4, Player*

P5 owns an Apple Watch and likes what it currently does for him, but would like it to do more:

> *"I do have an Apple Watch. That I use... I think it works pretty well you know there's a few things that I don't that I don't necessarily care for like it doesn't. It keeps track of your pushes but it doesn't keep track of the miles you know so it will tell you you've done 2000 pushes but I'm like ' well how far is that?' but I guess it's kind of push is different for everyone" - P5, Player*

The remaining two players did not have direct experience with automatic tracking but had either seen or heard of others using fitness devices.

Summary of Previous Experience

Participants had mixed experiences with fitness tracking devices. Three players had direct experience with a device either a Fitbit or Apple Watch. Two participants were not satisfied with the information provided by their devices. One participant stopped using the device because of this. The other participants had not used a device themselves.

Current and Desired Tracking and Training Activities

Current Activities. Participants mentioned several activities that they currently track as part of their training and preparation:

P4 described how he wears his Fitbit, measures the time it takes for him to perform different exercises, and his shooting percentages:

> *"When I have been training, I like to like time certain exercises in terms of agility and speed and that sort of thing. And then in terms of shooting just kind of count uh percentage wise say I shoot 50 shots form a spot um just kind of keep track of how many makes and a percentage." - P4, Player*

P5 mentioned using his Apple Watch to track his activities in practice:

> *"I use it when I work out. just uh when I'm playing basketball I'll war it at practice and stuff just to know how far I've gone or whatever, you know, as far as pushes and you know burning calories it keeps track of that and you know your heart rate and all that fun stuff too." - P5, Player*

Coaches Perspective

P1 described how as a coach measuring and assessing performance is part of the regular routine for training:

> *"We do preseason testing...testing for med ball throws, chin ups, bench press, baseline to free throw sprint and then 20meter sprint, with and*

without the ball...[We measure] time and power output...We have laser timers for all of our sprint work. We'll do 30-minute drill every day and they have to complete it and give us their time. So for beginners they'll come in and it'll take them the whole 30 minutes. Our guys that have been here 3- 4-5 years they can now complete it in 18-21 minutes. So we use that kind of as a bench mark for fitness." - P1, Coach

Desired Activities. In addition, participants expressed an interest in tracking the following metrics and activities: P2 was interested in tracking the distance travelled as well as speed and acceleration:

"I don't know if you ever see an NFL game I think it would be interesting to see the distance travelled. Some people might go straight down the court and back. other people are picking, and they're um hand on the ball and going around all sorts of people., you know they might travel twice as far in the same vertical distance." - P2, Player

"I think uhh different speeds like a top speed or acceleration track could be measured. or like stopping distance. Like somebody is flying down the court and they they power stop how quickly do they stop. a deceleration over a long range?" - P2, Player

P4 described his desire for having something to give warning signs for fatigue before it becomes a problem:

"Instead of waiting to actually feel tired and waiting for that fatigue to actually set in if this technology can like give you a sign beforehand. like hey you're running low or you're slowing down type of thing. um that

> *could kind of be proactive and prevent that. that fatigue from setting in." P4, Player and Coach*

He also mentioned that heart rate could be beneficial for measuring fatigue:

> *"I think heart rate would be beneficial. I don't know what else I don't have a great medical background in terms of signs and stuff for fatigue that would be useful for that." P4, Player and Coach*

Coaches Perspective

In addition to individual metrics described by and for individual players, coaches were also interested in determining the position of players on the court at different times:

> *"Their movement their position um where they are and let's say a certain player you can pull that up and say look on this play you were over here whereas maybe you should have been in this position type of thing." P4, Player and Coach*

Summary of Current and Desired Tracking

Players and coaches engaged in tracking different activities currently. Two players described using their existing devices to track their physical activity during practices. Coaches also described their measurement and tracking routines. They also described desired tracking activities, providing individual metrics of interest such as distance travelled, heart rate, player movements, and positions.

