ABSTRACT

Title of Dissertation: DESIGNING AND IMPLEMENTING ACCESSIBLE WEARABLE INTERACTIONS FOR PEOPLE WITH MOTOR IMPAIRMENTS

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Emerging wearable technologies like fitness bands, smartwatches, and head-mounted displays (HMDs) are entering the mainstream market. Unlike smartphones and tablets, these wearables, worn on the body or clothing, are always available and have the potential to provide quick access to information [7]. For instance, HMDs can provide relatively hands-free interaction compared to smartphones, and smartwatches and activity trackers can collect continuous health and fitness-related information of their wearer. However, there are over 20 million people in the U.S. with upper body motor impairments [133], who may not be able to gain from the potential benefits of these wearables. For example, the small interaction spaces of smartwatches may present accessibility challenges. Yet, few studies have explored the potential impacts or evaluated the accessibility of these wearables or investigated ways to design accessible wearable interactions for people with motor impairments.

To inform the design of future wearable technologies, my dissertation investigates three threads of research: (1) assessing the accessibility of wearable technologies like HMDs, smartwatches and fitness trackers; (2) understanding the potential impacts of sharing automatically tracked fitness-related information for people with mobility impairments; and (3) implementing and evaluating accessible interactions for HMDs and smartwatches.

As part of my first research thread, I conducted two formative studies investigating the accessibility of HMDs and fitness trackers and found that people with motor impairments experienced accessibility challenges like problematic form factors, irrelevant data tracking and difficulty with existing input. For my second research thread, I investigated the potential impacts of sharing automatically tracked data from fitness trackers with peers with similar impairments and therapists and presented design opportunities to build tools to support sharing. Towards my third research thread, I addressed the earlier issues identified with HMD accessibility by building custom wearable touchpads to control a commercial HMD. Next, I explored the touchscreen and non-touchscreen areas (bezel, wristband and user's body) of smartwatches for accessible interaction. And, lastly, I built and compared bezel input with touchscreen input for accessible smartwatch interaction. The techniques implemented and evaluated in this dissertation will enable more equitable and independent use of wearable technologies for people with motor impairments.

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by

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Dedication

To my family

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Chapter 1 : Introduction

Motivation

In the recent decade, wearable technologies like head-mounted displays (HMDs) and wrist-worn devices have entered the mainstream market (e.g., Google Glass, Fitbit, Apple Watch). These wearable devices are always available, have the potential to offer quick access to information and can also track continuous health and fitness-related data of their wearer. Compared to smartphones, these wearable devices have a lower risk of dropping and damaging the device, can offer relatively hands-free interactions. However, there are more than 20 million people in the U.S. with upper body motor impairments affecting the hands and arms such as tremors, lack of sensation and spasms [133] - motor impairments could, in turn, impact the accessibility of wearable devices. While many studies have highlighted challenges experienced by people with upper body motor impairments with mobile computing devices such as performing multi-touch gestures (e.g., [3]), text entry (e.g., [62]), or even pulling out the phone from a pocket or bag [98], little is known about the use of and potential impacts of wearable technologies for people with motor impairments.

For mobile computing devices like smartphones and tables, people with motor impairments make several physical adaptations like using head and mouth sticks on touchscreens and physical guides to make these technologies usable (e.g., [3]). On the other hand, many studies have focused on making these mobile computing devices accessible. Some examples include utilizing the physical edges of the device [38,140] for better gesture stability, or touching and sliding the finger (called swabbing) [135] for target selection or analyzing touchscreen gestures to better understand the input preferences for people with motor impairments [35,45]. Particularly for wheelchair users and more closely related to my dissertation, Carrington et al. [21] explored alternative input/output spaces on and around the wheelchair for accessible mobile computing and later, built a pressure-sensitive input technique on the armrest of the wheelchair to help people with motor impairments interact with mobile computing devices [22]. As mobile computing expands to devices that can be worn on the body, clothing or wheelchair, people with motor impairments may experience similar and new challenges related to input and output.

In my dissertation, I investigate the potential of popular wearable technologies for people with motor impairments by exploring, designing, implementing and evaluating novel accessible interaction techniques for equal and independent access. I provide evidence to support my thesis statement:

"Popular wearable technologies like head-mounted displays, fitness trackers, and smartwatches can be made accessible for people with upper body motor impairments by improving input accuracy over default input mechanisms and supporting custom input for wearable interaction thus providing quick access to information and enabling independent use of technology."

Approach and Overview

This dissertation investigates three threads of research: (1) assessing the accessibility of three common classes of wearable devices—head-mounted displays (HMDs), smartwatches, and fitness trackers; (2) understanding the potential impacts for people with mobility impairments of sharing fitness data from existing activity-tracking wearables; and (3) implementing and evaluating accessible interactions for HMDs and smartwatches.

Thread 1: Accessibility of Existing Wearable Technologies

Compared to smartphones, some striking features of wearable technologies include their ability to offer access to information on-the-go and to gather continuous information about the wearer (e.g., heart-rate, location). To understand if people with motor impairments can reap these benefits, it is important to: (1) assess if the wearable technology itself is accessible and (2) understand the potential advantages and disadvantages of these wearable technologies. To this end, we conducted a series of exploratory studies investigating the following research questions:

- **RQ1:** To what extent are existing HMDs accessible to people with upper body motor impairments for information access?
- **RQ2:** To what extent are existing wrist-worn and clip-based wearable technologies accessible to people with mobility impairments for health and fitness tracking?

Accessibility of Head-mounted Displays: Toward the first research question, we conducted a formative study with six people with upper body motor impairments to understand the extent to which an existing HMD (Google Glass) is accessible [80]. While participants listed potential benefits of the HMD, like not having to hold the device, almost half the participants could not use the device's built-in manual touchpad because of their motor abilities. Based on this preliminary study, the need arose to implement an alternative input mechanism that would be easy to learn and use by people with varying physical strengths in hands and arms, be socially acceptable and support use in a mobile context.

Accessibility of Activity Tracking Wearables: Toward the second research question in this thread, we conducted an in-person study with 14 people with a range of mobility impairments [81]. Study sessions included interview questions, evaluation of two commercial wearable trackers, and a participatory design activity. A subset of participants also opted into a week-long field trial to evaluate the accessibility of a mobile fitness app. From the in-person and field evaluations, we found that people with mobility impairments experienced problems like irrelevant tracking targets such as steps and floors climbed, an inaccessible form factor, and the small size of the display and buttons. Our participatory design activity revealed that all participants wanted a wearable form factor that would be easy to put on, unobtrusive, and embedded within an existing object to overcome stigma associated with assistive technology. Participants also wanted a wearable that could track safety and have the ability to share their fitness data with relevant people. Lastly, we provided design guidelines to build a personalized tracker to support a wide range of users with mobility impairments.

Thread 2: Implications of Sharing Activity Data:

As mentioned earlier, wearable technologies can automatically collect continuous health and fitness-related data about their wearer. Previous work has suggested that sharing this data can yield benefits like increased motivation and peer support (e.g., [131]). For people with motor impairments, the Apple Watch 2 can now (since August

2016) support tracking of wheelchair pushing. As commercial technologies start supporting activity tracking for people with motor impairments, it becomes essential to examine the potential impacts of tracking towards the wearer himself and the therapists. Hence, we explored:

- **RQ3:** What are the potential impacts of sharing automatically tracked health and fitness data of people with mobility impairments with therapists and peers who have similar impairments?

The desire to share automatically tracked activity data with others with similar impairments was evident from our previous work [81]. Toward the second thread of my dissertation research, we deep dived into this idea by conducting semi-structured interviews and a design probe activity with ten therapists, and shorter semi-structured interviews with ten people with mobility impairments [82]. The website *PatientsLikeMe* was used in the design probe activity to understand the perceived utility of therapists' patients' tracked fitness data. Based on our interviews with both groups, we presented design opportunities to build tools to support sharing of tracked data with peers with similar impairments and therapists.

Thread 3: Designing, Implementing and Evaluating Accessible Wearable Interactions

Previous work with people with motor impairments has shown challenges associated with performing touchscreen interactions on smartphones (e.g., [3,45,98,132]). Existing wearable technologies like head-mounted displays and smartwatches also use touch gestures but on a smaller interaction space compared to smartphones. Hence, it is timely to explore alternative input techniques to make these devices more accessible.

In this thread of research, we investigated the following questions related to novel wearable interaction techniques:

- **RQ4:** What are the advantages and disadvantages of personalized switch-based wearable touchpads to control a head-mounted display for mobile information access?
- **RQ5**: Can the space on and around the wrist-worn wearable be used to provide accessible input for users with motor impairments compared to current smartwatch input?
- **RQ6:** Can input on the bezel of the smartwatch provide accessible control compared to input on the touchscreen for people with upper body motor impairments?

Personalized, Wearable Touchpads to Control HMDs: From our formative work (Thread 1), we defined a set of design goals for accessible control of a HMD. Based on these goals, we built an alternative input mechanism consisting of four switch-based touchpads of three sizes made from pressure-sensitive conductive sheeting [80]. To assess the input performance of the three sizes of touchpads and personalization patterns employed by participants (e.g., placement at different locations on the body or wheelchair), we conducted a controlled experiment with 12 participants. We found that all participants could use the wearable touchpads to control Glass, as opposed to the built-in Glass touchpad. Participants' choice of touchpad placement depended on individual motor abilities. While these results show wearable touchpads offer one promising solution for accessible HMD input, practical issues like interference with everyday activities and accidental taps should also be considered in future work.

Accessible Interactions for Smartwatches: To examine accessible smartwatch gestures, we employed a participatory approach with eleven people with upper body motor impairments [78]. Participants were asked to elicit gestures for common actions (e.g., view notification) on the touchscreen and non-touchscreen (bezel, wristband and skin near the watch) areas of the smartwatch. We found that from the non-touchscreen areas of the smartwatch, body locations were least preferred and the bezel and wristband locations closer to the dominant hand were preferred. Participants also experienced problems with standard touchscreen gestures that need space to be performed (e.g., zoom in). We conclude by presenting design guidelines to build accessible smartwatch interactions for people with upper body motor impairments.

Bezel Interactions for Accessible Control of Smartwatches: Toward the last question of this thread of research, we leveraged the idea of utilizing the hard edges of the smartwatch and expanded the interaction space of existing smartwatches to include the bezel as a potentially accessible solution compared to the touchscreen. We implemented and compared bezel interactions with touchscreen interactions with two layouts in terms of trial completion times and error rates with 14 people with upper body motor impairments in a controlled study. Our findings revealed that the touchscreen was significantly faster than the bezel interactions but was also significantly more error prone. Participant's motor impairments impacted their overall preferences of locations between the touchscreen and bezel tasks. We also highlight some challenges presented by the bezel input technique for future work.

Contributions

Through my dissertation work, I contribute to the growing body of work on assessing, designing, implementing and evaluating accessible wearable interactions for people with motor impairments. The specific contributions of my dissertation are:

Thread 1: Accessibility of Existing Wearable Technologies

- Empirical evidence demonstrating the extent to which an existing interaction mechanism (built-in touchpad) of an HMD is accessible to people with upper body motor impairments.
- Potential benefits of HMDs for people with upper body motor impairments.
- Empirical evidence demonstrating the extent to which existing mobile and wearable fitness trackers are accessible for users with mobility impairments, based on use (1) in the lab and (2) in the field.
- Guidelines for how to design more inclusive activity tracking devices for people with mobility impairments.

Thread 2: Implications of Sharing Physical Activity Data

- Identification of opportunities for building tools to help therapists make personalized therapy decisions about their patients using data from activity-tracking wearables.
- Characterization of attitudes and concerns about sharing health and fitness data from the perspective of both therapists and individuals with mobility impairments.

- Design recommendations to build tools that support inclusive sharing of fitness-related activities with peers who have similar mobility impairments.

Thread 3: Designing, Implementing and Evaluating Accessible Wearable Interactions

- A simple, customizable input solution to allow users with upper body motor impairments to control an HMD via switch-based touchpads.
- Empirical results from a performance and subjective comparison of three sizes of touchpads, and, secondarily, between these touchpads and the default manual control on an off-the-shelf HMD.
- Characterization of personalization patterns and design considerations to support accessible wearable input for users with motor impairments.
- Guidelines to build accessible smartwatch gestures by including the touchscreen and the non-touchscreen (bezel, wristband and skin near the watch) areas of the smartwatch based on input created by people with upper body motor impairments.
- Empirical results from a performance and subject comparison of bezel interactions with existing touchscreen interactions for smartwatches.

Organization of the Dissertation

This dissertation is organized as follows: Chapter 2 covers literature related to accessible computing, wearable input technologies, sharing of health and fitness-related data on online platforms, and social implications associated with wearable technology. Chapter 3 consists of a formative study that explores the accessibility of an existing wearable technology, HMD, and performance evaluation of an alternative interaction technique. Chapter 4 investigates the accessibility and potential impacts of existing fitness tracking wearables and mobile apps. Chapter 5 examines the impact of sharing activity data automatically tracked by wearables with therapists and peers with mobility impairments. Chapter 6 focuses on the accessibility of existing smartwatches and ways to build accessible interactions by utilizing the non-touchscreen areas of the smartwatch. Chapter 7 presents the design and comparison of bezel interactions with touchscreen interactions for accessible smartwatch input. Lastly, in Chapter 8, I conclude by discussing directions for future exploration that emerge from this dissertation research.

Chapter 2 : Related Work

In this chapter, I cover four areas related to my dissertation research. First, I discuss the potential benefits and challenges of existing mobile computing technologies for people with motor impairments, as well as research addressing these challenges. Second, I discuss wearable input technologies that offer mobile computing possibilities, more specifically, head-mounted displays, health and fitness trackers and smartwatches. Third, I discuss related literature on sharing health and fitness-related data on online platforms. And lastly, I discuss the social factors that may influence the use and adoption of wearable technology.

Accessible Mobile Computing

Mobile computing devices using touchscreen technologies like smartphones and tablets have become pervasive. In addition to common benefits like access to information on-the-go, these devices may empower people with disabilities to be more independent [62,98]. However, Duff et al. [33] found that people with motor impairments exhibit more errors with touchscreen technology than those without. Additionally, people with upper body motor impairments can experience difficulties performing multi-touch gestures and text entry [3,132] or even pulling a phone out of the pocket or a bag [98]. Irwin et al. [61] investigated the use of touchscreen technology by people with gross motor impairments and found that this group exhibits longer dwell times compared to those without. When touchscreen input was compared with mouse input, Findlater et al. [35] found that though touchscreen input was faster for people with motor impairments, it also led to a three-fold increase in pointing (tapping) errors on the touchscreen compared to the mouse.

Some approaches to address these problems have used the edge of the screen to stabilize gestures [38,140], or a swiping ("swabbing") interaction rather than tapping, which allows the user to stabilize their finger on the screen itself [135]. For common touchscreen gestures like tapping, crossing and directional gesturing, Guerreiro et al. [45] found that targets located at the bottom of the screen and next to the preferred hand were the easiest to select. Specific to tap gestures, while Montague et al. [92] investigated touchscreen interaction behaviors in the wild and built and evaluated a novel approach to accommodate individual differences, Mott et al. [94] built and evaluated a technique to accommodate multiple touch points to map the user's intended behavior. These studies highlight that mobile devices like smartphones and tablets can offer benefits like independence, but accessibility challenges still exist. The focus of this dissertation is wearable technologies that may have smaller touchscreen areas (e.g., smartwatches) when compared to smartphones and tablets for interaction which may result in additional challenges.

General Wearable Input Technologies

There is extensive research exploring general wearable input for quick information access like using gesture-based interactions for wrist worn wearables (e.g., [76,112]), twisting and sliding interactions with rings (e.g., [6]), muscle-computer interfaces (e.g., [118]), and on-body or skin-based interactions (e.g., [47]). However, people with upper body motor impairments may find it challenging to use these input techniques. For people with upper body motor impairments, wearable device research has largely focused on wearable sensors for medical diagnoses or motor rehabilitation purposes [148]. Some projects have investigated wearable input to control wheelchair movement (e.g., using the tongue [59]) or to control desktop computers (e.g., inertial sensors [111]). However, these projects are different from my goal of exploring ways to make existing wearables accessible. In the following subsections, I discuss literature on the three common classes of wearables: head-mounted displays, health and fitness tracking wearables and, lastly, smartwatches.

Head-mounted Displays

Extensive work has been done with head-worn displays in the fields of augmented and virtual reality spanning applications in areas as military, navigation, industrial design, and medicine. Techniques to control the information in augmented reality have included fingertip tracking (e.g., [73]), gaze tracking [70] and speech input (e.g., [101]). More specifically related to accessibility, head-mounted displays have been employed to provide memory or other cognitive assistance for older adults [71] or users with cognitive impairments [48,144]. For example, Kunze et al. [71] conducted semi-structured interviews and shadowed three older adults using Google Glass to identify potential application scenarios. The scenarios included short-term memory augmentation, long-term capture and access, timers and reminders, and instructions (e.g., for cooking). While most of the studies have focused on exploring opportunities for different groups of people, my dissertation research investigates interaction techniques to make head-mounted displays accessible to people with upper body motor impairments.

Three studies closest to the goals of this dissertation come from McNaney et al. [88] and Carrington et al. [21,22]. McNaney et al. [88] investigated the applicability of Google Glass for users with Parkinson's disease and found potential benefits with Glass like support for self-management. Their participants also experienced issues with Glass' built-in touchpad and voice recognition. Furthermore, the first study by Carrington et al. [21] employed participatory design to explore input-output mechanisms on and around the wheelchair for mobile computing. In a follow-up, Carrington et al. [22] proposed a pressure-based touchpad input device mounted on the wheelchair's armrest that could be used to control a mobile device. As with the earlier design investigations, Carrington et al.'s focus was not on controlling information on a head-mounted display; however, the approach could be used in that context.

Health and Fitness Tracking Technologies

In a survey of mobile-health interventions, Klasnja and Pratt [68] found that automated fitness tracking most commonly targets walking, running, biking, and climbing stairs. Benefits have included positive impacts on health-related behaviors, increased awareness of one's own behaviors, and support for opportunistic engagement in desired behaviors [68]. Issues, however, include people's perceptions about how activities are tracked [145], dealing with tracking errors, visualizing large amounts of data, and respecting users' privacy [68]. The ultimate goal of these technologies is often to impact long-term behavior change but Harrison et al. [53] describe the challenges associated with long-term studies, including unreliability of devices and engagement with them. Hence, Klasnja et al. [67] argue that an important role for human-computer interaction (HCI) researchers is to focus on the user experience, design, and shorter-term evaluation of new prototypes; our work aligns with this role.

The majority of design-oriented research on activity tracking has targeted the general population and, to a lesser extent, older adults. As an early example, Consolvo et al. [27] combined wearable activity sensing with ambient mobile phone displays to promote fitness. Focusing on older adults, Davidson et al. [28] examined use of health-related apps and, through participatory design, identified potential improvements such as tracking social interaction. In contrast, little work has studied the accessibility of activity tracking for people with mobility impairments with the exception of Carrington et al. [18] where they investigated the use of wearable fitness trackers with five wheelchair athletes and three caregivers. While none of their participants had first-hand experience with wearable trackers, participants demonstrated interest in tracking wheelchair movement, breathing, heart rate and/or nutrition. Although not studying people with mobility impairments specifically, Beevi et al. [12] showed that pedometer accuracy decreases as walking speed slows. Several other studies have investigated activity tracking for manual wheelchair users, finding that off-the-shelf trackers are not accurate [56]. However, custom sensing algorithms that primarily use accelerometer data have provided high accuracy in detecting wheelchair activities [55,105,127]) such as resting, propulsion, arm ergometer, and desk work. For propulsion, placing the accelerometer on the person’s arm is more accurate than placing it on the wrist or seat [100]. Simple classification of floor surfaces has also been examined [36]. This body of work shows that more accessible sensing algorithms exist even if they have not yet been adopted in commercial devices. However, the technical focus of these studies leaves open questions about what users want to track and how to design the interfaces to be accessible. An exception comes from the recently released Apple Watch 2 [4] which can track two manual wheelchair activities like wheelchair rolling. But, little is known about the general accessibility of this device, a problem that we address in Chapter 6.

