Wearables and Chairables: Inclusive Design of Mobile Input and Output Techniques for Power Wheelchair Users

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ABSTRACT

Power wheelchair users often use and carry multiple mobile computing devices. Many power wheelchair users have some upper body motor impairment that can make using these devices difficult. We believe that mobile device accessibility could be improved through designs that take into account users' functional abilities and take advantage of available space around the wheelchair itself. In this paper we present findings from multiple design sessions and interviews with 13 power wheelchair users and 30 clinicians, exploring the placement and form factor possibilities for input and output on a power wheelchair. We found that many power wheelchair users could benefit from *chairable* technology that is designed to work within the workspace of the wheelchair, whether worn on the body or mounted on the wheelchair frame. We present participants' preferences for chairable input and output devices, and identify possible design configurations for wearable and chairable devices.

Author Keywords

Power Wheelchair; Natural User Interface; Wearable Computers; Input; Output; Participatory Design; Mobile Computing; Accessibility

ACM Classification Keywords

K.4.2 Social Issues: Assistive technologies for persons with disabilities.

INTRODUCTION

Mobile computing devices such as phones and tablets are now carried everyday for communication, education, entertainment, and employment. However, power wheelchair users may experience multiple challenges when interacting with these devices. First, many wheelchair users experience motor impairments that affect other body parts, including their hands, arms, neck, and head. Second, a power wheelchair user's ability to interact with computing technology may be physically restricted by the wheelchair's frame, which can obstruct movement or limit reach. Interaction can be further impaired if the individual is "on the go" and attempting to interact with the world while moving [25,14]. As a result, users of power wheelchairs must often resort to complex workarounds in order to use mobile computing devices, such as using a stylus or rigging a device in a certain position [1]. Perhaps due in part to these challenges, people with motor impairments tend to own fewer computing devices than non-disabled people [15], and are less likely to use the Internet [10].

Figure 1. We collaboratively designed new input and output techniques for and with power wheelchair users. Participants explored two primary form factors: wearable technology embedded in clothing or on skin, and chairable input and output devices installed on and around the wheelchair itself. These form factors maintained the original wheelchair dimensions, minimized obstructions, and were less noticeable.

Solving these accessibility problems may be best accomplished by designing new user interfaces that take advantage of the physical abilities of wheelchair users, as well as interfaces that work well within the wheelchair user's reachable workspace. One exciting possibility is to design input and output devices on and around the wheelchair itself (Figure 1). The wheelchair has several

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underutilized spaces that could be used to hide wiring, small devices, and batteries. In addition, a power wheelchair can carry the load of computer devices, rather than placing the weight upon the user. We propose the term *chairable* computing to refer to technology that takes advantage of the (currently underutilized) space on and around a wheelchair, much as wearable computing leverages on-body and worn mobile technology.

In this paper we present the concept of chairable technology and the results of our user-centered approach, consisting of a multi-method, six-month-long exploration of challenges and opportunities for chairable computing. We conducted formative interviews and design sessions with power wheelchair users, developed design prototypes in a series of focus group-style design sessions with clinicians in a spinal injury rehabilitation clinic, and evaluated these designs in design interviews with power wheelchair users. Overall, we collected design input from 13 power wheelchair users and 30 clinical staff members (Figure 2). We discuss the implications of our results on the design and development of interactive systems for power wheelchairs.

RELATED WORK

Wheelchair-Based Computing

Intelligent wheelchairs have been developed to support autonomous driving as well as to provide alternative methods of control for driving functions. Braga *et al.* [5] created the Intellwheels platform to support the modular design of intelligent wheelchairs. Lin *et al.* [18] created a system to improve the ability of intelligent wheelchairs to identify indoor and outdoor terrain changes. Our approach differs in that we focus on utilizing physical features of the wheelchair to create solutions that enable access to computer I/O, rather than augmenting the wheelchair's driving functions. O'Conner *et al.* [20] developed a system to allow manual wheelchair users to control a game by driving their wheelchair.

There are few examples in the HCI literature of designing wheelchair-based information technologies. Nischelwitzer *et al.* [19] created MediaWheelie, which enables a wheelchair user to control computing devices using their wheelchair's joystick or a sip-and-puff device. Wobbrock *et al.* [29] enabled text entry in power wheelchairs using the EdgeWrite alphabet.

Adopting a participatory approach to designing assistive technology can be integral to the success and eventual adoption of solutions. Cook and Polgar [8] provide guidelines for conducting participatory research for assistive technology design with wheelchair users. Kim *et al.* [17] 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 [16] for a wheelchair-based computing system using an interactive tray.