Ideal Mobile Tracking Solution

Participants suggested locations on the wheelchair to attach devices and sensors. P2 suggested a location under the seat of the chair would be a safe place:

> *"There's like a cross bar under there um that doesn't have direct contact with other wheelchairs so if you fall down you're not going to crunch it. If there was a way to secure it to that I think that would be the probably safest point." P2, Player*

He also suggested that wearing something on the body might also be permitted:

> *I mean yeah you could wear a head band or a sleeve, an arm band...I don't know if you could integrate it into one of those...I don't see any reason why a ref would tell you to take it off. P2, Player*

P4 also suggested that wearing a chest strap for respiration might be desirable. P5 described his desire for something that could attach to his chair but also something that might contact the body:

> *"You could possibly use it if it was attached to the chair someway for sure. and it wasn't so big and bulky you don't want it to be heavy. but like a wrist band would work. and then also we have like a click strap which are basically like ski straps that clench down into your chair. If you could figure out most people have wrist bands that they put over the clicky part to keep you from, you know getting jabbed by it if you fall on em, so something in there could work. If you could figure that out, it'd be a good place for something. P5, Player*

The descriptions of an ideal mobile tracking solution seemed to be as much about what to track as how and when it is tracked. Participants identified important considerations for both personal preference and adherence to the rules, regulations, and practices of people who play the sport.

> *"Everybody pushes harder in games. everybody goes harder in games. um you may not get the same effect in practice when maybe you're not going at 100% or you're not in that high speed environment of a game. so I think it would be more beneficial in game." P4, Player*

P7's discussed how a device that detected movement and speed information might useful at the national level of competition:

> *"I think probably to have like a national level it would probably apply the most. I don't see why you wouldn't want to do that if you're at the national level and if I were them I would already be doing that. I just think at that point its one way to measure yeah measure any type of show or perform with it. and I just think from a health perspective there some way to kind of motivate." P7, Player*

He also described that such a device might also be useful for people at every level but would likely be too expensive for newer players, like him, to make that kind of investment. Three other participants also mentioned that tracking information like this might be most useful at elite or national levels, since they are more likely to use that type of "analytical information".

Coaches Perspective

Coaches confirmed possible form factors by were generally interested in having more information about their players. One coach described the lack of options out there and the opportunity for improvement:

> *"It is a wide-open space. There's nothing out there but we definitely need information if were gonna maximize our training with our athletes just like with the able bodied athletes." P1, Coach*

Summary of Ideal Mobile Tracking Solution

Participants described that a solution for mobile tracking might involve attaching sensors or devices to the wheelchair. These devices would need to be attached in such a way that they would be shielded or out of reach from collisions or contact with other players. On-body sensing devices would need to take on the form factors of existing, approved, athletic equipment. This includes headbands, hats, a chest strap or fabric. Both coaches and players were interested in new information regarding their performance. However, given that few people use devices every day, participants especially one coach felt that there is an unmet need for more information.

4.6.4 Summary of Fitness Tech Interviews

Participants in the interviews had some experience with automatic tracking for fitness but, as expected, all were concerned with their performance and assessment of their goals or team's goals. Specific metrics such as heart rate, number of pushes, and speed were mentioned as well as several different basketball related activities or situations for when this information might be useful. These interviews were used to focus our observations and survey questions. The results from the interviews informed the design of the survey questions including desired metrics and activities.

4.7 Automatic Tracking Survey

I conducted an online survey to learn more about wheelchair basketball players' and coaches' interest in automatic tracking for stamina and fatigue management. While the survey focused on players interest in tracking we also captured information regarding their preferences for devices, perceived benefits of using devices, and concerns surrounding the use of mobile devices or sensors for tracking. In this section I describe the survey design and high level results. The majority of the findings presented here focus on the potential benefits, concerns, and form-factor preferences as they relate most to players relationships and identity with regard to their wheelchairs. Additional details can be found in the conference paper (Carrington et al., 2017).