Smartwatches

Studies on smartwatch usage patterns (e.g., [120]) have found that smartwatches are used as an extension to smartphones, commonly to receive notifications. Compared to smartphones, benefits of smartwatches include faster access to information and less likelihood of misplacing the device [7].

However, the small input/output interaction space may result in the fat-finger problem (e.g., [5]). To overcome these problems, many research studies have focused on new interaction techniques for smartwatches, albeit not usually with accessibility in mind: wrist-based interactions to keep hands-free (e.g., [44,46]); mechanical input techniques utilizing the watch faces (e.g., [143]) and non-visual gestures like covering the watch face (e.g., [102]); utilizing the wristband for multi-touch gestures (e.g., [2]) and text entry (e.g., [39,42,142]); using page flip gestures for interactions [50]; utilizing non-vocal acoustic input [49]; and, lastly, utilizing the space around the smartwatch (e.g., [52]). Kerber et al. [66] compared existing mechanical inputs (bezel rotations and digital crown) and touch interactions of a smartwatch and found that users preferred the digital crown interaction over others. To enhance the user experience of the smartwatches, while Gong et al. [43] explored haptic feedback mechanism that displaces the watch from its original location, Huang et al. [58] utilized a shape-changing display on the back of the smartwatch to allow the user to sense feedback on their skin. In terms of interaction in different settings, Mo et al. [91] investigated the use of smartwatches in mobile contexts like walking and running and found that while walking and operating the smartwatch was similar to sitting, running impacted overall use. In addition to contexts like walking and running, Singh et al. [125] explored interaction techniques in cases when only one hand is available compared to both hands for panning and zooming gestures.

For people with disabilities, various smartwatch applications have been explored. Some examples include applications to inform people who are hard-of-hearing about environmental sounds [89], to help people with mild cognitive impairments overcome challenges related to employment [30], to help people with ADHD overcome stress and anxiety and maintain focus via intervention techniques [29], to track the safety of people with complex communication needs [134], to support daily activities for the elderly [75] or activities for young adults with intellectual and developmental disabilities that require emotional and behavioral skills [147] and also as a fall detection system [13]. Smartwatch applications are also commonly used for tracking and monitoring purposes like monitoring the physical health of people with dementia [14], monitoring patients in intensive care and alerting the doctors [130], monitoring symptoms of [122] and also adherence to speech and voice exercises [32] for people with Parkinson's disease. For people with vision impairments, applications for face recognition system [128] and navigation [40] have also been investigated.

In terms of accessible interaction techniques, a combination of smartphone and smartwatch for gesture control for people with low vision has been explored [104], with the smartwatch acting as an input device to record participants' arm gestures. The smartphone then recognized the gesture and performed the desired task. Chen et al. [24] also explored a set of blowing-based gestures into the smartwatch, as an interaction technique for stroke victims, people with epilepsy or spinal injuries. However, none of these studies have investigated the general accessibility of devices for people with motor impairments. We address this gap in Chapter 6 and also design and evaluate a potentially accessible interaction technique in Chapter 7.

Sharing Health and Fitness Data

Online support groups with shared goals to manage different conditions have been widely studied for long-term behavioral change (e.g., [33]). For people without mobility impairments, sharing data from automatically tracked fitness activities has been shown to offer benefits such as motivation and reflection, but concerns can also arise around privacy and feelings of self-consciousness [37]. Previous studies have recommended types of health and fitness-related data to share (e.g., calories burned) [96] and with whom to share (e.g., people with similar goals) (e.g., [96]). At the same time, sharing broadly with an entire social network can lead to a disinterest in sharing owing to lack of support from social networks [96]. Another concern with sharing health and fitness data on the internet is that users will misdiagnose themselves [1], but previous work also suggests that patients do not use these communities as primary sources of medical information [129].

As already mentioned, people with mobility impairments may be interested in sharing health and fitness data with other users who have similar conditions [19,81]. However, what data to share, how to share it, and the potential impacts of this sharing have received little attention for people with mobility impairments. One exception, published only as a poster, is a study where 248 people with multiple sclerosis (MS) used a commercial wearable, Fitbit One, to track and share their activity data (e.g., number of steps) with other MS patients in the online community *PatientsLikeMe* [86]. Sixty-eight percent of participants reported that the Fitbit One helped them track and manage their MS better. Inspired by this work, we conduct a technology design-oriented study with both therapists and participants who have a broad range of functional abilities, and report in greater depth on the perceived implications of sharing this automatically tracked data (Chapter 5).

Social Considerations of Wearable Technologies

In my dissertation, I investigate the potential benefits and challenges of emerging wearable technologies for people with motor impairments and implement and evaluate ways to make these technologies accessible. While mainstream wearable technologies can offer new or improved functionality compared to smartphones and tablets, interacting with these wearable technologies may give rise to several social concerns (e.g., [34,108,109,114,115]), which may also impact overall adoption [64,109], such as: To what extent will a wearer be comfortable wearing and interacting with the device in public settings? Are some locations on the body, clothing or assistive aids such as wheelchair more suitable and appropriate than other locations? What are the perceptions of bystanders (e.g., privacy concerns) about the use of wearable devices in public settings?

For people with disabilities, these concerns may be heightened as the design of the device may mark the wearer as having a disability or may bring unwanted attention [81,124,146]. In terms of locations for wearable input, people with visual impairments expressed that the hands and arms were the most socially acceptable for on-body locations [99]. For female users, locations like the sternum may be socially unacceptable; however, opinions may change in contexts like running or walking [64]. Previous research (e.g., [109]) has found that the perceptions of bystanders are important to consider too. Profita et al. [108] explored bystander perceptions about the use of an HMD in social settings and found that bystanders find it acceptable if an HMD is used to support a person with a disability. At the same time, privacy concerns for the user and the bystander (e.g., *Is the device recording me?*) still remain unaddressed. As wearable technologies are worn on the body, clothing or wheelchair, they have an additional social consequence such as being subject to judgement by bystanders. Factors such as their appearance, location on the body where the wearable is worn, and interaction design should be examined while designing future wearables. In Chapter 3, we built wearable touchpads of different sizes such that they could potentially be used in social settings. We examined their use and overall social acceptability and reported on participant perceptions in Chapter 3.

Summary

In this chapter, we discussed the state-of-art in four areas related to my dissertation. First, our work extends research on existing mobile and wearable computing technologies by enriching the understanding of the potential benefits and challenges of emerging wearables like head-mounted displays, fitness trackers and smartwatches for people with motor impairments (Chapters 3 and 4). Second, we investigate the potential of sharing health and fitness-related data tracked by wearables and its impact on stakeholders including therapists by building on current research about online sharing of health and fitness data in Chapter 5. Lastly, we build on the growing body of work on the design and evaluation of input technologies for people with motor impairments for head-mounted displays and smartwatches and also reflect on the design for social use in Chapters 3, 6, and 7.

Chapter 3 : Personalized Wearable Control of a Head-mounted Display for Users with Upper Body Motor Impairments

Introduction

Wearable technologies like head-mounted displays (HMDs) are always available and have the potential to offer hands-free interaction for mobile information access for people with motor impairments. These technologies also have the potential to mitigate manual input challenges already experienced by people with motor impairments when using smartphones and tablets (e.g., [3,98,132]). To ensure that people with motor impairments have the opportunity to use these wearable technologies, we investigated the accessibility and the potential impacts of HMDs and designed and evaluated a novel accessible input solution for HMDs. More specifically, we investigated the following research questions:

- To what extent are existing HMDs, e.g., Google Glass, accessible to people with upper body motor impairments?
- What are the advantages and disadvantages of personalized switch-based wearable touchpads to control a head-mounted display for mobile information access?

Toward the first research question, we conducted a formative study with six people with upper body motor impairments. In this study, participants performed a series of tasks on a Google Glass device using the built-in input (touchpad and voice commands) and output (visual display in front of the right eye) mechanisms. We found that while some participants faced challenges like not being able to reach the Glass touchpad, others thought Glass offered benefits like not having to hold the device. Based on the findings from this study, we built simple, customizable wearable touchpads that could be placed anywhere on the body or wheelchair of the participant to use Glass. Towards the second research question, we conducted a controlled experiment with twelve participants and evaluated the input performance of three sizes of touchpads and explored personalization patterns of touchpad placement (on-body or wheelchair). All participants from this study were able to use these wearable touchpads. We also found that touchpad placement depended on participant's motor abilities, highlighting the need for personalization. This study demonstrated one alternative accessible way for people with upper body motor impairments to control an HMD like Google Glass.

The first research question contributes to the first thread of my dissertation and the second research question contributes to the third thread of my dissertation. This work was published at the *ACM Conference on Human Factors in Computing Systems (CHI)* in 2015 [80].

Background

Users with upper body motor impairments such as tremor, lack of sensation, or spasm, experience accessibility challenges with smartphones and other mobile devices such as performing basic multi-touch gestures like *zoom in* and *out* [3,132], text entry [3], or even pulling out a phone from the pocket [98]. In contrast, emerging mainstream head-mounted displays such as Google Glass offer new possibilities for accessible computing. Such devices are always available and offer relatively hands-free interaction, potentially alleviating the manual input challenges of today's smartphones and tablets. Recent work by McNaney et al. [88], for example, showed in a field trial with four participants with Parkinson's disease that Google Glass provided a sense of independence and security, and that few accessibility issues arose with device interaction. Similarly, Carrington et al. [21], conducted participatory design work on input and output opportunities that employ the space around a power wheelchair. Though participants in their study did not use a head-mounted display, several felt that it would be a useful output modality. In a follow-up to [21], Carrington et al. [22] proposed a pressure-based touchpad input device mounted on the wheelchair's armrest that could be used to control a mobile device. As with the earlier design investigations [21], the focus here was not on controlling information on a head-mounted display; however, the approach could be used in that context. The two studies presented in this chapter extend a small body of recent work [21,88] by both motivating the need for further research on accessible input for head-mounted displays and by providing promising directions for how to provide that input. Compared to smartphones, potential advantages of head-mounted displays included not having to hold the device while interacting with it, not having to look down to see the screen, and not having to worry about dropping and damaging the device.

ID	Age	Gender	Diagnosed Med. Condition	Mobile Device
P1	46	Male	Spinal cord injury (C5)	None currently
P2	25	Female	Cerebral palsy	Apple iPhone 5
P3	53	Male	Cerebral palsy	Basic phone
P4	25	Female	Cerebral palsy	HTC smartphone
P5	22	Female	Cerebral palsy	Apple iPhone 5S
P6	53	Female	Essential and orthostatic tremor	Basic phone

Table 3.1. Study 1 participants. All but P6 used a wheelchair.

Accessibility of Google Glass

To collect preliminary data on the potential impacts of a head-mounted display for people with motor impairments, we conducted a small study with one specific, yet popular device: Google Glass. While the findings from this study were limited to Google Glass, they motivated the subsequent and more general study on wearable touchpads.

Method

Six participants (4 female) with upper body motor impairments were recruited. Details are shown in Table 3.1.

Each session lasted one hour and included a background questionnaire (demographics and current mobile use), tasks with Google Glass, and a semi-structured interview on the experience of using the head-mounted display. Glass provides input through a touchpad on the right arm of the device that senses taps and swipes, and through voice commands. Output is through the head-mounted display that sits in front of the right eye and a bone-conduction headphone. For the Glass tasks, the researcher first demonstrated the touchpad and voice commands. The participant then completed a series of tasks for about 20 minutes, such as viewing activity on the timeline, looking up the weather, and taking pictures. The task completion required at least 8 forward swipes, 3 backward swipes, 11 downward swipes, 12 taps, and 10 voice commands. Because of accidental taps and swipes, these numbers are a lower bound. For participants who could not reach the touchpad, the researcher performed that input.

	Visual Display		Touchpad Gestures		Voice Commands
	Comfort	Ease	Comfort	Ease	Ease
Median	2	2	3	2	1
M	2.2	2.2	3	2.7	1.7
SD	1.2	1.2	2.2	1.9	1.2

Table 3.2. Ease of use and physical comfort ratings for Glass interactions in Study 1 (1=very easy/comfortable to 5=very difficult/uncomfortable).

Following the tasks, participants used 5-point scales to rate the physical comfort and ease of use of the touchpad and the visual display, and ease of use of the voice commands. The session concluded with open-ended questions about the potential impacts of head-mounted displays and brief feedback on design ideas for alternative forms of input beyond the built-in touchpad. Sessions were video recorded and analyzed to observe interaction successes and challenges, and to summarize open-ended responses.

Findings

Table 3.2 summarizes participant ratings on ease of use and physical comfort. Overall, ratings were neutral to positive.

Input Mechanisms: Touchpad and Voice Commands

The accessibility of the touchpad depended on each participant's motor abilities. For P1, P3, and P5, the touchpad was not accessible at all and the researcher ultimately had to perform their taps and swipes. P1 and P5 could not physically reach the touchpad, although for P5 the touchpad use may have been possible had it been on the left side of the device; she had limited movement in her right hand. P3, in comparison, could reach the touchpad but could not tap or swipe on it without physically displacing the device. After a few attempts, he asked the researcher to perform the gestures. The other participants, P2, P4, and P6, encountered fewer difficulties, although their error rates when attempting taps or swipes were still 11% (of 61 interactions), 37% (of 93) and 18% (of 65) respectively. For P4, by far the most common problem was that the touchpad did not respond to her input. This issue occurred 16 times, and was perhaps due to the angle at which she was able to approach the touchpad. She also had persistent trouble correctly locating the touchpad, despite intervention.

For voice commands, only P3 encountered difficulty. He had dysarthria (slurred speech) and for him the device only successfully recognized the word ‘Google.’ P1 and P4 expressed surprise at how well Glass recognized their voices. P2 suggested that Glass should be fully accessible by voice and wanted voice commands like ‘Go Back’ or ‘Home Screen’ to replace swiping or tapping multiple times on the touchpad. These findings are in contrast to McNaney *et al.* [87], whose participants experienced issues with voice input perhaps because they used Glass in a variety of settings and for a wider range of tasks.

Visual Display

All participants were able to read text on the display when prompted. However, P3, P4, and P5 needed the display to be frequently adjusted because it moved when they tapped or swiped. P4 had problems keeping her head upright, which impacted her ability to look at the display. During the session, she asked to be strapped to her wheelchair so that she could sit up and see the display better. Participants did not complain about the font size or size of the display.

Potential Impacts of a Head-mounted Display

Comparing Glass to a mobile phone, three participants mentioned the touchpad on Glass as a disadvantage. Advantages, however, included, not having to look down at the display (P2, P4), keeping the hands free (P2, P4, P6) and reducing the risk of dropping and damaging the device (P1). For example, P1 said:

> *"That someone who has limited mobility could wear a technological device without fear of dropping or damaging it that seems a lot more useful than a notepad or a laptop in my aspect, in my living situation."*

P2 expressed the ease of not having to hold her phone:

> *"My hands are free. It didn't require me to pick up anything as opposed to having to pick up this [phone] and you know look down on it and you know I was looking up so I didn't have my head down."*

Feedback on Alternative Input Ideas

At the end of the session we briefly introduced theoretical alternatives to Glass's touchpad: mid-air gestures, wearable physical buttons, and a portable touchpad. While the responses were generally positive, each participant had different yet specific places where they would like the touchpad to be located, like the armrest, joystick or tray. We explore this finding further in Study 2. Participants also spoke about using body and facial movements and customized voice commands as other alternatives.

Summary and Discussion

For our six participants, Google Glass presented exciting possibilities for mobile information access but also serious accessibility challenges. The always-available nature of Glass allowed easy access to information on the go, without the physical requirement to hold a mobile phone. At the same time, half of the participants could not use the touchpad input. These findings motivated our next study, where we evaluated personalizable wearable touchpads of different sizes to control Glass. Again, our goal is to design and assess alternate input systems for head-mounted displays like Google Glass that can provide mobile information access for users with upper body motor impairments.

Personalized Wearable Touchpads

To investigate the use of configurable, wearable touchpads for accessible control of a head-mounted display, we built a prototype system and conducted a controlled experiment with 12 participants with upper body motor impairments. The study was designed both to assess user performance with different sizes of touchpads as well as to characterize how participants would want to customize touchpad locations.

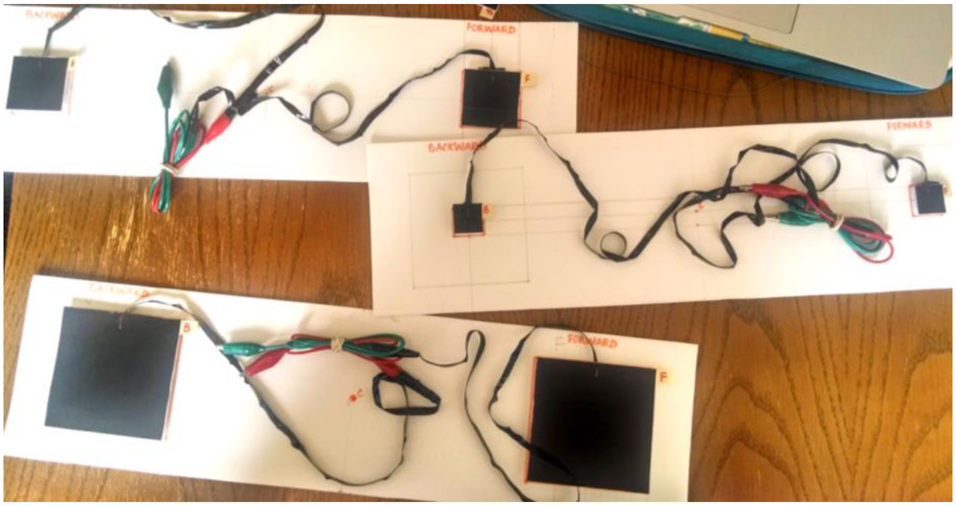

Figure 3.1. Two touchpads labelled forward and backward were placed 32cms apart. Participants tapped back and forth on each size – small (2cms), medium (4cms) and large (8cms) based on fits law.

ID	Age, Sex	Reported Medical Condition	Smartphone?	Uses wheelchair?	Box-and-Block (# denotes dominant hand)	
					Right	Left
P1	46, M	Spinal cord injury, C5	Yes	Yes	0	$16^{\#}$
P2	25, F	Cerebral palsy	Yes	Yes	$8^{\#}$	2
P3	21, F	Cerebral palsy	No	Yes	2	$12^{\#}$
P4	23, M	Spastic quadriplegia, neuromuscular scoliosis	Yes	Yes	$32^{\#}$	23
P5	25, M	Cerebral palsy	Yes	Mobility scooter	$22^{\#}$	10
P6	23, F	Cerebral palsy, Spastic quadriplegia	Yes	Yes	0	$4^{\#}$
P7	47, M	Myotonic muscular dystrophy	Yes	No	$10^{\#}$	7
P8	31, M	Spinal cord injury, C6 and C7	Yes	Yes	$29^{\#}$	11
P9	53, F	Essential and orthostatic tremor	Basic*	No	$53^{\#}$	48
P10	22, M	Cerebral palsy	Yes	No	46	$46^{\#}$
P11	52, M	Right side paralysis	Basic*	Yes	7	$23^{\#}$
P12	61, F	Hemorrhagic stroke	Yes	Yes	$53^{\#}$	0

Table 3.3. Study 2 participant demographics, smartphone use, wheelchair use, and Box-and-Block Test results for both hands (higher values represent higher manual dexterity). *P9 and P11 used basic phones and reported iPad use. (L=left hand, R =right hand)

Method

The study included three tasks: (1) a reciprocal tapping task to measure baseline performance with three sizes of touchpad; (2) another controlled tapping task, but with the touchpads placed at custom locations on the participant's body or wheelchair; and (3) a more realistic task where participants used their preferred touchpad configuration to control a small app on the head-mounted display.

Participants

Twelve participants (5 female) with upper body motor impairments were recruited. See Table 3.3 for detail. To gain a baseline understanding of manual dexterity and variation across participants, we administered the standardized Box-and-Block Test [85]. This 5-minute test involves moving blocks one at a time across a partition and provides dexterity scores per hand. Typical adult scores range from about 80 for younger adults to about 60 for older adults [85]. Our participants' scores, shown in Table 3.3, ranged from 0 (no use of the hand) to 53. Three participants (P1, P2, P9) had used Glass in the preliminary study, while the others had no prior experience. All participants were volunteers and were compensated for their time.