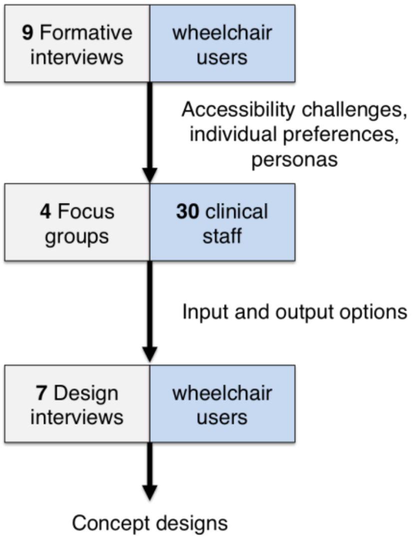

Figure 2. Overview of our study procedures. We conducted formative interviews with power wheelchair users; held a series of design-oriented focus group sessions with clinical staff; and validated design recommendations from the focus groups with one-on-one design interviews.

Input for People with Upper Body Motor Impairments

Individuals who use power wheelchairs often have an underlying health condition that affects their upper body mobility, including reduced movements in their hands. Although the diagnosis may differ, many health conditions have similar effects on upper body mobility, such as reduced strength, limited range of motion, or tremor, that can affect use of a computer interface [26]. Prior research has explored ways to improve mobile device usability, including leveraging the edges of the screen as physical barriers [29,11] or providing alternative gestures for selecting items [12]. Touch screen tablets may be more accessible than traditional input devices such as a trackball for some, but not all, users with motor impairments. Many people with motor impairments are able to successfully use existing tablet interfaces by using parts of their body other than the finger, such as the back of the hand; by using a stylus or pointing device; or by propping or mounting the device [1]. However, these types of workarounds require extensive effort on the part of users, and may not be robust to different applications or use while on the go.

Wearable and On-body Input

Wearable and body-based inputs provide opportunities for new interaction styles, which may be useful for chairable applications. Brewster *et al.* [5] used sound and gestures to interact with a belt-worn computer. They used both head and hand gestures to interact with the system. ShoeSense [3] captures hand gestures using a depth camera on the user's shoe. Ashbrook *et al.* [2] demonstrated the importance of the location of wearable devices by showing that it takes less time to access a wearable device on the wrist compared to one attached to the hip or in a pocket.

Saponas *et al.* [22] used EMG to capture muscle activity related to different grip styles. Harrison *et al.* designed Skinput [13], a technology that allows the user's skin to be used as an interaction surface via finger taps. Tongue interfaces [23] use sensors placed in the mouth to detect input and to enable interactions with computing devices.

Interactive objects such as clothing, accessories, plush toys, costumes, sculptures, and biking accessories have been created using the LilyPad Arduino, which can be sewn into a user's clothes [7]. Textile-based computing devices can also be used as output devices, as in Fabcell [28], which combines fabric and liquid crystal ink to create fabric displays. Very little research has explored wearable computing specifically for wheelchair users.

Social Barriers to Technology Use

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. Elliot *et al.* [9] use the term *stigma* to describe the social interactions created when people are thought not to meet expectations of "normal." Bispo and Branco [4] note that assistive technologies such as wheelchairs often act as symbols of stigma. Parette and Scherer [21] noted that stigma might be affected by the design of an assistive technology, such as its aesthetics or whether it has been universally designed. Shinohara and Wobbrock [27] 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 user's perception of stigma appears to vary across contexts, it is clear that people with disabilities consider the form factor of a device, and its noticeability, when considering using that device.

Other research has explored design guidelines for accessible mobile technologies "on the go." Kane *et al.* [14] 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. We considered these factors when conducting our own interviews about technology use and during design sessions. Kim and Smith [17] explored the accessibility challenges faced by wheelchair users when using laptop and desktop computers. They found that many of the accessibility problems were related to storage, positioning, and physical access to the device. Our present research explores alternative mobile device form factors that may reduce these accessibility problems.

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.

Table 1. Profiles for power wheelchair users in our study. † participated in technology use interviews; ‡ participated in individual design sessions; + participated in design interviews; * used as a persona in focus group sessions.

FORMATIVE INTERVIEWS

We began our research with nine 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.

Participants

We 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 1.

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 & 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 & 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/ 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.)

Table 2. Mobile app classifications, based on popular app categories, used to focus discussions in our formative interviews.

Procedure

We conducted nine semi-structured interviews (four in-person and five via phone and video chat). We asked participants 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. Participants did discuss ADLs in relation to the devices they used to assist in completing those ADLs. We asked participants 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, we asked participants about the challenges they faced when using computing devices. We discussed some device characteristics that they would find useful or desirable for users with mobility impairments who use wheelchairs.

We also asked participants to identify 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[1], the Mac App Store[2], and the Google Play[3] store. Each store listed apps in 20-25 categories, which we 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 2. Using these categories allowed us to systematically identify desirable computing tasks based on users' goals rather than specific technological constraints.