4.7.1 Survey Design and Distribution

The survey consisted of 19 questions and took approximately 10-15 minutes to complete. The survey was designed to be short so it could be completed during breaks at the tournament, while allowing an opportunity for participants to take part in future interviews. The survey was divided into two main sections, one for players and the other for coaches. If a person was a player but had no experience with coaching they were not presented with the section for coaches, and vice versa. Each of the two sections consisted of nine to ten questions asking about the following:

- Levels of competition (National, Division 1-3)
- Functional classification (Table 2)
- Overall Interest in Automatic Tracking of Stamina and Fatigue
- Interest in- Stamina and Fatigue related metrics (derived from interviews)
- Open-ended questions about motivations, potential benefits, and concerns related to automatic tracking

The survey was administered online through Google Forms and available for two weeks following the start of the tournament.

4.7.2 Survey Results

The survey link was shared with all players and coaches who registered with an adult team at the 2017 NWBT (48 teams). There were a total of 94 responses. Responses with erroneous data (entering short answers to numerical questions etc.) and incomplete responses (blank sections, multiple skipped questions, etc.) were removed. A total of 76 responses representing 59 players, seven coaches, and ten who were both players and coaches were analyzed. Each of the five adult competitive divisions and eight functional classes are represented in the sample (Table 4.5 and Table 4.6). The results of the survey are summarized in the following subsections.

Table 4.5: Highest competition levels for players and coaches

Players		**Coaches**	
(Inter-) National	6	(Inter-) National	2
Division 1	15	D1	2
Division 2	20	D2	3
Division 3	20	D3	5
College	8	College	2
		Varsity	3
Total	69	Total	17

Table 4.6: Functional classifications of survey participants

Classification	Number of Players
1.0	10
1.5	4
2.0	8
2.5	11
3.0	9
3.5	4
4.0	9
4.5	10
Not Provided	4
Total	**69**

Interest in Automatic Tracking

Participants were asked to indicate their level of interest in automatic tracking both overall and their interest in specific metrics on a 5-point scale from Not Interested to Extremely Interested. Overall, the results of the survey confirm that there is interest from both players and coaches in automatically tracking this kind of information. More than 85% of players and more than 97% of coaches indicating that they were at least Somewhat Interested in tracking. The distributions of overall interest levels are shown in Table 4.7. Coaches were extremely interested in automatic tracking because of the benefits it could provide their team in the form of information.

Table 4.7: Overall interest in automatic tracking of stamina and fatigue for players and coaches

	Players (n=69)*	Coaches (n=17)*
Extremely Interested	18.8%	43.8%
Very Interested	24.6%	18.8%
Somewhat Interested	42.0%	31.3%
Slightly Interested	13.0%	6.3%
Not Interested	1.4%	0.0%
*These sample includes 10 responses from players who were also coaches. These responses were counted for both groups.		

We also asked participants to rate their interest in specific metrics that were identified through the interviews. Those metrics included Number of pushes, Movement/Speed, Heart Rate, Distance Travelled, and Respiration. Coaches only were also given the option for Position of players due to an interest expressed during an interview to know whether players are in the positions/locations where they are supposed to be at different times. These results are summarized in tables 4.8 and 4.9.

Table 4.8: Distribution of level of interest in individual metrics of players regarding themselves.

	Extremely Interested	Very Interested	Somewhat Interested	Slightly Interested	Not Interested
Number of Pushes	20.3%	31.9%	34.8%	7.2%	5.8%
Movement/ Speed	34.8%	37.7%	17.4%	7.2%	2.9%
Heart Rate	26.1%	36.2%	26.1%	8.7%	2.9%
Distance Travelled	29.0%	24.6%	34.8%	8.7%	2.9%
Respiration	30.4%	36.2%	24.6%	8.7%	0.0%

Device Form Factor Preferences

Survey participants were asked to indicate their preferred form factors for a device by choosing from four options shown in Table 8. Each participants could cast multiple votes for multiple options. For players (91 total votes), something that could attach to either receiving the most votes, followed by “part something you wear and part something attached to the chair”, then “something that attaches to your chair”, and finally “something you wear on your body”. The results for coaches (23 total votes), were similar and are summarized below in Table 4.10.