Apparatus

We built a custom, reconfigurable system that used four touchpads made of pressure-sensitive conductive sheeting to control a Google Glass device (Figure 3.1). The touchpads, each on a piece of flexible foam backing, were connected to an Arduino Uno board that sensed taps using the CapSense library. Touchpads of different sizes could be easily swapped out during the study. A Motorola MotoX phone running Android v4.4.2 acted as a mediator between the Arduino and Glass. The phone was paired with the Arduino via a BlueSMiRF HID Bluetooth modem, and communicated with it via the Amarino app [65]. This app received data about the taps from the Arduino and sent it to a custom Bluetooth chat application on the phone (built in Java), which in turn forwarded the input to Glass. An Android application was written for Glass to display visual task prompts and communicate with the phone. It also logged interactions with the wearable touchpads.

Procedure

Study sessions lasted two hours. The session began with a background questionnaire on demographics and technology experience, followed by the Box-and-Block Test. Participants were briefly introduced to Glass and tried out swipes and taps on the built-in touchpad. They then completed the three following tasks:

Task 1: Reciprocal Tapping. Participants tapped back and forth between two touchpads placed on a table in front of them (Figure 3.2 left). Three touchpad sizes were presented in counterbalanced order: 8 cm (large), 4 cm (medium), and 2 cm (small). The two touchpads (per size) were placed 32 cm apart, as measured from the centers of the touchpads. We chose these widths (W) and the distance (D) between them to cover a theoretical range of pointing difficulties. The Fitts' law indexes of difficulty (ID) were 2.3, 3.1 and 4.0 for the large, medium and small touchpads respectively, where $ID = \log_2 (D/W+1)$ [60].

For each touchpad size, participants performed four practice taps (2 on each touchpad) using their dominant hand. The test trials were then presented—16 alternating taps—and participants were asked to tap as quickly and accurately as possible without stopping. The Glass display presented visual prompts to "*tap forward*" (right) or "*tap backward*" (left) for each trial. Success and error sounds played for correct and incorrect taps. The software only advanced to the next trial after the correct touchpad was tapped. After using each size, participants rated ease of use and physical comfort of performing the taps on 5-point scales. Overall feedback was solicited after all three sizes were complete.

Task 2: Location Customization and Tapping. Four touchpads labeled *forward*, *backward*, *select* and *cancel*, based on the four basic manual inputs of Glass were used. Sizes were presented in the same counterbalanced order as in the reciprocal tapping task. For each size, participants were asked to place the four touchpads anywhere on their body or wheelchair that was “accessible and comfortable” for them. The researcher affixed the touchpads to skin, clothing or the wheelchair using Velcro straps, Velcro tape, or adhesive tape (Figure 3.2 right). Participants then tested out the touchpad locations and practiced tapping each one twice (a total of 8 taps) and were given the opportunity to adjust the locations if desired; 6 did so. Then, 32 test trials were presented (8 per touchpad). The order of prompts was randomized, with the constraint that no two consecutive taps could be on the same touchpad. As with the first task, participants were asked to tap quickly and accurately, and success and error sounds played. After each touchpad size, participants rated ease of use and physical comfort on a 5-point scale. They were also asked to provide rationale for their choice of locations. At the very end of the task, we asked about overall size and location preferences.

Task 3: Final Configuration and Realistic Use. Briefly, to provide a reminder of Glass’s functionality, we again had participants try the swipes and taps on the default touchpad (~1 minute). Then, to provide a more realistic experience of using wearable

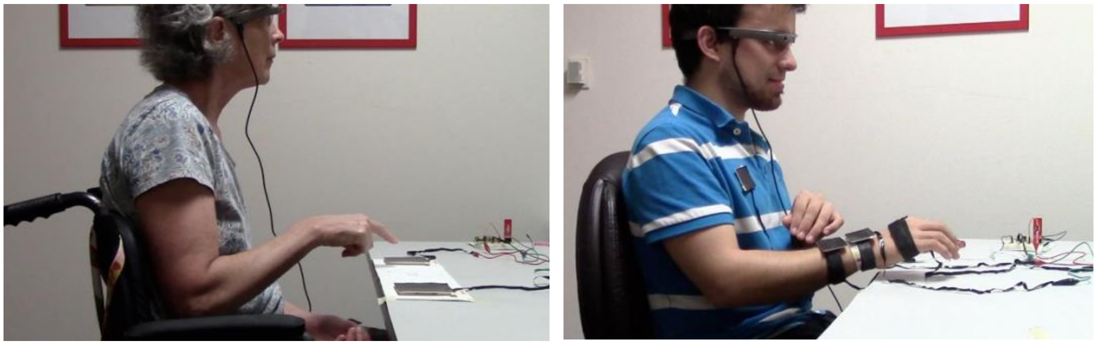

Figure 3.2. Touchpad configurations in the two tasks. P12 performing Task 1 with large touchpads placed 32 cm apart on the table (left). P10 performing Task 2 with the medium touchpads placed on selected locations: on the wrist, palm and chest (right).

touchpads to control a head-mounted display, participants used a simple, custom Glass application. It included pictures, description and weather information on two cities, ordered hierarchically with 3 screens per city. Similar to Task 2, participants created a personalized input system by choosing different locations. In this task, however, they could select any size of touchpad and mix different sizes in case some were deemed to be more useful for particular locations. The four touchpads emulated the functionality of the Glass touchpad: *forward* and *backward* navigated the current level of the hierarchy, *select* provided more detail on an option (*e.g.*, moving down a level in the hierarchy), and *cancel* closed the current page or returned to the previous level. Participants first tapped on each touchpad to make sure they could reach it and were given a chance to change the locations or sizes. Participants were asked to take a few minutes to explore the application and had to try using each of the four inputs at least three times while doing so.

The session concluded with a final semi-structured interview on the experience of using the wearable touchpads and their potential impacts on accessibility of a head-mounted display. All interviews were audio and video recorded. P7 was not able to see the Glass display due to a visual impairment, so for him all visual prompts were presented on a laptop screen instead.

Design and Counterbalancing

We used a within-subjects design with a single factor of *Touchpad Size.* It had three levels: *small* (2 cm), *medium* (4 cm), and *large* (8 cm). For a given participant, touchpad sizes appeared in the same order for both tasks. Order of presentation was fully counterbalanced, with an equal number of participants randomly assigned to each order.

Data and Analysis

One-way repeated measures ANOVAs with a single factor of *Touchpad Size* were used to analyze the timing data for each of the first two tasks. Post-hoc comparisons were protected against Type I error using Tukey HSD. Our primary performance measure is speed. The system did not advance until the participant had correctly completed the current trial, which means that *speed* includes an implicit error penalty. We do not present a separate error analysis because the system could not detect missed taps, such as hits just outside a touchpad's bounds.

While all participants completed the full study procedure, only 10 participants are included in these performance analyses for Tasks 1 and 2. For both tasks, the log files for P1 were not accurate because of a calibration issue with the touchpads. For Task 1 only, we excluded P6's performance data because we had to reduce the distance between the two touchpads to accommodate her limited range of motion. For Task 2 only, we excluded P4's performance data because he placed the small touchpads very close to each other, which caused interference for the capacitive sensing. In all, we analyze 2×8×3×10 = 480 trials for Task 1, and 4×8×3×10 = 960 trials for Task 2 (number of touchpads × repetitions × sizes × participants). For rating scale data, we used non-parametric Friedman tests. Finally, open-ended responses were analyzed based on themes of interest [15] (*e.g.*, rationale, impacts of motor ability), while allowing for new, emergent themes.

Results

We cover performance and subjective results for Tasks 1 and 2, as well as, based on Tasks 2 and 3, themes in personalization rationale and the experience of using wearable touchpads to control a head-mounted display.

Performance

Task 1: Reciprocal Tapping Task. This task provides a baseline performance assessment for the touchpad sizes in an ideal setup. As expected, *Touchpad Size* significantly impacted tapping speed. As shown in Figure 3.3, the average tapping time per trial was 2.7s ($SD = 1.3$) for the small touchpads, 1.8s ($SD = 1.0$) for medium, and 2.0s ($SD = 1.1$) for large. A one-way repeated measures ANOVA revealed a main effect of *Touchpad Size* on average trial completion time ($F_{2,18} = 8.57$, $p = .002$, $\eta^2 = 0.49$). Post-hoc comparisons indicated small touchpads were slower than both the medium ($p < 0.01$) and large ($p < 0.05$) sizes. No significant difference was found between medium and large sizes.

For subjective feedback, most participants ($N = 8$) found the large touchpad easiest to use, followed by medium and small ($N = 2$ each). The majority of participants ($N = 7$) also found the large touchpad to be the most physically comfortable, while 4 said medium, and 1 felt all sizes were similar. Participants provided ratings on ease of use and physical comfort, which are summarized in Table 3.4. While the mean ratings on both measures improve (*i.e.*, become closer to 1) as the target size increases, Friedman tests were not statistically significant for either measure.

Task 2: Location Customization and Tapping Task. As with Task 1, *Touchpad Size* again impacted tapping speed. As shown in Figure 3.3, average trial times were 3.2s (*SD* = 1.5) for small, 2.5s (*SD* = 1.3) for medium, and 2.2s (*SD* = 0.96) for large touchpads. Across all touchpad sizes, these speeds are only 0.4s more than the baseline tapping speeds collected in Task 1, which shows that the personalized locations offer feasible input performance. A one-way repeated measures ANOVA revealed a significant impact of *Touchpad Size* on tapping speed ($F_{2,18} = 9.55$, $p = .001$, $\eta^2 = 0.51$). Post-hoc comparisons showed that the small touchpads were significantly slower than both the medium ($p < 0.05$) and large ($p < 0.01$) sizes.

Overall, large and medium touchpads appeared to be preferred to small touchpads for this task, with the following distribution of votes for most preferred size: 4 (large), 5 (medium), and 2 (small); one participant could not choose between small and medium. The ease of use and physical comfort ratings, shown in Table 3.4, support this trend. The mean ratings for the small touchpads were worse than for medium and large touchpads, although a Friedman test did not find a statistically significant impact of *Touchpad Size* on either measure. Encouragingly, the mean ratings for the larger two sizes were about 2 on a 5-point scale, meaning “*easy*” and “*physically comfortable*.”

Personalization: Touchpad Placement and Rationale

We provide detail on placement and rationale findings from Task 2. Because rationale trends were similar in Task 3, where participants could personalize their input with

Task 1: Reciprocal Tapping	**Small**		**Medium**		**Large**	
	Comfort	**Ease**	**Comfort**	**Ease**	**Comfort**	**Ease**
Median	2	3	2	2	1	2
M	2.4	3.4	2.1	2.5	1.8	2.3
SD	0.9	0.9	0.9	1.2	0.9	1.3
Task 2: Location Customization	**Small**		**Medium**		**Large**	
	Comfort	**Ease**	**Comfort**	**Ease**	**Comfort**	**Ease**
Median	2	3	2	2	2	2
M	2.7	2.8	2.0	1.9	2.1	2.0
SD	1.2	1.1	1.0	0.8	1.1	1.1

Table 3.4. Ease of use and physical comfort ratings for Tasks 1 and 2 (1 = very comfortable/easy and 5 = very uncomfortable/difficult). (N = 12)

multiple touchpad sizes at once, we highlight only the choice of sizes selected in that task.

Placement. In Task 2, participants chose a wide variety of locations for touchpad placement; see Table 3.5 for detail. Of the 8 wheelchair users, 2 placed all sizes of touchpad on their body only (thigh, wrist, palm, and chest), 3 chose their wheelchair only (tray and joystick), and 3 chose a combination of wheelchair and body locations. P5, on a mobility scooter, placed all touchpads on his body, "*Because I'm not on my scooter all the time, it has to be on my body. It will be easier for me.*" Among all the locations, the most popular choices were the thigh (*N* = 7) and wrist (*N* = 5). For wheelchair users, the tray was the most common location, followed by the joystick. While P9 and P12 chose

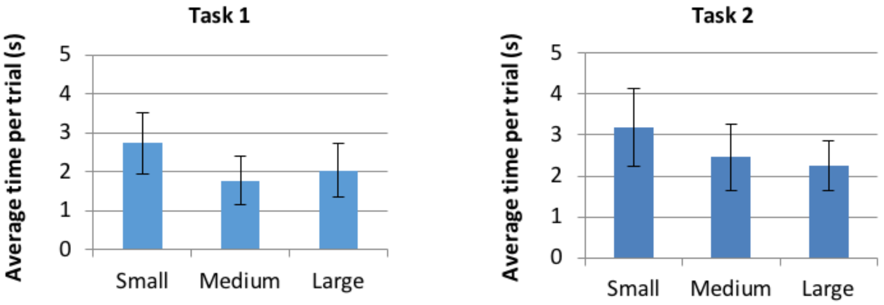

Figure 3.3. Average time per trial in Task 1 (reciprocal tapping) and Task 2 (location customization). The small touchpads were significantly slower than the other two sizes in both tasks. (N = 10; error bars: 95% confidence intervals).

the same locations for all three sizes, P1 and P5 had to adjust their configuration to accommodate the largest size (for P5 this meant using both thighs instead of one).

Rationale. Rationale for touchpad placement was an open-ended question and participants could provide more than one reason for each touchpad size. The reasons were similar across sizes, so we present an aggregate analysis.

As expected, participants' motor abilities impacted their touchpad personalization. Overall, the most common reasons for selecting locations were ease of reach ($N = 8$) and proximity to the dominant hand/arm ($N = 6$). For example, P6 had a Box-and-Block score of 4 in her left (dominant) hand and we had adjusted the touchpad locations in the reciprocal tapping task so that she could reach. She accommodated this limited range of motion by placing all touchpads on her tray close to her left hand, saying: "*I didn't have to stretch too far*." As another example, P7 initially placed all large touchpads on his left arm. After the practice, however, he moved the topmost one to his knee because of the difficulty of lifting his arm high enough to reach it: "*Easier to tap and [on the arm it had been] difficult for my hand to reach as far as I need to.*"

Another anecdote on the impact of personalization comes from P8, who described a problem in how he typically uses his touchscreen phone. He cannot point perpendicularly to the screen because the low strength in his hand causes instability when the fingers bend. Instead, he taps the screen with his knuckles. With the personalized layout, he placed the touchpad sideways on the wheelchair cushion, which allowed for tapping with the side of the hand; Figure 3.4. He thought of this option in time for the last touchpad

Figure 3.4. Large and medium personalized touchpad placement for P8, showing a perpendicular approach that requires bending at the knuckles (left) compared to an "easy" approach from the side with vertically placed touchpads (right).

size (medium in his case), saying, *"It was just easy."*

Three participants (P8, P9 and P12) talked about placing the touchpads close to where their hands rest in their natural state. For P9, the desire to rest her hands was due at least partly to her tremor. She said before initial touchpad placement: "*I mean most naturally my hands would rest here [points to thigh] so like I guess on my thighs.*" Other reasons for placement included arranging touchpads based on their meaning (*e.g. forward* in front of *backward*) to remember the order (*N* = 4), wanting the touchpad to be easily visible (*N* = 3), reducing interference with the wheelchair (*N* = 2), and using familiar locations (*N* = 10).

Finally, three participants commented on the emergent benefit that their touchpad placement allowed for eyes-free use so they could maintain visual attention on the head-mounted display—an important practical consideration for control of such a display.

Interference with Typical Movements

An important potential downside of wearable input is the possibility of interfering with typical body movements or other worn items. The majority of participants (*N* = 8) felt

ID	Small	Medium	Large
P1	Joystick, wrist, neck lanyard	Joystick, wrist, lanyard on neck	Joystick, wrist, thigh, neck lanyard
P2	Tray	Tray	Tray
P3	Tray, joystick	Tray	Tray, joystick
P4	Fingers	Fingers, wrist	Chest
P5	Thigh	Thigh	Thigh
P6	Tray	Tray	Tray
P7	Wrist	Thigh	Arm, thigh
P8	Thigh	Cushion of wheelchair	Thigh
P9	Thigh	Thigh	Thigh
P10	Chest, neck, palm	Chest, palm, wrist	Thigh, back of hands
P11	Joystick, armrest, wrist, thigh	Joystick, armrest, back of hand	Joystick, wrist, thigh
P12	Thigh, Wrist, Palm	Thigh, wrist, Palm	Thigh, wrist, palm

Table 3.5. Choice of touchpad locations per participant per size. All but P5, P7, P9, and P10 use a wheelchair.

that the large touchpads would interfere with body movements, and few (*N* = 4) also felt they would interfere with items worn on their body. P1, for example, said of the large size, "*…they would alter the way I would normally do things.*" Only at most 3 participants felt the small or medium touchpads would interfere with body movements, worn items, or wheelchair movements. Two participants (P8, P9) had mentioned taking interference into account during touchpad placement. Another issue considered by P12 is that an ideal placement while seated may be different while walking.

Overall Location and Size Comparisons

Preferences regarding the touchpad sizes after Task 2 varied. The surface area of the large touchpads was an advantage for some participants as it did not require precise tapping (P5, P11), but a disadvantage to others, who felt that it led to accidental taps (P6 rested her hand close to the touchpads), was too cumbersome (P9), or took up too much space (P6, P7, P8). The small touchpads, however, provided more options for placement (P6, P9) but required more precise movement (P7, P12). The medium size was a nice compromise for some (P5, P7, P8, P12). When asked to compare locations they had tried across the three sizes, many responses were similar to the earlier rationale responses (*e.g.*, thigh is easy to reach). P1, however, commented that the lanyard placement he had used was difficult because it made for a moving target.

In Task 3, participants mixed different sizes to create a personalized input system with four controls. The variation in choices again supports the need for personalization. Eight out of 12 participants combined different sizes: 4 used medium and large, 3 used small and medium and 1 used all three sizes. Other participants used all small (P1, P9), all medium (P8), or all large (P4) touchpads. Dominant reasons provided for these choices were similar in pattern to those at the end of Task 2, such as ease of reach.

Comparison to Glass's Built-in Touchpad

Participants used Glass's built-in touchpad twice during the study: once as an introduction and briefly as a reminder before Task 3. The wearable touchpads were considered by almost all participants to offer accessible control of a head-mounted display, and compared favorably to Glass's built-in touchpad. While 4 participants (P1, P3, P6, P7) could not reach the touchpad on Glass, all 12 were able to use the wearable touchpads to complete the study tasks. Six of the 8 participants who *could* reach the Glass touchpad still felt that the wearable ones would positively impact their ability to use a head-mounted display, for example, *"More accessible"* (P10), and:

> *"For me, with my arm and hand issues, it's much more difficult to keep going here [points to Glass] than it is to rest my hands on my lap and just tap what I need to." (P9)*

When asked how the wearable touchpads would impact their ability to independently use a head-mounted display compared to Glass's touchpad, nine felt that the wearable option would provide more independent use, and two thought the options were similar. That said, one participant (P12) mentioned an important drawback of the wearable approach—that it requires effort to do the customization rather than having an all-in-one device.

As it did with placement rationale, the desire for eyes-free input arose again. Participants were split on how the wearable option would impact their ability to pay attention to their surroundings. On the positive side ($N = 6$) were participants like P9, who felt the wearable touchpads were easy to tap without looking, "*Because I got to choose where they were [...] plus it was all kind of the same movement*." On the negative side ($N = 2$), P12 appreciated that Glass's default input was designed to not require visual attention.