Prototyping Activity

During three of our formative interviews, the first author and the participant collaborated on a medium-fidelity prototyping activity. We used a MaKey MaKey[4] microcontroller board (Figure 3) 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. The researcher demonstrated how the MaKey MaKey can be used to create controls using household objects such as screws, aluminum foil, and Play-Doh.

After the demonstration, we 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, *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.

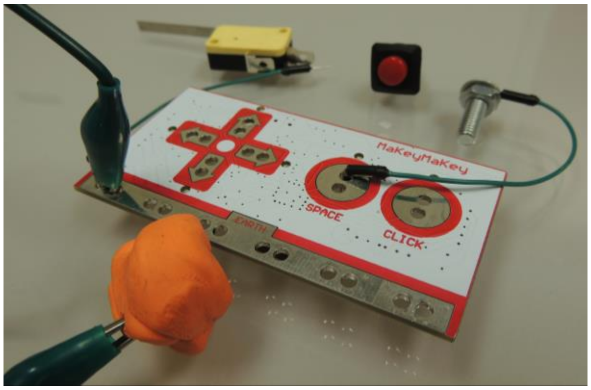

Figure 3. Medium-fidelity prototype created with the MaKey MaKey microcontroller board and various button materials.

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[1] http://www.apple.com/ios/

[2] http://www.apple.com/osx/apps/app-store.html

[3] https://play.google.com/store?hl=en

[4] http://www.makeymakey.com

Findings

All three authors participated in open coding of field notes from the interviews 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 repositioning a device. Participants also had difficulty managing multiple devices.

Based on our conversations with participants, we identified several design guidelines 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 us 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 1) had significantly 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 interfaces during the design activity. These designs used a single button to move a cursor through a list of options (Figure 4). They preferred these designs due to the 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.

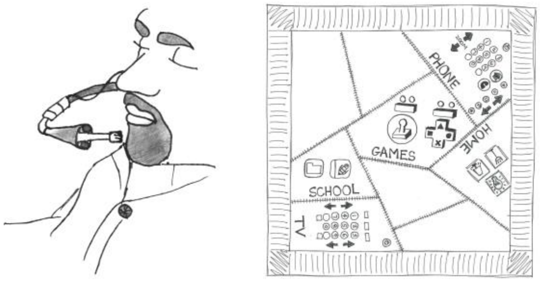

Figure 4. New input devices proposed by our participants. (Left) P7, who is paralyzed below the neck, designed extra inputs around the straw of his sip and puff control. (Right) P9 designed a wearable quilt, containing conductive fabric controls for devices and applications at school and home.

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 wheelchair's 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 the blanket could be plugged into (Figure 4).

Despite our small sample size, we found strong evidence that an individual's abilities strongly influence their preferred control layout. Our 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. As this session was focused on input, we did not explore output options in detail, although we did explore output in subsequent design exercises.

FOCUS GROUP DESIGN SESSIONS

After conducting our interviews, we collected feedback from physical therapists and other clinical support staff. Doctors, therapists, and family members are frequently involved in the process of choosing a wheelchair that is suitable for an individual's 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.

We 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.

Participants

30 physical therapists, occupational therapists, and rehab techs participated in our focus groups. All focus group sessions took place at the clinic during lunch hour. Our focus group met for four sessions, each covering a different topic. Our focus group participants were invited to attend multiple sessions, although not all participants were able to. Table 3 summarizes the participants and session topics.

Procedure

We conducted 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. Because of this, we created personas based on our interview participants (see Table 1). Focus group members designed solutions to meet the needs and abilities of these personas (Figure 5). During the early sessions, we found that participants were conservative with their designs. To promote creativity, we included technology probes 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.

Focus Group 3: Input Modes

In this session, participants discussed different input modalities. Participants were shown a video of the Worldkit system [30] 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 [13] 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.

Findings

Our four focus group sessions provided insight about the placement and usefulness of various input and output devices. Each group identified unique design concerns.

Focus Group 1: Phone Design

This group designed a relatively 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 persona's 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 wheelchair's joystick. Some participants raised concerns about the complexity of these interfaces, and others raised concerns about accidentally activating these controls.

Figure 5. We conducted 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.

Topic	# OTs	# PTs	# Techs	# Repeats
Phone	3	7	1	
Game Controller*	3	7	5	
Input Modes	3	4	5	10
Output Modes	3	4	5	9

Table 3. Discussion topics, participants, and repeat participants for each focus group session.
***Session included one power wheelchair user and caregiver.**

Focus Group 3: Input Modes

The Worldkit [30] 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 user's mobility in that location: for example, the team placed a trackball under the user's left arm, because that user had sufficient gross motor function to move the trackball. This group also placed pressure switches behind the user's 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 [13]) and head-mounted displays (via Google Glass). Focus group members 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 user's 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 user's phone or tablet. This design raised concerns about whether the user would have to deactivate the wheelchair's 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 wheelchair‘s 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, our focus group participants generated a variety of input and output form factors. As in our initial interviews, our focus group members 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 user's range of motion in that body area. Focus group members were excited about new display technologies, but raised concerns about potential distraction and noticeability.