Table 4.9: Distribution of level of interest for individual metrics of coaches regarding their players

	Extremely Interested	Very Interested	Somewhat Interested	Slightly Interested	Not Interested
Number of Pushes	52.9%	29.4%	5.9%	11.8%	0.0%
Movement/ Speed	82.4%	11.8%	5.9%	0.0%	0.0%
Heart Rate	52.9%	35.3%	11.8%	0.0%	0.0%
Distance Travelled	47.1%	23.5%	11.8%	5.9%	11.8%
Respiration	64.7%	23.5%	11.8%	0.0%	0.0%
Position of Players	52.9%	17.6%	29.4%	0.0%	0.0%

Table 4.10: Summary of form factor preferences indicated by survey participants

Form Factors [Something worn on]	**Players (For Self)**	**Coaches (For Players)**
Body	12	3
Chair	19	5
Either, Body OR Chair	34	10
Both, Body AND Chair	26	5
Total	91	23

4.8 Considerations for Wheelchair Athletes

Similar to the previous chapter, I discuss here five considerations for chairable computing with regard to wheelchair athletes based on these research studies:

1) **Always-available.** Due to the nature of physical activity monitoring it is important that these devices be available whenever the user engages in the activity. In the context of basketball, a fitness or activity tracking device would need to be available at any time the user is participating in sport related activities. The basketball wheelchair is a requirement for participating in the sport thus whenever it is used, the fitness device should also be available.

2) **Maintain wheelchair form factor.** The basketball wheelchair is specifically designed to be lightweight and maneuverable. Much like an everyday wheelchair, athletic wheelchairs are typically designed to fit the specifications and measurements of the individual user. Higher-end wheelchairs use specific materials and are designed to meet the exact needs and preferences of the athlete. Care should be taken when adding new technologies to minimally interfere with the wheelchairs dimensions and specifications. A custom wheelchair uses over 15 measurements of the person's body and parts of the wheelchair in order to provide the best fit. Athletes, in general, are often very particular about what they wear while playing a sport. Thus wearables should maintain accepted forms of currently worn garments or equipment whenever possible. Wheelchair-attached sensors and devices should adhere to sport-related restrictions as well as maintain the qualities of the customized basketball wheelchair.

3) **Consider wheelchair-based vs body-worn devices.** In most cases, players would not be able to wear devices on the body as they may present hazards to other players. However, sensing for certain activities may require attaching the sensor to the body as it would not be available from a wheelchair-attached sensor. For instance, in order to measure how a person shoots the basketball a sensor that primarily detects movements of the wheelchair may not be very useful. In this case, an on-body sensor would be more appropriate. In other cases, as has been demonstrated previously (Cooper et al., 2008; Sporner et al., 2009), measurement using wheelchair-based sensing can be a viable option for capturing movement details.

4) **Familiarity to existing solutions.** Fitness technologies have been seen in the wheelchair basketball community. For the most part, athletes and coaches in basketball, had indirect experience with wrist worn devices like the FitBit or Apple Watch. They also had seen polar respiration straps and therefore these types of devices were familiar to them. It was advised that new devices for basketball take on these familiar form factors. In addition, some participants mentioned using other articles of clothing or parts of the wheelchair embedded with sensors to accomplish their automatic tracking goals. When considering new solutions devices should take on familiar form factors to increase acceptance.

5) **Robustness or ruggedness.** Wheelchair basketball is typically played indoors. The sport requires certain conditions for games. Devices used for wheelchair basketball should be able to be used in all settings where the game is played or practiced. In most cases the device just needs to be able to withstand impacts from other players and wheelchairs. It is important that the device is both safe from impact and that it would not cause harm to the user or another player.

4.9 Chapter Summary

In this chapter, I described an exploration of opportunities for wheelchair-based and wearable fitness tracking technologies for wheelchair athletes. Through two interview studies I identified accessibility challenges associated with the design of wearable technologies that limit their perception among wheelchair athletes. I also describe opportunities and interest in automatic tracking for wheelchair basketball, a popular wheelchair sport. This research highlights a strong interest from the population in using wearable technology to augment their participation in physical activity and sports. I identify five considerations for designing wheelchair-based technologies for wheelchair athletes, primarily based on feedback from wheelchair basketball players. Similar to the previous chapter, these considerations involve issues of hardware selection, placement, and independent use. However similar these considerations are described specifically for designing technologies for wheelchair athletes using wheelchair basketball as an example sport.