Social Considerations

Issues such as aesthetic design and social awkwardness are common with wearable devices [110], and, unsurprisingly, a few participants mentioned such concerns. P1 and P9 felt the large touchpads would be awkward to use in a public place. P8, who had placed the touchpads on the cushion of his wheelchair for his personalized setup said:

> *"You're a bit more incognito [than with Glass's touchpad...] I could sit there for a while clicking on [the wearable touchpads] and I bet this [Glass's touchpad] would be weird and stupid and annoying sitting over here tapping on my face for longer than 30 seconds or 8 taps."*

One participant mentioned stigma around assistive technology [123], a concern that could be magnified in the context of wearable devices. P1 said of the large touchpads:

> *"…I don't want to look like R2-D2. I want people to see [name] and not his [wheel] chair so I would not use these big ones […] they stand out too much."*

Some participants offered new ideas for controlling the head-mounted display, and again social considerations arose. P8 compared head movements to voice input, saying: *"Speaking is not something I want to do in public, only nodding to cancel is something I would want to do."*

Discussion

The two studies presented here extend a small body of recent work [20,87] by both motivating the need for further research on accessible input for head-mounted displays and by providing promising directions for how to provide that input. In Study 1, participants reacted positively to the idea of using a head-mounted display, as embodied by Google Glass. Compared to smartphones, potential advantages included not having to hold the device while interacting with it, not having to look down to see the screen, and not having to worry about dropping the device. While preliminary, these findings suggest that such a device may offer important opportunities to increase mobile computing accessibility for users with upper body motor impairments.

Design Reflections

The findings from Study 2 point to the promise of a wearable switch-based control that can be personalized to a user's motor abilities. All 12 participants were able to use the wearable touchpads to control the display, including those four who could not use Glass's built-in touchpad. The relatively small difference between performance in the baseline condition (reciprocal tapping on the table) and the wearable condition supports the feasibility of our approach in terms of providing efficient input. Finally, in contrast to work with wheelchair users only (*e.g.*, [20]), our participants also included non-wheelchair users and one person with a mobility scooter. This diversity provides a degree of generalizability to the population of users with upper body motor impairments, although more work is needed.

The utility of personalizing wearable input to support individual motor abilities was demonstrated in Study 2, and provides evidence to strengthen suggestions made in previous work [20]. Participants selected varied locations (wrist, thigh, arm, tray, armrest) for the wearable touchpads and even mixed sizes when given the opportunity. The most common reason for selecting a location was “ease of reach,” with detailed description often revealing the participant’s consideration of their motor abilities. A downside of personalization is the effort required (*e.g.*, mentioned by P12) and the potential, particularly for wearable input, that the input device will need to be adjusted each day. An important area of future work is thus to investigate easy-to-adjust wearable mounting mechanisms or permanent placement on the chair itself for wheelchair users. Carrington *et al.*’s [20] chairables work provides guidance in this latter direction.

Wearable touchpads do present some practical issues. The possibility of interfering with everyday activities such as body or wheelchair movements was of particular concern with the large touchpads. Smaller touchpads may mitigate this issue. Capacitive touchpads, as used in Study 2, are also not likely to be the best approach. Although they require little strength to activate, they are also more susceptible to being accidentally triggered than a mechanical button would be. However, the findings from our study should apply to other switch-based input if the goal is to support personalization.

Our focus was to build a solution that could: be socially acceptable, support use in a mobile context, be easy to learn, and be accessible to users with varying levels of physical strength. Our wearable touchpad approach supported these goals yet is only one potential solution. Alternatives to manual input will also be important to explore. For example, ideas of eye-gaze and head-controlled input were raised by our participants. Using a smartwatch to remotely control the information on an HMD is also another possible, and an accessible solution of this form could be based on the findings in Chapters 6 and 7. Expanded speech input offers another possibility for accessible control of a head-mounted display, but it was not usable for one Study 1 participant due to dysarthria and was mentioned as inappropriate for social reasons in Study 2. The need for accessible manual input remains important.

Conclusion

In conclusion, our first study brought up accessibility challenges with Google Glass and our second study with simple, personalized wearable touchpads offered one promising direction for accessible control for people with upper body motor impairments. In addition to HMDs, the wearable technology spectrum also includes devices like fitness trackers and smartwatches which have the potential to offer benefits and overcome existing problems with smartphone interactions. The next chapters in this dissertation focus on the accessibility of fitness trackers (Chapter 4) and smartwatches (Chapters 6 and 7).

Chapter 4 : Toward Accessible Health and Fitness Tracking for People with Mobility Impairments

Introduction

Another genre of wearable technologies are health and fitness trackers that sense data like steps taken, calories, floors climbed, distance walked/run. These wearables act as facilitators to maintain or change health-related behaviors [103]. In the United States alone, there are 15 million people who have mobility impairments and find activities like running, walking and climbing stairs difficult or impossible and may use assistive aids like walkers, canes and wheelchairs [17]. These impairments impact can physical activity levels, thus putting people with mobility impairments at a higher risk of obesity and other medical conditions like diabetes [136]. However, little is known about the accessibility of existing mobile and wearable activity trackers for this group. Hence, we investigated two research questions:

- To what extent are existing wearable and mobile health and fitness tracking technologies accessible to people with mobility impairments?
- How can we build accessible fitness tracking technologies for this group?

To investigate these questions, we conducted in-person interviews where we evaluated two commercial wearable trackers and concluded the session with a participatory design activity with 14 people with a range of mobility impairments. A subset of this group also opted in a week-long field trial to evaluate the accessibility of a mobile fitness app. As a result, we found multiple accessibility problems: irrelevant tracking, inaccessible form factor, small size of the display and buttons. Our participatory design

ID	Age, Sex	Diagnosed Medical Condition	Mobility Aid(s) Used
P1	26, F	Cerebral palsy	PWC
P2*	26, F	Cerebral palsy	PWC
P3*	22, M	Cerebral palsy	No
P4*	56, M	Spinal cord injury, L1, T12, paraplegia	MWC
P5*	62, F	Hemiplegia, stroke	Cane (home); MWC (long distances)
P6*	37, M	Cerebral palsy	PWC; MWC (home)
P7	72, F	Osteoarthritis; knee replacement	Walker (home); walker with a seat
P8*	32, M	Spinal cord injury, C6	MWC with power assist wheels
P9*	31, F	Spinal cord injury, T6	MWC; walker occasionally (home)
P10	63, M	Spinal cord injury, T11, paraplegia	MWC; leg braces (sometimes)
P11*	38, F	Muscular dystrophy type 2	PWC
P12	47, M	Spinal cord injury, C5, tetraplegia	PWC
P13	56, F	Multiple sclerosis	PWC
P14	23, M	Cerebral palsy	No; PWC & MWC; crutches

Table 4.1. Participant demographics and self-reflections on fitness level. '*' denotes participants who also completed the optional diary study. For participants who reported use of multiple mobility aids, the one used on the day of the study is listed first.

activity revealed that all participants wanted a wearable form factor that would be easy to put on, unobtrusive and embedded within an existing object to overcome stigma associated with assistive technology. Additionally, we provided design guidelines to build a personalized tracker that would support a wide range of users with mobility impairments and include guidance on user safety and sharing data with relevant people.

These research questions contribute to the first thread of my dissertation. This work was published at the *International Conference on Pervasive Computing Technologies for Healthcare* in 2016 [81].

Method

We conducted a study with 14 participants with mobility impairments to assess the accessibility of health and fitness trackers. All participants completed an interview and participatory design activity, while eight also opted in a week-long field evaluation of a mobile app. The initial session captured health and fitness attitudes, and use and

ID	Rating^a (1=Extremely fit, couldn't be better; 2=I'm almost fit; 3=I don't think I am fit, I need some work; 4=I'm not fit at all)	Frequency of Fitness Activity^b (days/week): Rarely=1-2 days, occasionally=2-3 days, almost every day=5-7 days	Activity Duration
P1	3	Rarely	30 – 60
P2	2	Occasionally	30 – 60
P3	3	Rarely	30 – 60
P4	2	Occasionally	60 – 90
P5	3	Almost everyday	30 – 60
P6	4	Never	N/A
P7	3	Rarely	30 – 60
P8	3	Rarely	< 30
P9	1	Almost everyday	60 – 90
P10	2	Occasionally	60 – 90
P11	3	Rarely	< 30
P12	3	Rarely	< 30
P13	4	Almost everyday	30 – 60
P14	2	Almost everyday	60 – 90

Table 4.2. Participants' self rating, frequency of fitness activities and activity duration.

perception of tracking tools, while the field portion captured challenges encountered in practice.

Participants

We recruited 14 people (7 female) with mobility impairments, ranging in age from 22 to 72 (*M* = 42.2, *SD* = 16.9). Details are shown in Table 4.1 and 4.2. Participants were recruited through a local organization that works with people with mobility impairments and by word of mouth. All were volunteers and were compensated $40 (for time and travel). Eight of them opted into the field study.

Fitness Trackers

Participants evaluated three complementary fitness trackers: Fitbit One and Moov, wearable devices and Pacer, a smartphone app (Figures 4.1). The *Fitbit One* uses a three-axis accelerometer and an altimeter to continuously track steps, distance, calories burned, stairs climbed, and sleep. It uploads the data to a computer or phone for users to set goals, record food intake, and communicate with their social network. It is often

Figure 4.1. Left: Fitbit One (top) and Moov (bottom) devices used in the lab session. Right: Examples of prompts used for the participatory design activity: form factors (left), measurement targets (top), output (right), and input (bottom). Blank paper was also provided to sketch new ideas.

worn clipped to clothing; without the clip, it is eight grams and 19×48×10 mm. The *Moov* fitness band, in contrast, attaches to the wrist or ankle. It includes an accelerometer, a gyroscope, and a magnetometer. Unlike Fitbit's always-on tracking, Moov is billed as a personal fitness coach for workout sessions. The band provides limited interaction, but a paired smartphone app provides audio output and access to data (e.g., cadence, time, calories). It weighs eight grams and has a 36mm-diameter face. Finally, for the diary study we selected *Pacer*, a simple tracking app that is popular, free, and available for both Android phones and iOS. It does not require a login ID, which we felt could be a barrier to participation. It uses the phone's built-in sensors to track steps, calories, distance and active minutes, and GPS to track activities like biking.

Procedure

The procedure included a 90-minute interview and design session, followed by a field study. All interviews were semi-structured.

Interview and Design Session in the Lab

This session was conducted in a controlled setting. It consisted of:

Background (10 minutes). This section covered demographics, current motor abilities, and use of mobility aids.

Current fitness practice and attitude (20 minutes). We asked about the importance of physical fitness, physical activities and/or reasons for not participating in fitness activities, and challenges faced in doing these activities. We also asked about experience with professional fitness trainers and therapists and with health and fitness tracking mechanisms, including wearable devices, mobile apps, or low-tech strategies (e.g., paper diaries).

Assessment of wearable devices (30 minutes). Participants evaluated the Fitbit One and Moov in turn. For each device, we first briefly introduced the main features. The participant then placed the device where they wished on their body or mobility aid and moved around for a few minutes (walked or rolled their wheelchair). Afterward, the participant and researcher reviewed the tracked data together. The researcher asked about the overall experience of using the device, accessibility issues, and relevance of the data. Finally, the participant compared the two devices.

Participatory design activity (20 minutes). Participants designed a tracking device that would meet their health and fitness needs. Participants first viewed a slideshow of seven existing wearable and mobile technologies for inspiration. They then described their ideal device in terms of: form factor (e.g., wearable, mobile app), what activities to track, and interface input and output. For each dimension, a set of paper prompts was provided (Figure 4.1) but participants could also sketch or describe new ideas.

Field Study and Follow-up Interview

Participants could opt into a week-long diary study if they owned an Android or Apple phone and were willing to install the Pacer app. Each evening for a week, they took a screenshot of the app and completed a short online questionnaire (~5 minutes) that included: (1) a physical activity report for the day, (2) perceived accuracy of the app in terms of reflecting the day's activities, and (3) unexpected experiences with the tracking. After a week, we conducted a 30-minute phone or in-person interview on the participant's experience, perceived changes (if any) to their activity level, and, once again, perceptions of activity tracking.

Data and Analysis

All sessions were audio recorded and transcribed. Because this was an exploratory study, we used a thematic coding approach with a mixture of inductive and deductive codes [15]. Members of the research team discussed and iterated on the initial set of codes. One researcher then independently conducted a pass over the data, refining the code set and adding new codes, followed by another team discussion. After another refinement cycle, we used a peer debriefing approach for validation [10]: another person not on the research team, but who was familiar with accessibility issues, critically analyzed coded transcripts randomly selected from four participants (two initial session transcripts and two follow-up interview transcripts). For each transcript, the peer reviewer and the original coder resolved disagreements and uncertainties through consensus; only seven disagreements occurred out of 161 total codes. The final code set included 32 codes for themes that spanned the entire dataset, such as tracking interest, sharing, likes and dislikes, as well as smaller subsets of codes that only applied to specific interview questions (e.g., Fitbit utility).

Findings

Throughout, we focus on (1) the extent to which existing tracking mechanisms meet the needs of our participants, and (2) desirable features for more accessible designs.

Current Fitness Attitudes and Practice

All participants felt that fitness was at least somewhat important to them, with half saying it was very important. They reported a range of physical fitness attitudes and levels of activity (Table 4.1). Common activities included stretching (7/14), swimming (5/14), moderate walking (4/14), home chores like cleaning, vacuuming and cooking (3/14) and weight training (3/14). Two participants also used a Rifton stander[1] and gym equipment like functional electrical stimulation (FES) bicycles. P1 performed exercises like crunches, side bends and leg lifts in her power wheelchair.

Participants also discussed challenges to participating in fitness activities, including current health issues preventing them from performing exercises (6/14), cost (4/14), and self-consciousness (2/14). P11 said, for example, "*I've been to gyms and people stare, plus I cannot change clothes to wear appropriate workout attire*." Finally, another common issue (8/14) was not wanting to perform exercises alone, often due to low motivation, but sometimes the fear of injury. For example, P12, who had a spinal

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[1] http://www.rifton.com/products/standers

cord injury, said, *"…if I fall and I can't get back up and if I'm alone in my house, you know, that could be terminal."*

Physical therapists and trainers played an important role in participants' fitness activities. The majority of participants either currently (4/14) or previously had (7/14) a therapist or a personal trainer. These professionals helped with specific exercises such as stretching to improve range of motion or lifting weights, but also provided general motivation and assistance in using equipment at the gym. Several participants set goals with their trainers, like losing weight, building strength, and improving range of motion and motor control. For these participants, designing to support this relationship with a therapist or trainer could be useful.

Current Users of Tracking Technologies

Several participants used low-tech tracking strategies for health or fitness, while just under half had experience with mobile and wearable tracking (contrasting the participants in [18]).

Experience with Low-tech Tracking Strategies

Demonstrating an interest in health and fitness tracking, eight participants mentioned using a low-tech system like a diary or chart. Four participants tracked diet and nutrition using a paper diary, with one person (P9) also using it for swimming and sleep. Other mechanisms included daily tracking charts and forms required by the participant's adaptive gym.

A few participants (P9, P10, P14) wanted to improve their current tracking by making it electronic. However, highlighting the perception that high-tech trackers are inaccessible for people with mobility impairments four others thought their mobility issues would cause a problem with such a move. P5, for example, talks about how typing is inefficient due to limited use of her hand:

> *"Well, it's easier for me to use it on paper than it would be on a computer just because I only have one hand to type with."*

Experience with High-tech Tracking Strategies

While most participants were aware of health and fitness tracking apps, only a few had first-hand experience with them. P8 and P14 used *Fooducate* and *LooseIt* mobile apps to track diet, P5 used the *Runkeeper* app to track walking (P5), P14 used *Pact* to track gym attendance (P14), and P9 tracked swimming with *Meet Mobile: Swim*. Of these, *Runkeeper* and *Pact* do automatic activity tracking. For wearable devices, P3 had used a *Fitbit Flex* wristband for three months but replaced it with a *Pebble Watch* as he found that he could do more with the watch besides just fitness. P11 used a power wheelchair but had some experience with a Fitbit, through buying one for her mother and observing its use.

Participants found these technologies useful both for tracking specific data and for general motivation. P5, who walked with a cane for short distances, describes tracking her walks with the Runkeeper app:

> *"It tells me how fast I'm going and how long I've walked and how far, and it gives me information about my elevation."*

P11, was impressed by the social aspects of Fitbit:

> *"I think it's good because it motivates you. [...] You can have friends, so my mom had my two cousins and they would try to beat each other. So that was exciting."*

At the same time, all six participants also commented on accessibility challenges they had experienced, emphasizing the importance of more inclusive designs even for these experienced users. The physical form factor was mentioned by P3, who had difficulty keeping the wraparound band of the Fitbit Flex on his wrist. A more common challenge, however, was manual input, which three people mentioned as difficult with their mobile app (P8, P11, P14). This challenge, common with any manual tracking [11], may be magnified for people with motor impairments.

Another critical issue was tracking accuracy, which can impact users in different ways. P14, for example, found that the Pact mobile app, which uses an accelerometer to sense activity, sometimes overestimated his activity level:

> *"...because I walk with more movement than other people it believes that I'm exercising when I'm just actually walking."*

P5 had the opposite experience with Runkeeper, which uses GPS for tracking, finding that it sometimes did not recognize that she was moving: *"...my normal walking pace* *is so slow that they don't consider me moving.”* These two comments highlight the potential need for personalized algorithms to ensure inclusive tracking.

Overall Perceptions of Tracker Accessibility

When it came to accessibility for fitness tracking, specifically, most participants (8/14) felt that existing devices were not relevant to their abilities, which echoes a concern of Carrington et al.’s [18] wheelchair athletes. P8, for example, uses a manual wheelchair and has experience with mobile food tracking. He had considered using the Fitbit or the Apple Watch, but assumed they would not be accurate because they focused on steps and *“…I’m moving my arms and nothing else.”*

Summary

Interest in tracking health and fitness activities is evident not only from the current adoption of high and low-tech tracking strategies, but also from participant comments. However, even for participants who regularly used high-tech health or fitness tracking, accessibility barriers and uncertainties about the tracking functionality persist. At this stage in the study session, these concerns were hypothetical for most of our participants (and confirm similar findings from [18]’s smaller study), thus we now turn to a hands-on evaluation of two wearable trackers.

Lab Evaluation of Wearable Trackers

For the assessment of the two wearable fitness trackers, we focus on three emergent themes: physical design and placement, tracking functionality, and other accessibility barriers.

Fitbit One

Physical design and placement. Many participants were pleased by the aesthetics or size of the Fitbit and, directly related to accessibility, P4 and P8 commented that the rubber exterior made it easy to grip. At the same time, a critical challenge was to clip on the device without assistance—four participants said they would always need help. Seven participants placed the device on their clothing (e.g., collar or sleeve), four chose areas on the wheelchair (e.g., seatbelt, pouch or cushion; Figure 4.2), two chose a waist strap, and one chose the wrist. The most common justifications choosing a location were ease of use or ease of clipping on the Fitbit (9/14). P7, for example, referred to ease and independence when describing why she attached the device to her sleeve: *"…it's easily accessible, I can put it on myself, and I can read it easily from this angle."* Another concern was how to place the tracker to ensure it would work for non-walking movement. P12, who uses a power wheelchair, described his thought process:

> *"I don't know if it would measure [body movement] just by hanging on my shirt or clipping it to the fleece of my fleece sweats here. […] I could attach it to the collar of my shirt […] but since I'm moving my shoulder, I'm not sure what stimuli it's gonna be looking for to put it in the best place."*

What Fitbit tracks. While four participants thought steps would be useful, only two thought floors climbed would be useful. Calories burned was received much more positively (13/14), though in practice calories would be computed based on steps and floors climbed—so in effect would not be accessible.

Other accessibility barriers. Other challenges included pressing the button (P1, P12), not tracking data that would support wheelchair users (P2, P4, P6, P10), the small size of the display and button (P1, P3, P4, P7), accessing information on the go (P5) and being waterproof to support activities like swimming (P9).

Moov

Physical design and placement. With Moov's watch-like design, all but one participant wore it on the wrist; the exception was P8, who stored it in his wheelchair pouch as he had for the Fitbit. P4, who uses a manual wheelchair, initially experimented with placing it on his ankle. Despite the appeal of a familiar and unobtrusive form factor, nine participants were concerned about being able to put the device on independently.