DESIGN INTERVIEWS

While our focus groups generated many unique ideas, the design groups were primarily made up of clinical workers, rather than wheelchair users. To verify the feedback from the focus groups, we presented the ideas generated during the focus group sessions to seven power wheelchair users.

Participants

Seven power wheelchair users participated in these interviews. 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.

Procedure

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

Our 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, we showed participants an illustration of potentially reachable areas on a power wheelchair (those areas are highlighted in Figure 1). 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 user's 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 (similar to Figure 1) 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.

Findings

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 4). 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 our 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.

DISCUSSION

We conducted a variety of study activities (interviews, focus groups, and design exercises) with several stakeholders (wheelchair users, therapists, and other clinical staff). Our results therefore provide a range of perspectives and suggestions for designing new user interfaces for power wheelchairs. Unsurprisingly, our research has not identified one "ideal" wheelchair design, but has uncovered potential preferences and obstacles for designing future wheelchair user interfaces, and has demonstrated the extreme variations in ability and preference across individuals.

Priorities for Chairable Devices

Most current power wheelchair interfaces are similar, providing a small set of buttons, and possibly a joystick, at the end of one armrest. We asked our participants to envision wheelchair user interfaces that were substantially different. While participants came up with many different ideas, several themes reappeared repeatedly throughout our research. We can thus consider these to be guidelines for exploring the design of chairable input and output devices.

Maintain wheelchair form factor. Choosing an appropriate power wheelchair is a complex process that involves detailed assessments of the intended user's abilities, medical factors, and environment. This choice often involves trade-offs between the dimensions of the chair: if the chair is too wide, it won't 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 chair's shape.

Different controls for different 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 user's range of motion and the body part that will actuate it. Controls near the user's fingertips can be small, while controls near the user's shoulders must be larger.

Familiarity. 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. We believe simple switch controls should be provided as backup to these new interfaces.

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.

Designing NUIs takes practice. When asked to generate ideas for input and output devices, our participants universally began with simple user interfaces similar to the switch-based interfaces they had used previously. However, participants seemed more willing to explore new ideas after spending some time in the design group. In some of the later design sessions, participants suggested unconventional input methods, such as a wearable EMG bracelet similar to that designed by Saponas *et al.* [19].

Involving Therapists in the Design Process

Many of the wheelchair users we interviewed used adaptations developed by their occupational therapists. In the rehabilitation process, occupational therapists often work with their patients to identify alternative ways to complete everyday tasks. We observed that the physical and occupational therapists had different areas of expertise, which allowed them to generate clever design ideas.

Within the focus groups, the physical therapists and occupational therapists designed solutions that would be both physically reachable and functional. The physical therapists tended to make suggestions based on the biomechanical functions of the persona they were designing for. The occupational therapists, while also concerned with biomechanical abilities, focused on use of the technology and were more receptive to creative solutions.

Designing for Life in a Wheelchair

One recurring theme throughout the study was that participants were strongly tied to their wheelchair. While some participants were keenly interested to get out of their wheelchair, they recognized that the wheelchair was currently part of their life, and that any technology they use must be compatible with their wheelchair. One participant expressed his relationship with his wheelchair as follows:

> "My wheelchair is more than just a chair that I use to get around. I spend most of my day in it and I use it for most of the things that I do in and out of the house. In some ways it is like my home… it is a part of me. That's why I need it to do more for me."

LIMITATIONS

While people use power wheelchairs for many reasons, our study sample was biased toward individuals with spinal cord injury. Additionally, many of our participants had only used a wheelchair for part of their lives, which may have caused them to focus on appearance over function. Individuals who have been using a wheelchair for longer may have different perceptions of self-identity than those who acquired a motor disability later in life. Many of our participants were recruited from a rehabilitation environment, which encourages change, growth, and functional improvement, and were working to regain lost motor ability. This bias may have caused our participants to focus on short-term solutions.

FUTURE WORK

We intend to expand our study protocol to include power wheelchair users with more diverse abilities, including those who have used a power wheelchair for most or all of their lives. We will also develop chairable technology using our design findings, and will evaluate this technology with a diverse set of power wheelchair users.

CONCLUSION

This research provides new insight into power wheelchair users' preferences for mobile input and output devices. Overall, our participants were interested in wearable technology, as well as other *chairable* technology that fits with the form factor of their wheelchair. We believe this concept of chairable technology, and the guidelines that we discovered, may lead to new innovation in the design of technology for power wheelchair users.

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