Chapter 5

Discussion

5.1 Introduction

In this chapter, I compare and contrast priorities for wheelchair users representing each end of the spectrum. Using examples from previous chapters, I will highlight and discuss commonalities and distinctions for these two groups. This discussion will provide a basis for Carrington's Starting Five as priorities for chairable computing.

5.2 Wheelchair as an Extension of the Body

Overall, the projects discussed in this dissertation serve to identify priorities for designing computing solutions that take into consideration the wheelchair as part of the body when designing for wheelchair users. This involves a perceptual shift from designing assistive technologies that simply attach to the wheelchair as a means of delivery toward the thoughtful integration of technology into users' life and lifestyles. The following two sections provide guidelines for ensuring the consideration of the wheelchair as an extension of the body.

5.3 Practical Considerations for Wheelchair-Based Technologies

This thesis explored specific applications of computing technologies for wheelchair users: input for power wheelchairs, and automatic monitoring for manual athletic wheelchairs. Several common issues with wearable technology design are worth reconsidering for Chairable Computing. These issues include power, heat, load bearing, placement of devices, and device form factors (Starner, 1999).

5.3.1 Power

The power wheelchair uses a 24–volt battery system similar to what you might find in a car. It is possible to use this battery to power additional devices. While this may reduce the overall battery life, power wheelchair users tend to charge their batteries daily or multiple times per week and the battery will often last for multiple days on a single charge. In situations where it is undesirable to use the wheelchair's existing batteries, the load bearing capacity of the power wheelchair may allow the addition of a dedicated battery for computing devices as long as it still meets chairable specifications. This additional battery, could also be used by manual wheelchair users to power wearable or wheelchair attached devices as long as the additional weight is properly considered.

5.3.2 Heat

The additional heat generated by devices, especially batteries, can be mediated by the devices attaching to the chair instead of the user which means additional heat-proofing can also be added to protect the user and their wheelchair still without impacting the users goals or the wheelchairs normal function. This is especially important for wearable devices where the form factors are often compact and batteries and other components are more concentrated. This can cause significant discomfort or injury if not handled properly. Both the manual and power wheelchair frame can be used directly or with modifications to help separate components or diffuse heat across a larger area.

5.3.3 Load Bearing

For the power wheelchair, the primary benefit provided by the wheelchair is the capacity to carry additional weight. A power wheelchair may be able to carry weights of 300lbs or more. This is typically enough to carry a person and additional personal items without hindrance. Unless extreme the additional weight is not noticeable to the user and is thus not distracting. A manual wheelchair is typically designed to be more lightweight since their motion is human-powered. This is especially true for athletic wheelchairs. A basketball wheelchair may weigh around 20-25 lbs compared to a 160-200 lb power wheelchair. Thus, the capacity for additional electronics is greater for power wheelchairs, while it is more important for manual wheelchair users to have lightweight electronics.

5.3.4 Device Placement

This relies on placement of the devices in preferred locations for the user that will also not interfere with the wheelchairs mobility functions. Thus for the power wheelchair the burden of technology placement can be largely focused on the wheelchair and is more likely to be shifted away from the users body. Similarly, for a manual wheelchair, especially in the context of athletics, the wheelchair is not only capable but is preferred to carry the burden of device placement when possible. Since the wheelchair and components like straps contact the body some on-body sensing may be achieved by placing devices on the wheelchair.

5.3.5 Form-Factors

Wheelchair-based computing can take on multiple form-factors including both wheelchair-attached and wearable forms. Chairable devices maintain a certain overall form-factor or silhouette, however the components of such devices may leverage different locations and forms on and around the wheelchair and body. Effective utilization of these possible forms may lead to innovation across devices, for instance, the Gest-Rest prototypes utilize the same physical space but allow 4 different input techniques and multiple styles of interaction. In addition, the wheelchair-attached form factor may allow new technologies to be developed that empower users to collect and use new data about themselves, as in wheelchair basketball. The wheelchair allows for small electronic components to be distributed and hidden as not to be distracting. This also allows designers to choose between compact and miniature forms combined with larger components when needed. The power wheelchair, as stated, also allows the potential for heavier components and larger batteries to be used.