While four wheelchair users reported that placing the device on the arm was useful because their arms would generate the most activity, P10 was concerned that his choice of the wrist would cause interference with his ability to push his wheelchair: *"when I'm rolling, the arms are constantly moving and sometimes having any immovable object*

Figure 4.2. Two left images: P8 (left) stowed the Fitbit One in a pouch under his seat and P10 (right) clipped it on the seatbelt. Two right images: P3's log showing more activity than expected (left) and P9's log showing much less activity than expected (right).

attached to the arm is a little irritating." Participants also appreciated various aspects of the device, including the audio feedback (6/14) and aesthetics overall (6/14). P7 described the audio feedback as, *"…it's almost like she's another person walking with you or something. […] I like that."*

What Moov tracks. In contrast to the Fitbit, participants were less positive about what Moov tracks, with eight participants saying it was not relevant to them. The active coaching was frustrating for P11, for example, because it did not align with her abilities:

> *"It already told me that I wasn't walking brisk enough. So how do I know it was really measuring what I was doing?" Still, three participants appreciated the real-time feedback.*

Other accessibility barriers. Moov's two-device design—a band paired with phone for auditory and visual output—was problematic. Nine participants expressed concern about balancing the two devices. Some comments also reflected the general accessibility challenge of pulling out and holding a phone [97], such as when P7, who uses a walker, said: *"I was able to hold [the phone] and walk, but I'd say that's awkward. So, if it were all on the wrist, I think that would be great."*

Comparison and Summary

Participants spoke of positive aspects of both devices, including aesthetics and physical design details for Fitbit, and the familiar form factor of Moov. But, some participants had difficulty putting the devices on independently and the tracking capabilities did not meet most participants’ needs. When asked which device would best fit their abilities, eight chose the Fitbit, five chose Moov, and one was undecided. Participants who chose Fitbit primarily cited the problem of handling two devices with Moov.

Envisioning an Accessible Tracker

Following the evaluation of Fitbit and Moov, participants had the opportunity to design their own ideal fitness tracker. They often ended up creating multiple designs; for example, Figure 4.3 shows glove and wheelchair armrest designs from P6.

Overall design requests. Although the form factor prompts included a mobile app, participants unanimously created wearable designs. Most participants wanted a device that would be easy to put on, unobtrusive (similar to desires for accessible wearable devices in general [79]), or embedded within an existing object; Gloves were a popular form factor, selected by seven participants; for example, P10, a manual wheelchair user, said, *“…if the sensors could be embedded in the gloves that I'm already wearing that would be great.”* Although four participants chose a wrist-based form factor, using the Moov device earlier in the study also made some participants realize that a wrist-based device may be hard to put on independently and may interfere with wheelchair movement. This finding contrasts [18], where participants wanted a wrist-based tracker but had no first-hand experience using one.

Similar to [18], popular tracking targets were vitals, calories burnt and duration, all desired by half of the participants. Several participants also wanted dietary information

Figure 4.3. An example from the participatory design activity. Here, P6, who uses both power and manual wheelchairs, chose two form factors: wheelchair armrest and glove. The device should have simple button or knob input and visual, haptic, and LED output. He wanted to measure heart rate, calories, water consumed, food intake, and mental wellbeing.

like food and water intake (6/14). For input and output, half of the participants wanted a button, like on the Fitbit, to switch between information displays but three said they preferred no input at all. Others mentioned a swiping gesture, twisting, and other forms of buttons. All participants except P8 wanted output (in contrast to the Moov).

Impact of mobility level. To capture common variation due to mobility level, we grouped participants by the type of mobility aid used during the session: power wheelchair (6), manual wheelchair (4), and walker, cane or no aid (4). While all three groups followed the trends above, a few unique desires arose. Wheelchair users spoke about form factors on and around the wheelchair (e.g., on the joystick, armrest or wheels). These participants also showed interested in tracking activities related to their wheelchair, such as movement, pushing and miles rolled. One power wheelchair user wanted wheelchair movement but also posture tracking. Participants who used walkers, canes or no assistive aids commonly wanted to track walking. These differences highlight the need for building better tracking algorithms that would adapt to the person’s abilities, for example, the cases P5 (slow movement) and P14 (too much movement).

Safety features. P3, P5 and P12 also wanted to address the danger of falling while exercising (not one of our design prompts). P3 wanted a distress call feature that could detect falls and call for assistance, but at the same time, P5 mentioned the stigma associated with such devices for older adults. P5 thought that embedding fall detection functionality into the tracker would be useful, as it would be hidden within the mainstream device.

Social features. Although the design activity focused on the device itself, we asked participants earlier in the interview session about sharing fitness tracking data with others. Participants mentioned that they would like to share this data with their friends (7/14), family (6/14) and health professionals (12/14). Two participants also wanted to share information with other people who have similar motor abilities. P5, for example, discussed the idea of sharing data with a stroke support group:

> *“Well, I think sharing with other people in the same situation is, well, probably can't say always but almost always beneficial 'cause you all have the same struggles.”*

Summary

Participants’ designs and rationale suggest that: (1) an unobtrusive wearable form factor is best but it needs to be easy to put on and take off; (2) desired tracking functionality is largely similar to what existing devices support; (3) preferences related to mobility level suggest that it will be important to cater to the needs of each user (e.g., tracking rolling or posture).

Field Evaluation of a Mobile Fitness App

During the field study, eight participants made 48 diary entries and shared screenshots (Figure 4.2); P2 deleted the app after two days to free up space on her phone. The diary entries included a variety of physical activities, such as using the Rifton Stander, household chores, wheelchair rolling, and taking steps with assistance. Participants did not report accessibility challenges in using Pacer's touchscreen interface, but other problems related to the phone arose, such as limited storage space on the phone (P2) and high battery consumption (P8). The main emergent themes, however, were about tracking accuracy and participants' overall experiences with and attitude toward fitness tracking.

Tracking accuracy. Reinforcing earlier findings, half the participants felt the app did not accurately record their activity and the other half felt it worked only to an extent. At the same time, there were some positive surprises. For example, P4 experimented with "bike mode" after finding that the app did not sense his wheelchair rolling. As another example, P3 noted in a diary entry:

> *"I was surprised to see a [sic] finally reached a higher activity category than 'Sedentary,' and this felt good. I hope to surpass even this level at some point in the future! :-)"*

Participants also had differing interpretations of the impact of inaccurate tracking. For P9, not only were the steps inaccurate but also the calorie count and number of active minutes, measures she had expected to be more inclusive—after a full day of wheelchair use, the app reported only 1 minute of activity and 2-4 calories burned. But P8 interpreted the data more abstractly: *"…it's not accurate in the sense of the actual steps I was doing but it is accurate, it captures the same amount of activity level."*

Finally, participants speculated on reasons for inaccurate tracking. P2 and P9 thought the location of their phone might have been an issue. Seven of the eight participants sometimes missed an activity because they did not have their phone on them—this particularly affected P9, who swims and rows. P2 also mentioned a frequent issue of her aid holding her phone:

> *"She takes it from me and gives [it] back to me once I reach the top. I have a stair lift. I push the button and goes up and it tracks the steps for my aid."*

Follow-up attitude toward fitness trackers. Several participants liked the idea of a tracking app that could be tailored to their abilities and reported overall positive experiences during the field evaluation. P3, P4, and P11 felt they had been more active than usual during the week of the study and appreciated that effect, a finding shown in other short-term field studies with fitness trackers (e.g., [48]). P9 describes her positive experience:

> *"Neat to be able to track how physically active you are each day. I think my attitude changed for the better. But wearables would be even better, I would prefer a separate device."*

Conversely, two participants (P5, P8) were skeptical and thought mobile apps for tracking would not be effective for them. P5 said:

> *"It could be that [Pacer is] not just sensitive enough to low-level activity that a disabled person has. Like taking a shower is an activity for me but not for you."*

Summary. In contrast to [18], half the field study participants were positive and felt the tracker worked at least to some extent; three reported increased motivation to be active. The field study highlights the main problem of inaccuracy with activity tracking mobile apps. Another issue that majority of the participants faced was that the phone could not capture all of their activities since it was not always with them. These results also reinforce our findings from the in-lab assessment with wearables.

Discussion

This study builds on an emerging, but nascent, body of work on the design of accessible fitness technologies for people with disabilities. Our findings highlight the desire of participants with a spectrum of mobility impairments to use activity trackers. Even with an off-the-shelf mobile app, half of our field study participants were positive and felt the tracker worked at least to some extent; three reported increased motivation to be active. However, even participants who had already adopted tracking technologies encountered persistent accessibility issues, ranging from the basic form factor of the device to what is tracked.

We confirm several findings from Carrington et al.'s interviews with wheelchair athletes [18]—most notably the perception that fitness trackers are inaccessible for wheelchair users and that manual wheelchair users commonly want to track vitals, pushing and distance rolled. However, by employing a more complete methodology with a wider range of users than [18], we also extend our understanding of how to design accessible fitness trackers in several important ways (see next section). As well, unlike the underlying assumption in [18] that existing devices are inaccessible, we showed the extent to which these trackers do work, such as tracking distance using GPS, in unexpected use cases (e.g., bicycle mode to track rolling), as an abstract record of activity (e.g., more "steps" today than yesterday), and for people with mobility impairments who are ambulatory.

Toward More Accessible Fitness Tracking

As a formative, qualitative study, our findings help provide specific design guidance and ideas for future work.

A wearable form factor. Although we identified physical design issues with Fitbit and Moov, participants unanimously opted for wearable devices over mobile apps. This desire was partly due to the difficulty of holding the phone during activity; Moov's two-device approach (phone plus wearable band) was particularly problematic. One challenge with a wearable, however, is that either users need to be able to put it on independently or it needs to be incorporated into an existing object. One possibility of the latter for wheelchair users, as suggested by [18], is to mount the device on the wheelchair itself. While promising, this solution would not be effective for non-wheelchair users or for individuals who use a wheelchair part-time (four of our participants). Participants in [18] also wanted wrist-based trackers, but their opinions were hypothetical. In contrast, our participants used a wrist-based tracker during the study and were not as positive; gloves were more popular. Of course, questions of form factor and device placement will also affect how accurately different metrics can be sensed, so future work will need to balance accuracy with aesthetics (e.g., unobtrusiveness) and support for independent use.

Improved movement tracking—a role for personalization. There is a clear need for activity recognition that supports a wider range of human movement. Our findings suggest that personalized algorithms may play a key role in accommodating this range. From their study of wheelchair athletes, Carrington et al. [18] also called for updated algorithms, identifying the need for different algorithms for sport activity versus everyday wheelchair activity. Our findings, however, show that the problem of accessible tracking is more complex than sport versus everyday use. Manual, power and non-wheelchair users encountered different issues (e.g., inaccuracies with wheelchair tracking or low-level activity) and wanted to track different targets (e.g., posture, miles rolled). Even among those who were ambulatory, we observed different needs, such as slow vs. extraneous movement; problems with the former reflecting Beevi et al.'s [12] finding that pedometer tracking errors increase as walking speed slows. Future work will need to examine the extent to which personalized activity recognition can support this diversity of movement. If per-user calibration is needed, how to ensure that users can perform it independently and without undue effort is an open question. Finally, to mitigate issues of stigma surrounding assistive technology [123], it will be important to assess if these new algorithms can be incorporated into mainstream tracking devices with standard sensors.

Inclusive metrics. As a wider variety of movement is tracked to support people with mobility impairments, the metrics used in the user interface will need to expand accordingly. Some existing metrics already work: distance tracked by GPS was seen as useful in the Runkeeper app, while some ambulatory participants wanted “steps” or “stairs”. But, confirming Carrington et al. [18], “steps” as the primary metric is problematic, not least of all because it can lead to the misperception that these devices cannot measure other types of movement. While some participants in our study and in [18] were open to considering “steps” as an abstract measure of movement, others were understandably strongly against it.

S**ocial sharing.** Future design should also consider how to support social sharing effectively for users with mobility impairments. Some people may want to share data with other people who have similar mobility impairments (mentioned by two participants), which we revisit in depth in the next chapter (Chapter 5). Others may want to share with family members and friends without mobility impairments, but the question arises about whether it will be more motivating to present these comparisons abstractly (as suggested in our study), rather than, say, directly comparing a few hundred steps to another person’s few thousand.

Mental models. Participants had different perceptions about what activities are being tracked and how tracker placement impacted accuracy. Guidance for where to place a wearable tracker would be useful, especially for trackers with form factors that accommodate a variety of placements, such as Fitbit's clip or Moov's band. Educating users about how sensing technologies work will also help them understand what movement is counted as, for example, walking versus running steps.

Other design features. A few other design ideas arose. First, many participants were concerned about safety. Fall detection, which can cause stigma when provided in a standalone device, could unobtrusively be embedded within a fitness tracker. Second, a practical issue encountered in the field was inadvertent tracking when someone else pushed the user's wheelchair or held the user's phone (tracking device). The ability to quickly turn tracking on and off could prove useful for these situations.

Limitations

First, the assessment of the wearable trackers was limited to a lab setting and approximately 15 minutes each, while the field study was only one week long. Longer studies are needed to confirm our findings, since opinions could change with longer exposure to these trackers or to new, more accessible trackers. Second, as a formative, exploratory study, we conducted in-depth interviews to yield rich data. Our findings are thus largely based on self-report, with the exception of the daily screenshots from the Pacer app, and we cannot quantitatively determine the extent to which the tracking devices worked. Third, interesting patterns arose from grouping participants into three categories (power and manual wheelchair users, ambulatory participants), but further work with a larger sample size is needed to confirm these patterns. Lastly, our participants were all volunteers and we did not screen them based on how motivated they were to use tracking technologies.

Conclusion

In conclusion, our study identified several accessibility challenges but illustrated the enthusiasm that at least some users with mobility impairments have for activity tracking and the extent to which existing trackers can work, such as tracking distance via GPS or in unexpected use cases (e.g., a bicycle tracking mode). Future work needs to focus on wearables as opposed to mobile apps and on personalized tracking to accommodate a wide range of human movement.

A unique finding from this study suggested that people with mobility impairments wanted the ability to track and share their fitness related activities with peers with similar impairments. This motivated our next study (Chapter 5) where we investigate the impact of sharing health and fitness-related data with peers with similar impairments and also, their therapists.

Chapter 5 : Sharing Automatically Tracked Activity Data: Implications for Therapists and People with Mobility Impairments

Introduction

A unique component of wearables is its power to automatically and continuously collect and share large amounts of data about the wearer. A prominent example comes from activity-tracking wearables that offer the ability to share tracked activities often within online social networks but also for therapy purposes. Sharing fitness activity with peers can yield benefits like increased peer support and motivation (e.g., [131]). The recently released Apple Watch 2 is the first widely available mainstream device to track activities relevant to people with mobility impairments like wheelchair rolling. As activity tracking becomes more accessible to people with mobility impairments it is timely to consider what opportunities automatic tracking may offer to this population. We explore the potential impact of sharing automatically tracked data from wearable technologies with two groups – people with mobility impairments and their therapists. More specifically, we investigate the following research questions:

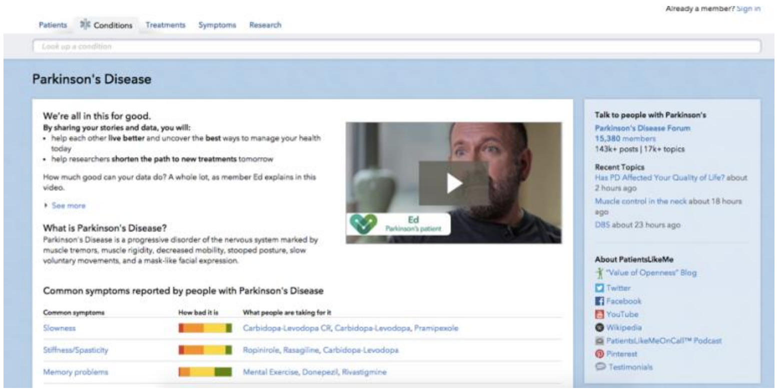
- How do people with mobility impairments feel about sharing automatically tracked data from wearables with their therapists and with peers who have similar impairments?
- How can automatic tracking technologies address issues related to therapy, inaccuracy and inconsistencies [72,126] from patient's self-reported fitness data, and potentially impact therapy practice?

To investigate these questions, we conducted semi-structured interviews with ten therapists and ten people with mobility impairments. The interviews with therapists also included a design probe activity with a website *PatientsLikeMe* to understand the perceived utility of their patient's tracked fitness data. Based on our findings, we present design opportunities to build tools to support sharing of tracked data with peers with similar impairments and therapists.

These research questions contribute to the second thread of my dissertation. This work was published at the *International Conference on Pervasive Computing Technologies for Healthcare* in 2017 [82].

Method

We conducted semi-structured interviews with 10 therapists (physical, occupational, recreational) and 10 people with mobility impairments. The interviews with therapists focused on understanding the opportunities and value of automatically tracked health and fitness data to therapy, while the interviews with people with mobility impairments focused on participants' interest in sharing such data both with therapists and with peers



Parkinson's Disease

We're all in this for good.
By sharing your stories and data, you will:

- help each other **live better** and uncover the **best** ways to manage your health today
- help researchers **shorten the path to new treatments** tomorrow

How much good can your data do? A whole lot, as member Ed explains in this video.

What is Parkinson's Disease?
Parkinson's Disease is a progressive disorder of the nervous system marked by muscle tremors, muscle rigidity, decreased mobility, stooped posture, slow voluntary movements, and a mask-like facial expression.

Common symptoms reported by people with Parkinson's Disease

Common symptoms	How bad it is	What people are taking for it
Slowness	🟥🟧🟨🟩	Carbidopa-Levodopa CR, Carbidopa-Levodopa, Pramipexole
Stiffness/Spasticity	🟥🟧🟨🟩	Ropinirole, Rasagiline, Carbidopa-Levodopa
Memory problems	🟧🟨🟩	Mental Exercise, Donepezil, Rivastigmine

Talk to people with Parkinson's
Parkinson's Disease Forum
15,380 members
143k+ posts | 17k+ topics

Recent Topics
Has PD Affected Your Quality of Life? about 2 hours ago
Muscle control in the neck about 18 hours ago
DBS about 23 hours ago

About PatientsLikeMe
"Value of Openness" Blog
Twitter
Facebook
YouTube
Wikipedia
PatientsLikeMeOnCall™ Podcast
Pinterest
Testimonials

Figure 5.1. Screenshot of the website PatientsLikeMe which was used as a design probe. This screenshot shows symptoms experienced by people with Parkinson's disease and treatments.

ID	Age	Gender	Type of therapist	Years of practice
T1	27	Female	Recreational therapist	4 years
T2	27	Female	Recreational therapist	4 years
T3	33	Female	Physical therapist	7 years
T4	42	Female	Physical therapist	1 year
T5	29	Female	Physical therapist	4 years
T6	29	Female	Physical therapist	5 years
T7	28	Female	Physical therapist	4 years
T8	26	Male	Physical therapist	1 year
T9	33	Female	Physical therapist	5 years
T10	44	Female	Occupational therapist	21 years

Table 5.1. Demographics of therapists.

who have similar impairments. We employed the *PatientsLikeMe* website (Figure 5.1) as a concrete model for how online sharing could work.

Participants

Participant details are in Tables 5.1 and 5.2. Participants were volunteers and were recruited through online advertising, word of mouth, and local organizations. All participants were compensated for their time. For the therapist group, we only recruited participants who had experience working with wheelchair users.

Interviews with Therapists

These semi-structured interviews were one hour long and consisted of the following sections.

Background (~5 minutes)

This section covered demographic information about the therapists, conditions and mobility impairments of their patients, and information about the number of patients they see and how often they see them.

Current Activities (~5 minutes)

We asked therapists about the activities performed by their patients during formal therapy sessions and use of any mechanisms to perform those activities. We also asked about what physical activities patients performed beyond regular therapy sessions and concerns patients may have about sharing those activities with the therapists.

Current and Desired Tracking Practices (~10 minutes)

We asked therapists about what physical activities contribute toward a patient's progress, the tracking mechanisms therapists use (if any) to monitor those activities, and the extent to which those mechanisms work. Therapists also answered questions about what physical or psychological data (the latter would need to be self-reported) they would want to see from outside of regular therapy sessions, as well as the perceived impact of this data towards therapeutic goals.

Existing Wearables and Exergames (~15 minutes)

We asked therapists whether they or their patients used any wearable or exergaming technology for health and fitness tracking purposes and the extent to which these technologies met their goals. We then explored the utility of these technologies toward therapeutic goals.