5.4 Carrington's Starting Five

5.4.1 Availability

The availability of devices is very important for supporting independent access. As the wheelchair's primary purpose is to support independent mobility, it is counter productive to have devices used while in the wheelchair require assistance. To that end, in Chapter 3 I discussed design considerations for power wheelchair users. This consideration of availability was primarily motivated by independent access. The Gest-Rest devices allowed power wheelchair users independent access due to the availability afforded by the input type and device positioning on the armrest of the wheelchair. In Chapter 4, I described how a physical activity monitor would need to be available to the user whenever they are performing athletic activities. In the case of wheelchair basketball, this could be accomplished by also making the device available whenever the basketball wheelchair is in use, given that the specialized wheelchair is a requirement for playing wheelchair basketball.

Overall, availability is very important to independent access and the experience of using devices. For wheelchair users it is important to consider the impact that new technology will have on completing the users desired tasks. Devices for wheelchair users should be always available to the user. This should be considered with regard to both the physical placement of the devices and the interaction with the devices.

5.4.2 Maintaining the Silhouette

Designing wearable computers has taught us that respecting the body's dimensions are important when carrying or wearing devices. People tend to respond well to wearable devices that match a desired form or do not significantly alter the accepted shape of the users body. As we learned in Chapter 3, the wheelchair itself often becomes part of how the user perceives themselves and therefore becomes part of their "silhouette". This acceptance is especially advantageous for developers of assistive technologies because the wheelchair offers additional space around the body for technology.

For power wheelchair users, people engage in a very involved process to select and configure their wheelchair to their individual rehabilitation and environmental needs. Participants in our studies shared concerns over the impact new devices would have on the dimensions of their wheelchairs as well as their conspicuousness. For manual wheelchair users (Chapter 4), maintaining the fom of the wheelchair is imperative for a different reason. As each chair is designed to allow the athlete move in a particular way, it is important to be careful when considering adding new devices. In addition, the rules of the sport restrict certain devices and dictate certain measurement limits on different aspects of the chair. Any devices would need to adhere to these restrictions. Again, each basketball wheelchair is configured or adjusted to meet the individual needs of the player and therefore any wheelchair-attached devices should not alter these parameters.

5.4.3 Tailoring

In chapter 3, I described the consideration for power wheelchair users to use different controls for different body regions. This consideration is due in large part to the variability in the range of motion of different body regions for each user. This variability affords different or multiple sizes for inputs and different styles of interaction. The Gest-Rest offered different interaction styles using the same popular form factor. This allows the device's use to be adjusted based on the users abilities.

In chapter 4, considerations of the body focus more on matching the activity to monitor with the available sensing. Designers should consider whether traditionally body-based sensing could be implemented as wheelchair-attached sensors.

Overall, devices and solutions should be tailored to match the abilities of individual users. While this concept of adaptation is not novel in assistive technology, tailoring for chairable devices focuses on tailoring to the physical body of the user and both their passive and active interactive capabilities.

5.4.4 Familiarity

Power wheelchair users found the familiarity of the touchscreen gest-rest to be appealing. During the focus groups users initially developed interfaces that were very physically similar to their existing solutions. Over time they became more willing to explore other form factors. I saw something similar with the wheelchair athletes in chapter 4. Although many of the existing wearable fitness trackers were not designed to meet the particular needs of wheelchair users, participants associated fitness tracking with those devices. Many of these devices had the opposite perception to familiar mobile devices for power wheelchair users. Power wheelchairs users perceived their existing mobile devices to work well whereas wheelchair athletes perceived existing fitness devices as ill-equipped to work for them. This familiarity should be considered when designing new devices as a way to inform future use. The similarity between new and old devices leads to carryover (both positive and negative) in how users perceive those devices.