Design Probe (~20 minutes)

We used the website *PatientsLikeMe* as a design probe to explore opportunities that a similar website, but for health and fitness tracking of people with mobility impairments, could bring for therapists. *PatientsLikeMe* is a social network where patients share their health experiences with other patients who have similar conditions. As an example, searching for Parkinson's disease yields results including reported symptoms experienced by patients, drug treatments and patients' perceived effectiveness of those treatments, and demographic information of the patients who reported this data. We

ID	Age, Gender	Diagnosed Medical Condition	Mobility Aid(s) Used	Previous or current experience with therapist
M1	64, F	Mixed connective tissue disorder	Forearm crutch	PT and hand therapist
M2	65, M	Quadriplegic	MWC	PT and OT
M3	45, M	Friedreich's ataxia	PWC; scooter	PT and physical trainer
M4	32, M	Quadriplegic C4-C5	PWC	PT and OT
M5	32, F	Incomplete SCI	MWC; walker (at home)	PT, OT and RT
M6	64, M	Complete paraplegic	MWC	PT and OT
M7	63, F	Hemiplegia, stroke	MWC (long distances); cane (at home)	PT, OT and RT
M8	73, F	Osteoporosis	Walker with wheels and a seat	PT
M9	43, F	Arthritis	Mobility scooter	PT and OT
M10	49, M	ASIA A complete CSC T5-T6	MWC	PT, OT and RT

Table 5.2. Demographics of people with mobility impairments. MX is used to indicate a person with a mobility impairment. (MWC = manual wheelchair, PWC = power wheelchair, PT = physical therapist, OT = occupational therapist and RT = recreational therapist)

also asked therapists to predict patients' interest-level in sharing health and fitness activities on a website like this.

Interviews with People with Mobility Impairments

These semi-structured interviews were 30 minutes long. They began with demographic questions and current or previous therapy practices related to health and fitness. We asked participants about the physical activities they performed outside regular therapy sessions. We also asked questions to capture attitudes and concerns towards sharing these physical activities with others like therapists, friends, family members and peers. We roughly described a design idea of a platform like *PatientsLikeMe* for health and fitness tracking purposes and asked about the perceived utility of such a site.

Data and Analysis

Except for two participants with mobility impairments, all sessions were audio recorded and transcribed. We used a thematic coding technique with both inductive and deductive codes [16] and created two codebooks – one for each group. For example, codes for advantages of a website like *PatientsLikeMe* from interviews with people with mobility impairments included “motivation,” “peer support” and “other.” One member of the research team iteratively refined the code set with multiple rounds of feedback from a second member, including adding new codes, merging and deleting. For validation, we adopted a peer debriefing approach [10] where another person not on the research team investigated randomly selected coded transcripts of two therapists and two people with mobility impairments. A total of 22 conflicts were identified and resolved with discussion. The final code set included 2–12 codes per open-ended question, for a total of 106 codes from the interviews with therapists and 107 codes from the interviews with people with mobility impairments.

Findings

We first report on the interviews with therapists followed by the interviews with people with mobility impairments. Therapists are referred to by IDs T1-T10, while participants with mobility impairments are referred to as M1-M10.

Interview with Therapists

We asked therapists about their existing and desired health and fitness tracking and sharing practices for their patients. As already mentioned, only therapists who had experience working with patients who use wheelchairs were recruited. More specifically, the responses here are also based on the therapists’ experiences working with patients with a variety of conditions like spinal cord injury (9 out of 10 therapists), stroke (9/10), traumatic brain injury (9/10), knee/hip replacement (4/10), multiple sclerosis (3/10), and amputation (3/10).

Current Fitness-Related Activities and Tracking Practices

To get a general sense about therapists' interest in tracking patient activities, we asked them about existing patient activities during and outside of therapy sessions, tools used to track those activities and therapist's engagement with patients and their family members outside of sessions.

Outside therapy sessions, five therapists said only some of their patients were physically active, four were unaware, and one (T8) thought his patients did nothing to stay physically active. Therapists recommended different strategies to patients to stay active: exercises to perform at home (2/10), wheelchair propelling (3/10), adaptive sports (3/10), and wellness programs (T5). Only T5 and T8 thought their patients would have concerns about sharing these activities with them. T8 said his patients may want to hide activities that they are not supposed to do, for example, a spinal cord injury patient trying to stand on his own. The two main factors therapists felt impacted a patient's progress included compliance with doing exercises at home (5/10) and self-motivation (4/10). T7 describes home compliance as the biggest factor, "*If they're practicing what we ask them to practice, that would be the best way to make improvements, I think.*" Other factors included financial stress (T1) and cognitive levels of the patient (T4).

All therapists tracked their patients' progress by manually recording it using online documentation tools (e.g., MediTech) and four also used files or charts. While four therapists had no concerns with these existing documentation tools, two thought they could be improved. For example, T4 specifically wanted to see statistical data of her patients,

> *"So, there's definitely room for improvement in terms of seeing statistics of improvement on a very granular level from day-to-day, week-to-week."*

In terms of access to these documentation tools, T5 wanted her patients to have access to these tools to see their progress over time. Furthermore, three therapists were also dissatisfied with the existing methods of assessing a patient's progress (also identified in [74]), including that their existing system was insurance-driven (T8) or did not capture all relevant activities (T4, T7). Related to this lattermost point, T7 commented on the difficulty of knowing how performance within a therapy session pertained to general fitness level:

> *"The only thing I think that is a barrier is on the day that we assess patients. If they're having a bad day, it might look like they're not doing better, but I might know that they are on it most other days, kind of thing."*

We also wanted to understand therapists' engagement with their patients beyond therapy and with the family members of the patient. Only T1 and T4 had the time to speak with their patients outside therapy sessions, while the others were too busy, "*I just don't know that that'd be realistic to have time to talk to people outside of their normal therapy session* (T6)." T1 and T2 used Facebook groups for their adaptive sports teams to communicate about research studies, upcoming events and news. All therapists except T1 communicated with the family members of the patients,

> *"I usually get family involved or encourage the family to have the patient do more of their activities at home or do their exercises more regularly." (T5)*

Summary: Similar to past work [74], therapists spoke about the uncertainty regarding patient's physical activities outside therapy. Although all therapists used documentation tools to track progress, some reported improvements including seeing statistical data. A barrier to further engagement with family members was therapist time constraints, confirming past work [25].

Wearables and Exergaming Technology

To assess general attitudes towards wearable physical activity trackers and exergames, we asked therapists about use of these technologies by them or their patients. In terms of personal interest, all but two therapists (T9, T10) had owned a wearable such as a Fitbit to track their health and fitness activities and six of them had had positive experiences. T1 used a Fitbit HR with a heart rate monitor and talked about its potential benefits for patients:

> *"So, I think that's good for a wheelchair user because their heart rate does go up when they're pushing their wheelchair despite that it's not a step."*

When we asked therapists about their patients use of wearable technologies, only two therapists (T1 and T2) were aware that a few of their patients used activity-tracking technologies; five others thought none of their patients used such technologies, while the remaining two were unsure. T2's patients complained about Fitbit's limited tracking abilities, while T1 had two wheelchair patients using a Fitbit and an Apple watch. T1’s patient was mainly interested in the device’s tracking ability for a wheelchair user:

> *“He wanted to be this person that's showing Fitbit, if it's working or not. He was giving them feedback and stuff. He wanted to do it for the pushes… So, it's a little different and he was trying to give feedback to Fitbit to try and have them develop something different.”*

Although not many patients were using an activity-tracking wearable, therapists identified potential benefits of such devices: holding patients accountable for the activity or lack thereof (5/10), collecting reliable data (4/10), capturing activities beyond therapy (3/10), motivation (2/10), and goal setting (2/10). T5 talked about patient compliance to activities outside of therapy sessions as follows,

> *“It would be an easy way to say, you say you're doing stuff at home, but this is saying you're active like five minutes out of the day, so that's not really very active.”*

Besides benefits like seeing weekly patient progress, T7 described the broader impact of this wearable technology with respect to insurance, “*I think it's also good to kinda show insurance, hey, we are making changes, you know, getting them better in this aspect.*” However, T7, along with T3 and T5, thought that cost could be a barrier. T1 also commented that the wrist-based form factor of the Apple Watch had interfered with wheelchair pushing for one of her patients, “*…he wore his watch and put his glove over it and then would tape around his glove so his Apple Watch wouldn't move.*” T2, T3 and T6 also said that existing wearables did not track activities their patients currently did, such as wheelchair propelling.

In terms of exergaming technology, all 10 therapists had previously used or were currently using exergames for rehabilitation purposes (e.g., Wii's balance board to improve balance). All therapists believed that exergames were useful for therapy as they made exercises fun and engaging (8/10) and helped with motivation (T1, T10). Two therapists (T3, T6) thought that cost or access to such technology could be a barrier to this group.

Summary: Patient interest in wearable technologies that track health and fitness is evident from T1 and T2's patients using Fitbits and Apple Watch. Similar to previous work [25], our therapists thought the primary value of automatic activity tracking was accountability and making informed decisions for patients.

Desired Tracking and Sharing Practices

To know more about what patient activity data would be beneficial to therapists, we asked about different types of activities and data. While activities performed during therapy were important to teach proper form (8/10), revamp fitness (T1, T2) and set appropriate goals (T3), all therapists except T4 and T8 thought activities performed *outside* of therapy sessions were equally important. (T8 only assigned basic activities to perform outside therapy because he was concerned about the safety of his patients.) Reasons cited included importance for understanding decline in progress (4/10), improving independence (3/10). T3 highlighted the importance of performing activities outside therapy:

> *"If they're coming to me with complaints of pain and feeling fatigued and they're just spending 30, 40 minutes with me and then going home and sitting on their couch or laying in bed all day, it's really... I'm not gonna be able to help them. So, I think I need to have a better understanding of what their daily lifestyle is to help them better."*

We asked therapists open-ended questions about their interest in tracking different physical (Table 5.3) and psychological (Table 5.4) data. Most of the therapists (8/10) were interested in tracking their patient's wheelchair pushes. Therapists also wanted to track mood (6/10) and energy levels (4/10). Additionally, three therapists (T3, T5, T9) wanted to see correlations between their patients' physical and psychological features:

> *"Okay. I guess the only other thing is how they feel after they do activities, maybe. Like their mood. Did it make their mood worse, better, the same?" (T9)*

All therapists except for T1 thought it would be useful to track overexertion, for example, to prevent injuries (T2). T1, in contrast, thought her patients were aware of their own abilities, so was not as concerned.

Owing to time constraints, therapists were interested in quick, easy-to-understand information about their patients' progress like: progress-decline towards goals (4/10) and activity versus no-activity in a day (2/10). Some therapists spoke about the

Type of physical activities	Therapists
Wheelchair pushes (going up/down an incline)	T1, T2, T3, T4, T5, T7, T8, T10
Number of active minutes	T3, T4, T5, T6, T7, T8, T9
Heart rate	T1, T2, T3, T6, T9
Distance pushed/walked (if applicable)	T3, T6, T7, T9, T10
Compliance with home exercises	T4, T5, T10
Stroke force and length while pushing	T4, T6, T8
Pressure relief	T4, T6, T7
Pushing speed	T3, T4, T8
Strength training (e.g. lifting weights)	T1, T2
Transfers	T4, T5
Safety	T7, T8
Curb negotiations for power wheelchair users	T3

Table 5.3. Therapists interest in tracking physical activities of their patients.

potential benefits of receiving this information, like setting/modifying patient goals (6/10) and monitoring compliance (3/10). Therapists wanted to receive these updates with varying frequencies: weekly (6/10), monthly (2/10), daily (2/10) or only during patient visits (3/10). T8 said, though unrealistic, he would like daily updates.

We asked therapists whether they thought their patients would be concerned about sharing physical and psychological data. Three therapists thought there would be concerns about sharing both physical and psychological data, while three others thought only psychological data would cause concern. T9 commented on the distinction between the two types of data:

> *"I think with psychological just cause it's very personal, and how you're feeling and your mood and all that. Physical, I think just because they may not want their therapist to know what they are doing or what they're not doing outside of therapy."*

T3 and T8 felt they already had access to a lot of patient data from the documentation tools and hence their patients would not have concerns about sharing tracked data.

Summary: Therapists spoke of the importance of physical activities both during and outside therapy sessions. Therapists also expressed interest in tracking patients' physical and psychological data and finding correlations between the two, though there may be some concern from patients about sharing psychological data.

Findings from Design Probe Activity with Therapists

During the design probe activity, we showed the website *PatientsLikeMe* to our therapists. None of the therapists had seen this website before or knew if their patients had used it. *PatientsLikeMe* encourages its members to share their health experiences with peers who have similar conditions, with the goal of positively impacting health outcomes. We asked therapists to imagine a website like *PatientsLikeMe* but for health and fitness tracking where their patients would share their automatically tracked fitness data. We wanted to get a therapist's perspective on: (1) the potential utility of such a website, (2) their patient's potential interest in sharing health and fitness data in this way, and (3) possible impacts of the site on therapy delivery.

Type of psychological data	Therapists
Mood	T1, T2, T6, T7, T9, T10
Energy	T5, T7, T8, T9
Level of tiredness	T3, T7, T9
Level of pain	T2, T6
Exertion	T2, T3
Sleep	T4, T10
Restlessness, alertness and gaze	T4

Table 5.4. Therapists interest in tracking psychological data of their patients.

Therapists' Perspective on Patients Sharing Fitness Data

All therapists except T4 and T10 thought their patients would be interested in sharing their health and fitness data, but anonymously. Similar to previous work [26,131], therapists also thought their patients could reap benefits such as motivation (7/10) and peer support (4/10):

> "*It would kind of be like a support group. Because without having to get to a physical place and meet people one-on-one, they could look at this data and be like, "Oh, these are the things that I could potentially be doing at my level*." (T3)

Additional perceived benefits for delivering therapy included being able to compare a patient against others with similar functional abilities (4/10), discovering new activities (2/10), and setting relevant goals based on patient abilities (T7). T2 also thought sharing could lead to competition within her adaptive sport group:

> *"If they are able to track and compare it […] with each other on the basketball team, I think that might improve their competitive side to try to get them to do more activity."*

An unexpected outcome was that three therapists identified different stakeholders like family members (T8), people at same level of injury as the patient (e.g., newly injured) (T3), and people with similar impairments (e.g., spinal cord injury) (T9) who may also benefit from such a website. For example, T3 talked about the benefits to newly diagnosed patients:

> *"I think sometimes for patients that are newly diagnosed with a condition that is going to keep them in a wheelchair, they might feel very isolated and almost depressed because of their condition, but something like this would help them feel like, Oh, I can still do so many things."*

Contrastingly, three therapists (T6, T9, T10) stated that there could be adverse side effects of sharing, specifically mentioning a risk of depression. For example:

> *"Some patients might be very interested to know how other people with the same condition are faring, […] 'cause if somebody else is doing better, it might make you depressed 'cause you're not there or you can't get there because of some other reason." (T10)*

Two therapists (T2, T7) also believed that their patients should consult a professional before trying new activities that they discover on the website.

Summary: Most of the therapists thought their patients would want to share their health and fitness-related data anonymously. Besides potential benefits to patients, a few therapists identified three other groups who may benefit from this shared patient data. Therapists also pointed out that depression could be a potential side-effect of sharing.

Potential Impact of Aggregated Fitness Data on Therapy

We asked therapists about the potential advantages and drawbacks of using a website like *PatientsLikeMe* to make therapy decisions—specifically, being able to view data from their own patients and from patients with specific types of profiles. Four therapists felt this website would be most useful to learn about activities other patients with similar functional abilities may be doing. T1 described the potential impact towards her practice as, "*It would give me fresh ideas, it would give me different adaptations that I* *might not have thought of.*" T3 also felt that she could use the data to help motivate her patients:

> "*I like to use evidence-based data or research to say like, Hey, this is what you should be doing at your diagnosis, at your age, at your gender, kind of a thing.*"

However, potential disadvantages of using a site like *PatientsLikeMe* in their practice were also identified by some therapists. Issues mentioned by one therapist each included the amount of therapist time it would require, the potential for patients being exposed to misleading information, and the potential for therapists getting distracted during therapy sessions. T10, for example, stressed the importance of providing concise information to save time:

> *"There'll be a lot of information on that screen. I don't know if therapists have enough time, yet again, to go through everything. So, it would have to be somewhat concise."*

Summary: Therapists outlined more potential benefits than drawbacks of using aggregated fitness data to inform therapy decisions, and were particularly enthusiastic about being able to learn about new activities that could be useful for their patients.

Interviews with People with Mobility Impairments

To understand the impact of sharing automatically tracked data with peers with similar impairments, we interviewed 10 people with mobility impairments. All participants with mobility impairments except M1 shared their health and fitness data with their therapists, family members (8/10), friends (6/10), people with similar conditions (3/10), and Facebook friends (2/10). Although seven participants were part of online social media groups pertaining to their condition, none of them shared their health and fitness-related data on such groups.

Current Health and Fitness Data Sharing Practices

None of the participants had any concerns about sharing their health and fitness-related activities with their therapists (M1 was currently physically inactive due to her condition and hence is not included in this section). Six participants already shared their activities in detail, for example:

> *"I tell her quite a bit of detail. But they are not formal fitness activities in the sense of having goals usually […] I talk to her about anything related to my recovery."* (M7)

Three participants shared only to some extent. Consistent with findings from therapist interviews, participants mentioned benefits of sharing with therapists like providing a realistic picture of activities outside of therapy sessions (4/9), increasing motivation levels (3/9), and setting appropriate goals (2/9).

As for sharing health and fitness data with peers who have similar conditions, only M2 and M10 expressed concerns. M10 currently only felt comfortable sharing his health information with people he already knew, including his Facebook friends, *"Yea I do status updates, I tell them about, its central to me maintaining my positive outlook on life."* Participants also found that sharing with people with similar conditions exposed them to new activities:

> *"If I see people in a similar situation with similar disability looking for things to do and way to do things. Quite often I would discuss with them and I find that generally other people make a decision if they want to share things you've done and allow you to tell them what you've done and get help." (M3)*

Summary: Most of the participants had no concerns sharing their health and fitness-related data with therapists and with peers with similar conditions. Participants also spoke about various potential benefits of sharing this data with both the groups.

Sharing on a Website like PatientsLikeMe

All participants thought they would feel comfortable sharing and interacting with others on a website like *PatientsLikeMe*. However, four participants wanted to share anonymously or use nicknames, reflecting the predictions of the therapists. M1 also mentioned that the website itself could present accessibility issues due to her dexterity impairment.

All participants said that sharing on a website would be most useful to learn from and experiment with new activities that others with similar conditions may be doing. Participants said this website could be useful in getting activity recommendations (7/10), getting support from users who had similar impairments (6/10), comparing with others to gauge one's functional abilities (4/10), motivation in seeing other people's successes (3/10) and finding similar patients to interact with (2/10). M5 described how getting ideas on new activities was important:

> *"Maybe you're just like pushing your wheelchair to the store and back each day and you think that's all you need to be doing or all that you can do but on a site like this if you are seeing other shared data of a whole bunch of other activities then that may give you some ideas, you know try something new or talk to your therapist about other things people are doing."*

However, some participants mentioned that looking at other people's data on a website like this could have adverse effects: demotivation (5/10) and misleading information (M10). Therapists also had the same concerns.