5.4.5 Robustness

The final consideration involves the different environments in which wheelchairs are used. The examples discussed in chapters 3 and 4 describe two kinds of wheelchairs used for two different purposes. The power wheelchair is typically used as an all-purpose mobility chair. Thus, it travels both indoor and outdoor environments, regularly. Morris et al. (2011) described this requirement for always-available inputs to cope with different and changing environments. It can be expected that the power wheelchair and any wheelchair-attached devices may encounter adverse weather conditions. In these cases, the devices should still be usable or at the very least not become damaged.

For wheelchair athletes these environments may be more predictable for individual sports. The majority of wheelchair basketball is played indoors. Players often travel with their athletic chairs to the location where they will be playing. Sensors and devices should be easily attached to the wheelchair or be simple to remove and reattach, if desired, to the chair. This would allow the user to move devices from one chair to another, if needed. It also allows the user to protect the equipment from weather and other environmental hazards during transport.

5.5 Chapter Summary

This chapter described Carrington's Starting Five as a set of considerations for designing wheelchair-based computing solutions. These guidelines should be used as a starting point when designing technologies for wheelchair users. They are based on the shift in perception from designing assistive technologies to augment the wheelchair as a mobility device to incorporating the wheelchair as an extension of the user's body. This fundamentally shifts the perception of a wheelchair more toward that of a wearable device and as such suggests both aesthetic and lifestyle considerations in addition to function. Practical considerations for designing such chairable technologies are also presented.

Chapter 6

Dissertation Summary and Future Directions

6.1 Summary of Contributions

Introduced Carrington's Starting Five: This research provides insight into wheelchair users preferences for mobile input and output devices. Overall, participants were interested in wearable technology, as well as other chairable technology that fits with the form factor of their wheelchair. Five aspects of designing chairable solutions were established and discussed: 1) availability, 2) maintaining the silhouette, 3) tailoring, 4) familiarity, and 5) robustness. These starting five considerations may be applied to designing or evaluating wheelchair-based solutions or computing solutions for people who use wheelchairs. These principles are built on the idea that the wheelchair should be considered as an extension of the user's body. Thus, design process for wheelchairs should more closely resemble designing wearable computers rather than solely medical devices for independent mobility.

Developed proof of concept Chairable input devices: I developed five wheelchair armrest-based input devices along with a set of twenty-seven gestures suitable for use on this type of device. These devices incorporated multiple input techniques including mechanical buttons, touch, and pressure based interaction styles. These input devices offer flexibility of input choices while maintaining the wheelchair form-factor and demonstrating a chairable form-factor. The prototypes were developed with input from power wheelchair users and clinicians throughout the process.

Identified Accessibility Challenges of Existing Wearable Fitness Devices: Through interview studies and analyses of currently available consumer wearable devices. In chapter 4, I highlighted accessibility challenges associated with the design of wearable technologies which lead to misperceptions regarding the technology itself.

Other Design considerations for Chairable Computing: In chapter 5, I described other practical design considerations for chairable computing. These include common issues with wearable technologies that may be overcome by utilizing the wheelchair as a platform for delivering those solutions.

6.2 Future Directions

6.2.1 Chairable Input

In chapter 3, I described the Gest-Rest and lessons learned about different interaction styles that may be appropriate for power wheelchair users. More research is needed to understand the relationship between different application types, such as communication, information seeking, and productivity, are best suited to these input types. In addition, more development is necessary to improve the recognition algorithms and interfaces associated with interacting with wheelchair-based devices. This is an important area of future work to answer questions around developing the wheelchair as an interactive platform.

6.2.2 Automatic Monitoring and Wheelchair Sports

This research explored the application of automatic tracking in one sport. Future work will aim to develop technical solutions based on the information collected about wheelchair basketball players preferences and desired features. Using Carrington's Starting Five, new devices can be created and existing solutions may be selected and evaluated to fit the needs of wheelchair athletes in different sports. While the individual sports may vary, the existence of sport-specific equipment restrictions persists. In the future, I will extend the findings from wheelchair basketball to other sports and physical activities in order to inform the design of fitness and physical activity monitoring in wheelchair sports.