Social interaction was also desired, a theme that the therapists we interviewed did not anticipate. Participants wanted interaction to be able to ask other users follow-up questions (4/10) and details about activities (4/10), for example:

> *"If I view that specific individuals were doing something that I had never considered doing or that I thought that I probably couldn't do I would be interested in interacting with them to find out how are they doing it, how they started doing it." (M6)*

Other social interaction motivations mentioned by one participant each included learning about others' personal experiences, finding places to exercise together, and encouraging and building confidence with each other. M5, for example, described finding people with similar interests to build a community:

> *"If you could see that they lived in your area and you could kinda do like a meet up like hey lets meet up at track and we could hand cycle together or you know go to this pool or ask about accessibility features or hey have you been to this venue to work out."*

Despite personal reservations in sharing, some participants were interested in seeing health and fitness-related activities from people with similar impairments (7/10), improvements after certain exercises (3/10) and information about their own condition (2/10). M1 describes learning about her condition as follows,

> *"I would like to learn some more about my condition. I would like to see other individuals. I never heard of my condition until I was diagnosed with this. I've never run into anyone else who have had this. I've gone online and read some stuff about it but it doesn't seem to have much information about it."*

Despite these potential advantages of an online forum for data sharing, drawbacks were also mentioned. Reflecting social and privacy concerns about sharing tracked data that have been expressed in other studies [37], two participants mentioned not wanting to share vitals or other tracked data. M6 also thought looking at other people's data may not be useful to him due to the personalized nature of therapy:

> *"Therapy is basically an individual sort of thing; it has to be tailored to the specific needs of the individual and to me that's something that my therapist and I have to decide and I'm not sure what other people are doing would necessarily be very helpful."*

Summary: At least four participants wanted to share their health and fitness-related data on a website like *PatientsLikeMe* anonymously. Some participants cited concerns like demotivation. There were also unexpected results like: desire for social interaction and reservations sharing objective data within this group.

Discussion

Our study contributes to an emerging body of work on tracking and sharing physical activities for people with mobility impairments. Our findings show that from the perspective of a person with a mobility impairment, potential advantages of automatically tracking and sharing data include learning more about one's condition and about new physical activities to try. From the therapist's perspective, having access to automatically tracked activity data could improve understanding of patients' actions outside of therapy sessions and, when aggregated on a website like *PatientsLikeMe*, could inform and inspire personalized therapy decisions.

These findings point to the unique benefits and challenges in sharing health and fitness data for people with mobility impairments compared to other users.

Peers. A strong theme from both therapists and participants with mobility impairments was the desire to compare to and/or share data with peers who are in some way similar based on their mobility impairment. Our participants also strongly desired social features and the ability to interact with peers, not just passively view their data. Most obviously, these peers could be defined as others who have similar functional abilities, but other possibilities worth exploring include people who are at the same stage (e.g., recently diagnosed) or who have the same medical diagnosis (e.g., cerebral palsy). An online system such as *PatientsLikeMe* could support searching for users along these criteria. Future work should also explore how these competing definitions of peer groups may offer different types of support or motivation for an individual.

New Activities. Another theme that arose was the potential seen by both the therapists and the participants with mobility impairments to learn about new physical activities. A user with a mobility impairment may need specific physical activities that are adapted to their particular motor abilities. An online portal could thus inspire users to try new activities by seeing what other users with similar functional abilities are doing. One therapist even thought such data could help her to convince patients to try new activities. This focus is different from the more general social support benefits of sharing automatically tracked fitness data among users *without* mobility impairments [37].

Challenges. In terms of challenges, while sharing specific activity data (e.g., number of steps) may benefit people without mobility impairments, as suggested by Fritz et al. [37], there may be a greater possibility among people *with* mobility impairments that comparison data could lead to demotivation or depression; this suggestion was made both by therapists and by our participants with mobility impairments. Therapists' need for statistical information indicates how both groups wanted different information about people with mobility impairments: therapists wanted objective data, whereas people with mobility impairments wanted subjective data. Future work should explore how different types of data could be automatically shared to benefit different groups. At least one therapist was also concerned about the safety of his patients when performing new activities outside of therapy sessions. A potential solution presented by a few therapists and people with mobility impairments could be to explore ways to allow the website to professionally validate any suggested activities.

Psychological Data. Though it is not currently possible to automatically track psychological measures such as mood, several therapists were interested in having access to this data in addition to physical data (e.g., miles rolled). Correlations between the psychological and physical data were especially of interest. However, whether patients would be comfortable sharing their psychological data with therapists is an open question; it was mentioned as a concern by some of our participants. Additionally, because psychological data would likely be collected through self-report it may be affected by issues of compliance and could be unduly burdensome for users with dexterity impairments (e.g., if done through a webpage or mobile app). Further work is needed to assess the extent to which psychological data is in practice a useful complement to automatically tracked physical data for therapy decisions and, if useful, how to appropriately collect it from this population.

Broader Impacts. Our study explores the opportunities that automatically tracked activity data can bring to stakeholders like therapists and people with mobility impairments. However, our findings also highlight potentially unintended implications for insurance companies. Though based on only one therapist's interest in showing her patient's progress data to insurance companies, this clearly raises issues of privacy. Researchers should seek answers to: How comfortable would people with mobility impairments be towards sharing their data with their insurance companies? To what extent will insurance companies rely on this data to make decisions about the patient's healthcare?

Design Opportunities. Finally, based on our findings, we identify the following design opportunities to explore in future work with people with mobility impairments:

- Support anonymous sharing or use of nicknames when sharing with peers with similar impairments
- Support the ability to find people based on similar conditions, goals and functional abilities.
- Support selective sharing (e.g., objective data with therapists, personal experiences with peers with similar impairments).
- Support social/peer learning for both therapists as well as people with mobility impairments.
- Support professional validation on physical activities before others with similar impairments can try.
- Support seamless integration with the existing documentation systems used by therapists.

Limitations

All findings from our study are based on the perceptions of therapists and people with mobility impairments rather than actual use. It will be important to confirm and compare our findings with a field study and actual use of tracking technologies. Second, automatically tracked health and fitness data could be sensitive, private information for many users. Even though most of our participants were open to the idea of sharing this data, by recruiting a broader pool of people with mobility impairments we will be able to identify concerns with sharing health and fitness-related data that were not already captured from our work.

Conclusion

In conclusion, we conducted semi-structured interviews with 10 therapists and 10 people with mobility impairments to understand the potential impact of sharing automatically tracked activity data for users with mobility impairments. Our findings highlighted the potential benefits of sharing this data both with therapists and with peers who have similar functional abilities, such as learning about new activities and as means to inform therapy decisions. At the same time, we also highlight open questions associated with sharing like privacy and depression and demotivation by looking at fitness data of others. Lastly, we present design guidelines to build tools to support sharing of tracked data with peers with similar impairments and therapists.

Smartwatches, another emerging wearable technology have the potential to offer benefits beyond fitness tracking like access to information in mobile contexts. While

Chapter 4 and the study presented in this chapter offer guidelines on building accessible fitness tackers with the ability to share tracked data, the general accessibility of wearable devices still remains an open question. The rest of my dissertation focuses on investigating and implementing accessible interactions for smartwatches.

Chapter 6 : Exploring Accessible Smartwatch Interactions for People with Upper Body Motor Impairments

Introduction

Previous chapters (Chapters 3-5) examined the accessibility and potential impacts of wearables like head-mounted displays and fitness trackers for people with motor impairments. Another mainstream wearable device is the smartwatch, which offers capabilities beyond fitness tracking. Smartwatches are always-available, provide quick access to information in a mobile setting, and can collect continuous health and fitness data. However, the small interaction space of these wearable devices may pose challenges for people with upper body motor impairments. More specifically, we investigated the following research questions:

- To what extent is existing smartwatch input accessible for people with upper body motor impairments?
- What touchscreen and non-touchscreen gestures do people with upper body motor impairments make for accessible interaction and why?

To investigate accessible smartwatch interactions for this user group, we conducted two studies. In the first study, led by Pramod Chundury, we assessed the accessibility of existing smartwatch gestures with 10 participants with motor impairments and found that not all participants were able to complete button, swipe and tap interactions. In a second study, led by me, we adopted a participatory approach to explore smartwatch gesture preferences and to gain insight into alternative, more accessible smartwatch interaction techniques. Eleven participants with motor impairments created gestures for 16 common smartwatch actions on both touchscreen and non-touchscreen (bezel, wristband) areas of the watch and the user's body. We present results from both studies and provide design recommendations.

These research questions contribute to the third thread of my dissertation research. This work was published at the *ACM conference on Human Factors in Computing Systems (CHI)* in 2018 [78].

Background

Over the last few years, wrist-worn wearables like smartwatches have become ubiquitous [107]. These devices not only allow people to accomplish tasks in a mobile computing scenario but can also track health and fitness data. Commercial smartwatches use touchscreens as an input modality for users to interact using multi-touch gestures. These gestures are created by system designers who may not have upper body motor impairments and may find it difficult to understand the challenges experienced by those with upper body motor impairments. The gestures that designers create may not be reflective of the abilities of people with upper body motor impairments, which may make performing these gestures difficult and may leave the technology unusable.

To create more intuitive and easy to perform gestures, Wobbrock et al. [139] employed a guessability study methodology that allowed users to elicit gestures for interactive tabletops. Their results comprised of a user-defined gesture set and mental models of the users who created these gestures. As validation of the user-defined gesture method, Morris et al. [93], in a study comparing gesture sets created by end users and HCI researchers for interactive tabletops, found that the former was preferred as the gestures were simple, easy-to-perform and easy-to-remember. Since then, this method has been adapted by various studies to investigate gestures for different users and in different contexts (e.g., [117]). For people with disabilities, Kane et al. [63] investigated how people with vision impairments use touchscreen gestures and compared the use with sighted users on tablets. They found that people with vision impairments tend to use the edges of the device for gestures. They also compared speed, size and shape of gestures created by both user groups. However, none of the studies have investigated smartwatches for people with motor impairments.

Study 1: Existing Smartwatch Accessibility

To assess the extent to which off-the-shelf smartwatches are accessible to people with upper body motor impairments, we first conducted a controlled lab study, led by Pramod Chundury. The study is summarized below as my role in this study was to offer feedback and guidance as and when required. The focus of this preliminary study was not to measure performance, but to explore accessibility and understand the potential uses of smartwatches for this user group.

For this study, we recruited ten participants (6 female, 4 male, average age = 29.1 years old and *SD* = 8.9) with upper body motor impairments. Participants completed 21 tasks covering 19 interaction techniques grouped into four interaction groups: *taps* (one-finger single tap, double tap, and hard press, and two-finger double tap), *swipes/flicks* (left/right/up/down directional swipes, left/right edge swipes, and up/down flicks), *physical buttons* (single press, double press, long press, and rotate of the crown button, and single press of the side button) and *text input* (manual input by “scribbling” the letters “T”, “A”, and “i”) and *speech input* of the phrase “Hi Siri.” These tasks were completed either in the native apps or in a custom-built app (to eliminate ambiguity caused by interactions like edge swipes and regular swipes). Tasks were randomly ordered, and participants completed three trials of each task. A trial ended upon successful completion of the task or a 45 seconds timeout. If the participant was unable to complete a trial within this time limit, we skipped any remaining trials to limit fatigue and moved to the next interaction technique. Participants also rated the ease of use of each interaction group on a 7-point scale (1 – very easy to 7 – very difficult) with the exception of manual and speech input which were rated separately. The session ended with a semi-structured interview about the overall use and experience of using the smartwatch, comparison with other devices (e.g., smartphone) and also feedback on how to improve smartwatch interaction. We analyzed task completion data for each interaction technique and interaction groups as a whole. For the 7-point subjective feedback ratings, we used a Friedman test to check the effect of *interaction groups* on *ease of use*, with post-hoc comparisons using Wilcoxon signed rank tests and a Bonferroni adjustment to protect against Type I error. Lastly, we thematically analyzed the open-ended interview responses and resolved conflicts that arose between two independent coders.

In terms of task completion rates for interaction groups, while Swipes/flicks and Buttons had the highest completion rates, manual text entry was particularly difficult with only three participants completing that task. Additionally, the *crown double press* was also difficult, with no participant successfully completing it. Excluding *crown double press*, only P2 successfully completed all trials for the remaining input tasks.

For the subjective ratings, Swipes/flicks and Taps were perceived to be the easiest *interaction groups*, with Text (manual) being the most difficult. Swipes/flicks had an ease-of-use rating of 2.3 on average (*Med* = 2.5, *SD* = 1.1), followed by Taps at 2.8 (*Med* = 2.5, *SD* = 1.4), Buttons at 3.3 (*Med* = 2.5, *SD* = 1.6) and Text (manual) at 4.3 (*Med* = 4.5, *SD* = 2.5). A Friedman test to check the effect of these manual interaction groups on ease of use was statistically significant ($\chi^2_{3,N=10} = 8.16$, $p = .042$). After a Bonferroni adjustment, Swipes were significantly different from Text (manual) ($p = .039$, $r = .48$). Text (speech) was considered to be very easy overall (*M* = 1.6, *Med* = 1.5, *SD* = 0.7). We also asked participants about their preferences in each interaction group. While there were no clear trends in terms of preferences within the swipes/flicks and taps interaction group, the crown double press was perceived as the most difficult action in the Buttons interaction group. Additionally, the majority of the participants preferred speech input compared to manual text input**.**

We also analyzed the video recordings from the study session to learn about user posture and input characteristics. The majority of the participants were seated in an upright position (6/10), but others also leaned forward (2/10), reclined (1/10) and alternated between leaning forward and reclining (1/10). This posture impacted the resting position of the dominant and non-dominant hand which in-turn could affect input difficulty. We also analyzed to videos to learn about participants’ non-dominant wrist position during the study: mid-air (5/10), resting on the table/wheelchair tray (2/10), varying between the two positions (3/10). In terms of the finger preferences, 61.8% trials were completed using the index finger, following by 11.8% using the thumb. For all other trials, multiple fingers or other fingers including middle, ring or little were used.

In terms of the overall experience, six participants reported an overall positive experience and four reported a neutral experience in using the watch, including the two who already owned a smartwatch. Participants reported several advantages of smartwatches over smartphones including compactness (P1), voice commands (P3, P9) and support to overcome situational impairments (P1, P4, P5, P6 and P10) by always being on the wrist. However, some disadvantages included the screen size (P5) and text entry (P1, P4, P5).

Summary

In this study, we found that participants experienced difficulties with existing smartwatch interactions, particularly with the crown double press button and manual text entry. Only one participant was able to complete all tasks excluding the crown double press. We also found that though the tapping task was perceived to be easy, it was prone to more errors and similarly while speech text entry was perceived to be easy, one participant was not able to use it because of dysarthria. However, the majority of our participants (8/10) expressed interest in using smartwatches.

Study 2: Accessible Smartwatch Gestures

The findings from Study 1 highlight the need to explore alternative accessible smartwatch interactions for people with upper body motor impairments. In this second study, we aim to understand overall accessible smartwatch input preferences and to compare user responses to touchscreen and non-touchscreen (bezel, strap, user's body) input areas. The non-touchscreen input areas offer different affordances than the touchscreen itself—increased input space and hard edges (shown to be useful for users with motor impairments [38,140])—that could ultimately improve accessibility. To achieve these goals, we adapted an input elicitation method [139] whereby we asked 11 participants to create gestures for common smartwatch actions like *view notification*.

Method

Participants created gestures under three constraints: (1) on the touchscreen, which allows us to compare and contrast existing gestures with what participants create; (2) non-touchscreen locations, to explore the use of larger interaction areas and hard edges; and (3) a mix of both locations to understand overall user preferences.

Participants

Eleven participants (7 female, 4 male) with upper body motor impairments were recruited through online advertising, word-of-mouth, and a local organization (see Table 6.1). All were volunteers and were compensated for their time. P2 owned a smartwatch, and P3 and P4 had limited smartwatch experience from Study 1. All except

ID	Age, Sex	Reported Medical Condition	Uses wheelchair (WC)?	Box-and-Block Test Right (R), Left (L)		Physical Ease (E) and Good Match (E) Ratings (7-point Likert Scale)					
						Touchscreen		Non-touchscreen		Mixed	
				R	**L**	**E**	**G**	**E**	**G**	**E**	**G**
P1	52, F	Essential, orthostatic tremor	No	35	39	6.81	6.93	6.43	5.56	6.37	6.62
P2	24, M	Cerebral palsy	No	39	38	7	6.68	7	6	7	6.93
*P3	28, F	Cerebral palsy	PWC	10	5	7	7	7	7	7	7
*P4	28, F	Cerebral palsy	PWC	13	0	6.25	6.37	6.12	6.06	6.06	6.37
P5	49, M	Spinal cord injury	PWC	0	10	6	6	6	6	6	6
P6	34, M	Spinal cord injury	MWC	29	21	7	6.68	6.87	6.81	7	6.62
P7	40, F	Muscular dystrophy	PWC	18	21	6.75	6.93	7	6.56	7	7
P8	58, F	Multiple sclerosis	PWC	0	25	7	7	7	7	7	7
P9	27, F	Osteogenesis imperfecta	PWC	44	47	7	6.87	7	6.81	7	6.93
P10	44, F	Juvenile rheumatoid arthritis	PWC	32	32	5.75	5	6.06	5.31	5.93	5.37
P11	22, M	Radial nerve injury	No	23	27	6	6.25	6	5.18	6	5.87

Table 6.1. Demographics, wheelchair use, Box-and-Block Test results for both hands, and average Likert scale (7-point) ratings for gestures per participant from Study 2. *P3 and P4 also participated in Study 1. All participants were smartphone users and right-handed except P8; P10 chose to use her left-hand for study tasks due to her impairment. (PWC = power wheelchair, MWC = manual wheelchair)

two participants (P8, P10) wore the smartwatch on their left hand during the study and performed gestures with the right hand. As smartwatches are most often paired to smartphones and offer similar functionality, we only recruited participants with smartphone experience, which also roughly established that all participants had baseline touchscreen efficacy. The study also included a 5-minute standardized Box-and-Block Test to assess manual dexterity [84]. For context, average adult scores for this test are around 80 for young adults and 60 for older adults [84].

Procedure

All sessions were two hours long and were audio and video recorded. The session started with a demographic and technology experience questionnaire. Participants then completed the 5-minute Box-and-Block Test with their dominant hand first, followed by their non-dominant hand. Participants were then asked to wear a 42 mm Apple Watch Series 1 smartwatch (same as used in Study 1). Following [5,31,69], we chose not to provide on-screen visuals or audio. We also switched off the smartwatch to avoid biasing participants toward the direct touchscreen input over gestures at other areas of the watch or body.

Participants completed three gesture creation tasks: (1) touchscreen only; (2) non-touchscreen only; and (3) a mix of both areas. The touchscreen and non-touchscreen tasks were counterbalanced and were always followed by the third task. For each task, participants completed 16 trials, where each trial consisted of being given an action name and description (Table 6.2) and creating a gesture that would be a good fit for the given action and the participant's physical abilities. We asked participants to think aloud while creating gestures, and to assume that all gestures can be recognized by the system. Participants were also told they could use existing gestures, invent new ones, or repeat gestures they had already created for a different action. Participants were asked to ignore the presence of existing buttons on the smartwatch during the entire study.

Table 6.2 shows the 16 actions, which include a subset from [5] as well as *view notification* and *dismiss notification* because these two are common smartwatch tasks [120]. Actions that would create an opposite effect appeared in pairs (e.g., 'select' was always followed by 'cancel', 'zoom in' was always followed by 'zoom out'). The order of the two single actions and seven action-pairs was randomized for each participant but remained the same for all three tasks. Participants were asked to repeat the gesture once after they created it. Participants then rated the gesture the y had created on two

7-point Likert scales: “The gesture I picked is physically easy” and “The gesture I picked is a good match for the action.” We also asked participants to provide a rationale for creating that gesture.

The session concluded with a semi-structured interview about input preferences and potential impacts of smartwatches. We also asked the participants to rate the gestures they created based on the comfort of performing those gestures in different public and private locations (e.g., public location like a library, private location like home).

Data and Analysis

Rationale for performing gestures and answers to open-ended questions were transcribed and analyzed using a thematic coding technique with a combination of inductive and deductive codes [16]. We also analyzed the videos by coding and classifying each gesture based on 10 properties (e.g., interaction style, use of different parts of the body, user posture). For validation, two research team members independently coded a randomly chosen participant video for gesture properties and rationale. Out of 480 codes, 13 conflicts arose and were resolved with discussion. Unlike the goal of Wobbrock et al.’s original study method [139], we did not compute *agreement*, as our goal was not to create a highly guessable gesture set but to characterize the range of gestures created and to compare preferences for touchscreen and non-touchscreen gestures.