Technology adoption in wheelchair sports is another interesting area in which to extend the findings of this dissertation. As emerging technologies continue to advance, it will be important to monitor the adoption of new technologies and the practices that form around their use by both individuals and teams.

6.2.3 Wheelchair-Based On-Demand Rehabilitation

I began exploring applications of chairable computing for rehabilitation. We discovered an existing project called passive haptic rehabilitation (PHR) in which vibration motors were attached to a glove to make a wearable rehabilitation tool. Mobile Music Touch (Figure 6.1) aimed to provide an engaging form of hand rehabilitation by combining Passive Haptic Learning and the therapeutic qualities of vibration. PianoTouch used vibration motors in a glove to demonstrate the passive learning effects that haptics can provide. The motors vibrate, repeatedly, in the order of piano keys used to play a simple song. The participant was encouraged to continue their regular activities while wearing the glove at home. Their study found that participants improved their keyboarding skills at a higher rate using the glove compared to a control group without the glove (Markow et al., 2010; Seim et al., 2014). Results have also shown that participants found MMT to be an interesting way to spend their time and were generally happy about the learning, and that the mechanical stimulation provided by the vibrations resulted in improved sensation in the users hands by an average of about 8% (Estes et al., 2015; Markow, 2012). The increase in sensation means an influence on hand and wrist control, which can lead to an improvement in the performance of daily living activities.

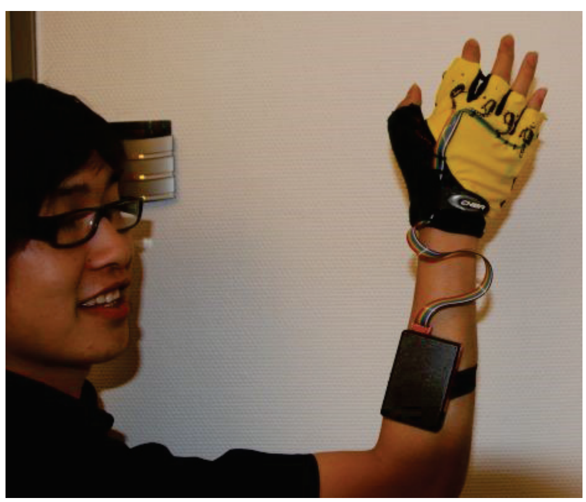


Figure 6.1: The Mobile music touch glove provides vibration stimulus to the user and allows them to passively learn to play melodies on a piano. This is achieved through a process called Passive Haptic Learning.

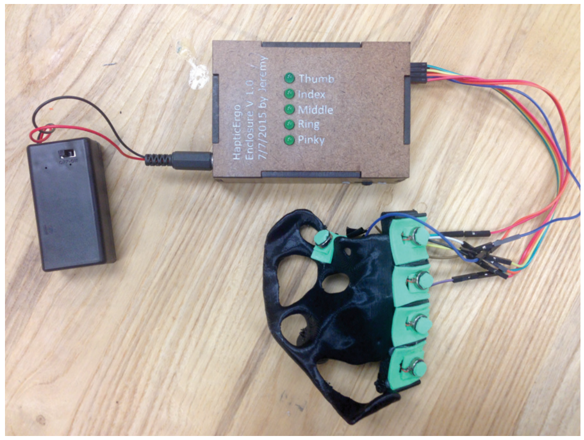


Figure 6.2: The prototype PHR joystick uses a modified ErgoJoystick Stingray to deliver the vibration stimulus to the users hands. The electronics can be attached to the existing joystick control box or under the armrest of the wheelchair to remain out of the way.

Future work will continue development of the Haptic ErgoJoystick, which began in 2016 (Figure 6.2). The Haptic ErgoJoystick allows power wheelchair users to experience PHR through the regular operation of a wheelchair, without the need to wear a glove. This prototype solution would need to be evaluated for feasibility regarding both as a treatment program and as a suitable device for everyday use.

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