Navigation Gestures (4)
Previous Horizontal, Next Horizontal Previous Vertical, Next Vertical (e.g., Previous Horizontal: I would like you to look at the smartwatch and imagine a horizontal list. Assume you are in the middle of this list. Make a gesture that will move to the previous item in this list.)
Panning and Zooming Gestures (4)
Pan Left, Pan Right Zoom In, Zoom Out (e.g., Zoom Out: I would like you to look at the smartwatch and imagine as if you were looking at a map. Now make a gesture that zooms the map out.)
Select and Cancel Gestures (4)
Select, Cancel View Notification, Dismiss Notification (e.g., Cancel: I would like you to look at the smartwatch and imagine that a task is selected on the screen. Make a gesture that would allow you to cancel that selection.)
Time-related Gestures (3)
Start Stopwatch, Stop Stopwatch View Time (e.g., Start Stopwatch: Assuming a stopwatch app is open, now make a gesture to start the stopwatch.)
Go to Home Screen: I would like you to look at the smartwatch and imagine an open application. Now make a gesture to go to the home screen from the currently open application.

Table 6.2. List of 16 actions that appeared in Study 2 with example descriptions. Actions separated by comma appeared consecutively in that order.

Findings

With 11 participants, 16 gestures, and 3 different locations, we collected a total of 11 x 16 x 3 = 528 gestures. We analyzed the session videos and present findings from the three tasks in terms of the gesture nature, rationale and properties (e.g., interaction methods).

Overall Trends

Of the 528 gestures created, 363 (69%) gestures were one-finger interactions (index, middle or little finger), 79 (15%) were single thumb, and 79 (15%) were multiple finger interactions (e.g., index and middle). Participants also created gestures using other parts of their body including knuckles (P5, P10), fist (P10) and the entire hand (P10). During the session, P6 requested to use his nose to create gestures as he often does so on his phone. Because the goal of the study was to explore gestures using hand movements, we restricted creating gestures using hands and arms only.

We analyzed the number of strokes performed by participants and found that there were only seven instances (out of 528) where the gestures had more than one stroke. This indicated the overall preference of participants in creating simple gestures. In terms of posture, 84% of gestures were created by participants in an upright position in their chair (or wheelchair). P3 and P4 leaned forward most of the time, and P10 leaned forward occasionally.

Touchscreen Task

Gesture nature and rationale. Overall, participants most commonly created one-finger swipe and tap gestures (Table 6.3). Participants also created gestures including swiping diagonally (5/176), swiping using all fingers (P10), long press (P9), and different variations of taps, including triple tap, quadruple tap, and tap followed by a double tap (3/176). Almost all gestures created (*N*=145; 82%) could be classified as native touchscreen gestures. The most common reason for choosing gestures for an action was previous use of touchscreen technology on smartphones and tablets (42/176). However, for P9, her physical ability took precedence over this familiarity,

> *"Again, the pinching is what you usually use on your smartphones is not always as easy for me cuz you have to be at the right angle. This just seems easier." (P9)*

Types of Gestures	Touchscreen	Non-Touchscreen	Mix
Swipes (one finger)	83 (47%)	67 (38%)	79 (45%)
Tap (one finger)	43 (24%)	49 (28%)	38 (22%)
Swipes (two fingers)	10 (6%)	11 (6%)	6 (3%)
Double Tap	9 (5%)	11 (6%)	17 (10%)
Drawing symbols	12(7%)	5 (3%)	9 (5%)
Squeeze	0	12 (7%)	6 (3%)
Pinch	9 (5%)	2 (1%)	14 (8%)
Force Press	0	6 (3%)	4 (%)

Table 6.3. Gestures created by participants in all three tasks in decreasing order for the touchscreen (% out of 176).

Participants also created gestures that were easy to perform (26/176), were the opposite of an already created gesture (23/176) or were based on their physical abilities (20/176). For example, P10 explained her choice of a tap gesture for the action *select* but at the same time highlighted that repeated use may be difficult,

> *"I think it's just because of the way my arms and fingers move. I think it's a combination of the way my right arm doesn't move as close to my body and my left hand doesn't move up. The lack of spread of my fingers so it might get a little hard to tap with one finger."*

There were seven occasions when participants created gestures because they found that standard touchscreen gestures either were already difficult or because the smartwatch touchscreen was too small for the standard gesture (e.g. *zoom in*, *zoom out*, *cancel* and *dismiss notification*). For example, P10 used her index finger to make a circle on the touchscreen for *zoom in,*

> *"[…on the iPad] I would use my fingers close to an open position but it's not that easy and it's really not that easy for me to do that on this screen because of the way*

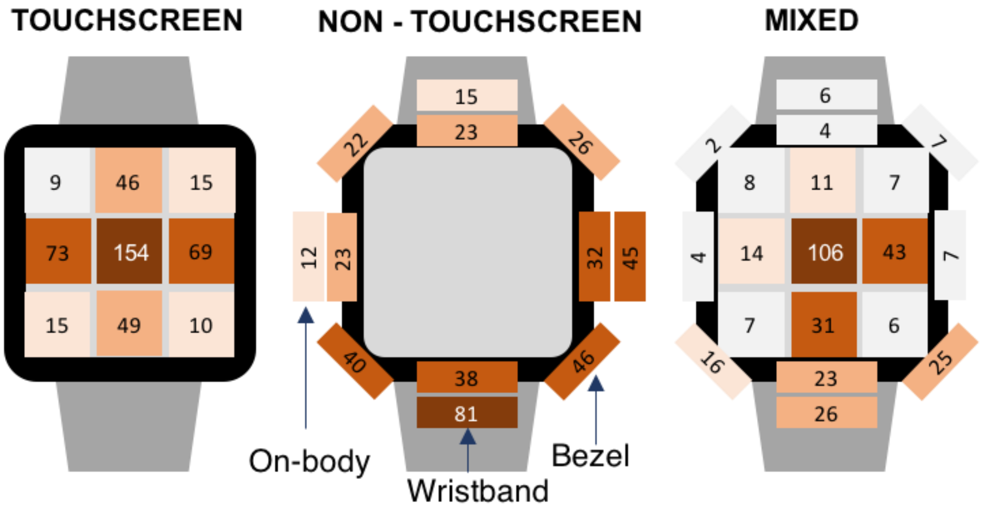


Figure 6.1. Areas touched during the three tasks for all 16 actions for all participants. In the mixed task, no participants chose to touch the skin locations. (Darker colors represent a higher frequency of gestures)

> *my right arm. I can't get my right arm close enough to my body and my wrist doesn't turn towards me."*

Similar to previous gesture elicitation studies [5,139], participants also created gestures that mimicked real world actions like pulling or pushing objects or lists for *navigation* gestures (14/176), reading or turning the pages of book for *cancel* or *panning* gestures (5/176), throwing objects away from the screen for *cancel* or *dismiss notification* (4/176), or using as a physical stopwatch (3/176). Some participants had difficulty creating gestures on the touchscreen area (7/176) because of the small size, which suggests exploring options beyond the touchscreen,

> *"I think it's hard cuz the surface is not very large so it can be harder for people. Because it's a clock and most clocks are round and you need to diversify the options. You are running out of ways to make gestures here." (P7)*

Gesture properties. Of the 176 gestures created by participants, 132 (75%) were created using one-finger interaction, 22 (12%) were created using a single thumb and 20 (11%) were created using multiple fingers (Table 5). Only P10 used her entire hand to create a *cancel* gesture,

> *"…it seems faster. Because I don't have to separate my fingers, I just have to keep them together."*

The most common one-finger interactions were using the index finger (85%) or a single thumb (17%). Multiple finger interactions used combinations of thumb, index, middle or ring fingers. P6 used his middle finger for all the actions in this task. Only P5 used his thumb knuckle to create a gesture for *previous vertical* to swipe from right to left on the touchscreen. The majority of participants performed gestures using the pad of the finger (150/176) but participants also used the finger side, tip and nails. As shown in Figure 6.1, the most common gesture locations on the touchscreen were the center of the watch followed by the left-center and right-center.

Summary. The majority of gestures created were one-finger interactions like taps and swipes based on previous experience with touchscreen interaction. However, participants' physical abilities also impacted location preferences (e.g., bottom area of the touchscreen) similar to findings from Guerreiro et al. [45] with handheld devices.

Interaction Method	Touchscreen	Non-Touchscreen	Mix
One finger	132 (75%)	111 (63%)	120 (68%)
Multiple fingers	20 (11%)	30 (17%)	29 (16%)
Thumb	22 (13%)	31 (17%)	26 (14%)
Knuckles	1 (.5%)	2 (1%)	0 (0%)
Fist	0 (0%)	1 (.5%)	0 (0%)
Palm	1 (.5%)	0	1 (.5%)

Table 6.4. Interaction methods showing largely similar patterns for all three tasks, with one-finger input being the most common. Each task includes 176 gestures (% of 176).

There were also instances when participants found standard touchscreen gestures that they knew from their smartphone experience to be difficult to perform on the smartwatch, so created alternative solutions. Lastly, the small size of the touchscreen was an issue mentioned by seven participants.

Non-Touchscreen Task

Gesture nature and rationale. Similar to the touchscreen task, participants created one-finger swipes and single tap gestures on the bezel, strap, or body (Table 6.3). However, five participants also created a squeezing gesture (12/176) where two fingers rested on and pressed the opposite sides of the bezel (left or right; top or bottom). Other gestures included rubbing (moving back and forth on a particular area, *N*=3), pinching (2/176) and variations of taps and swipes. Participants created 135 (77%) gestures that could be classified as native touchscreen gestures.

While creating gestures, participants considered ease of performing the gestures (37/176) and physical abilities (e.g., angle of approaching finger, rotation of hands and wrists, *N*=28). Like the touchscreen task, we observed instances of mimicking real-life actions, such as using a manual analog stopwatch for *time-related* gestures (22/176), and previous experience was cited as a reason for creating gestures (14/176). P9 described how even a seemingly easy gesture may be difficult for her to perform; in this case she instead created a tap gesture:

> *"So, panning left on the top of the touchscreen would be pulling it this way [to the right] but my first instinct would be to touch this side of the bezel [left] but I don't*

> *like making that movement so this is the closest I would get without wrapping my arm around that way. I have to reach too far and it hurts my shoulder."*

Other reasons for gesture creation included speed (11/176) and proximity to the reaching hand, like on the bottom bezel (7/176). For example, P5 created a swipe gesture on the bottom bezel for *zoom in*, saying that it was close to her.

P9 created a tap gesture on the bottom bezel that would be quick but at the same time also discussed practical issues of having to tap too precisely while pushing her wheelchair,

> *"I would probably end up constantly going to the middle [of the bottom bezel], but not having to like make sure that I was at a particular spot [on it] would make it easier just cuz I can imagine pushing myself with this on and then looking at it and then waiting to see more and then just tapping and not having to align myself constantly."*

Gesture properties. Similar to the touchscreen task, one-finger input was by far the most common. Out of 176 gestures, 111 (63%) used one-finger, 32 (18%) used a single thumb, and 30 (17%) used multiple fingers (Table 6.4). P10 also used a fist on the top bezel and her knuckles on the lower wristband to create gestures,

> *"I'll just tap on the message or on the band on the bottom part because that's easier for me to reach and I'll just tap on it with my left knuckle because my left wrist doesn't turn and my fingertip doesn't completely straighten."*

Further, P10 used all fingers to create a standard *pinch out* gesture on the lower wristband for the *zoom out* action. This was in contrast to the *drawing a circle* gesture that she had used for the touchscreen task. She attributed her rationale for creating gestures in both tasks to the available space.

The bezel was the most popular location for creating gestures, at 54% of gestures compared to 31% on the wristband and only 11% on the skin around the smartwatch. The rectangular form factor of the watch may have influenced participants' choice to use the bezel as a scroll bar: 56% (25/44) of the navigation gestures were created on the bezel. As shown in Figure 6.1, the areas closer to the dominant hand (bottom bezel and wristband, right side for right-handed participants) were more common than other non-touchscreen areas. P9 describes how reaching impacted her choice of location,

> *"So, the part of the watch more to my left, the left side of the watch is the hardest part for me to reach so I constantly avoided touching anything on that side."*

Only P11 created gestures (N=4) that spanned more than one non-touchscreen area, such as swiping from the right bezel on to the skin for panning left.

Summary. Participants most often created gestures that were easy to reach with their dominant hand, a common pattern for accessible wearable interactions (e.g., [80]). But, very few gestures were created on the skin. The wider space of non-touchscreen locations in some cases relieved the need for precise input with small targets, a known problem for users with motor impairments (e.g., [35]).

Mixed Task

For this task, participants could choose any location (touchscreen or non-touchscreen) to create gestures for the same set of 16 actions. Participants ended up creating gestures on both touchscreen and non-touchscreen areas of the smartwatch (Figure 6.1), but did not use the body (skin) as an input surface. There was again a high proportion of native touchscreen gestures (*N*=153; 87%). Because the trends on the types of gestures created by participants remain the same in all three tasks (Table 6.3), we discuss location preferences and highlight differences between the gesture properties for this task compared to previous tasks.

Locations chosen. Eight participants chose a mix of touchscreen and non-touchscreen locations, P3 and P10 chose touchscreen only, and P5 chose non-touchscreen areas only. In addition to rationale mentioned in the previous sections, participants chose locations where gestures were easy to perform (30/176), physically comfortable (19/176), and would not obscure the view (3/176) for *zoom in*, *zoom out* and *previous vertical*. Location-wise breakdown of gestures revealed that 68% of gestures were created on the touchscreen, 20% on the bezel, 10% on the wristband, and 1% (4 gestures) spanned multiple areas. As shown in Figure 6.1, the most common locations were the center of the touchscreen followed by right and bottom of the touchscreen, and the bottom wristband and bezel of the smartwatch. Comparatively, only seven gestures were created on the right bezel, four on the top bezel and four on the left bezel and six on the top wristband. Reasons for not creating gestures on the skin included wearing a brace (P8), location did not seem intuitive (P1, P8, P10), and limited physical ability (P9).

Gesture properties. Similar to the previous two tasks, gestures used mostly one finger (*N*=120; 68%), followed by multiple fingers (*N*=29; 16%), and a single thumb (*N*=26; 15%). Only one person created a whole-hand gesture (P10). In this task too, we noticed trends similar to touchscreen and non-touchscreen tasks for interaction method (Table 6.4).

Summary. Most participants chose both, touchscreen and non-touchscreen locations, but none chose on-body input.

Overall Comparison of Locations

Five participants favored gestures on the touchscreen, four wanted a mix of touchscreen and non-touchscreen, and two wanted non-touchscreen only. When asked, seven participants thought social acceptability of performing gestures on different locations was not an issue,

> *"This is something that's on your hand and won't be covered by clothing or anything. And timepieces have been in our culture for a long enough time that it's not something that's unusual so it wouldn't bring any extra attention to the user." (P6)*

Additionally, seven participants thought gestures created at different locations would interfere with items worn on the body. P2 also mentioned creating gestures that would not interfere with running or exercise.

Touchscreen areas. Direct touch manipulation was seen as an advantage (4/11 participants), for example,

> *"It's more intuitive, so when you want to click on stuff on the computer you actually click right on top of it so actually touching the app that you want or on the icon you want, makes sense." (P9)*

Participants also said the touchscreen was intuitive (P1, P3), felt familiar (P1), offered more control over the non-touchscreen areas (P6), and had the possibility of visual feedback (P7). At the same time, they also felt the touchscreen had limited interactive space (P1, P5, P7), obscured the view (P5, P6, P11) and made reaching targets on the small screen challenging (P7, P9, P10). P7 describes,

> *"It's so small that if you have any tremors or muscle fatigue it may be hard for you to get in that [target] area."*

Non-touchscreen areas. Six participants thought the larger surface area of non-touchscreen locations was advantageous as it required less physical effort (P5, P9, P10) to perform gestures and the locations were closer to the body (P5). Also, the non-touchscreen gestures reduced the demand for reaching precise targets (P2, P6, P9), did not obstruct the screen (P6, P11) and reduced the chances of accidental gestures (P2). Nonetheless, participants found performing gestures on non-touchscreen areas as unintuitive (P1, P10) and had doubts about the technology (P2, P7, P11).

Discussion

This paper investigates the relatively unexplored area of accessible smartwatch interactions for people with upper body motor impairments via two studies. We assessed the accessibility of existing smartwatch interactions and explored alternatives by eliciting gestures on touchscreen and non-touchscreen areas. Similar to previous work [5], gestures created by participants showed legacy bias. However, this bias did not fully dictate participants' behavior. For example, 59/264 gestures for actions that natively use swipes did not use a swipe, while 57/264 of gestures for actions that natively do not use swipes did use a swipe. Our findings indicate perceived benefits of smartwatches compared to smartphones like being always-available and speed to access information. Yet, our findings also highlight challenges with existing interactions and elicit design guidelines to create accessible interactions.

Designing Accessible Smartwatch Interactions

As the first work in exploring accessible smartwatch interactions for people with upper body motor impairments, we present design guidelines for future work.

Avoid Gestures that Need Precision and Large Areas to Do

Previous work has shown accessibility challenges with touchscreen interaction like performing *taps* on tablets (e.g., [35]) or multi-touch gestures on smartphones (e.g., [3]). Our work also highlights similar problems with *taps* and *pinch-to-zoom* for smartwatches. Given that smartwatches (and wearable devices like Google Glass as discussed in Chapter 3) have a smaller interaction space as compared to smartphones or tablets, it becomes critical to reassess existing touchscreen input and design alternatives to gestures that currently need precision and large area to perform.

Support Non-Touchscreen Input Close to Dominant Hand

The physical abilities of participants created a preference for non-touchscreen locations that were close to the dominant hand, like the bottom bezel and bottom wristband, as opposed to farther away. These locations should be the most accessible for bezel and wristband interactions and should be able to adapt based on handedness.

On-Body Locations May Not Be Preferred

A strong theme of avoiding on-body input (i.e., gestures on the skin) was observed in Study 2. Despite instructing participants to assume that the smartwatch can detect all gestures, participants were frequently skeptical about whether such input could be recognized. Participants also thought gestures created on the body were unintuitive. One participant was also worried about the possibility of harmful radiation due to the technology.

Design Navigation Actions on Bezel Locations

Previous studies [38,140] have leveraged hard edges of devices for high accuracy in target acquisition and stability of gesture motions for people with motor impairments. The bezel was particularly popular for navigation actions but may also more widely support accessibility. We investigate the bezel as an interaction space in the next chapter (Chapter 7). Additionally, transferring navigational actions to the bezel may also benefit a broader population using smartwatches by minimizing common problems like occlusion and fat finger.

Support Gestures On-the-go

The main advantage of smartwatches as compared to smartphones is to provide quick access to information on-the-go. While two participants showed interest in gestures on-the-go, we only investigated smartwatch accessibility in a fixed, not mobile context. For people with motor impairments, there may be several factors that could impact smartwatch use on-the-go, such as the position (e.g., seated), posture (e.g., upright) and use of assistive aids (e.g., canes). Posture may also depend on extra devices like trays fixed to wheelchairs. These factors will play a crucial role in the design of on-the-go gestures, an important next step, and may provide additional accessibility insight.

Limitations

Our findings are limited by the rectangular form factor of the smartwatch used in both the studies. Different trends may be observed if a circular watch were used instead. Also, while we only explored hand gestures in our study, other interactions may include using the nose (also cited by one participant), mid-air gestures, or voice input. Future work needs to examine other interaction techniques for smartwatch accessibility. Throughout the session, the watch was switched off and did not provide any audio or visual feedback to the participants. Participants' choice of gestures may be different with visuals on the smartwatch. Lastly, our participants' sitting position during both the study sessions may have influenced the types of gestures created by them.

Conclusion

In conclusion, we explored accessible smartwatch interactions for people with upper body motor impairments by expanding the interaction space to include the non-touchscreen areas of the smartwatch. We found that the physical abilities of the participants influenced location preferences, such as the desire to choose non-touchscreen locations close to dominant hand, and that the small touchscreen size created the need to explore alternative gestures for some standard actions (e.g., pinch-to-zoom). Lastly, we presented design guidelines for accessible smartwatch input.

Based on the findings from this chapter, Chapter 7 focuses on the design, implementation and evaluation of an alternative interaction technique for accessible smartwatch interaction.

Chapter 7 : Comparison of Touchscreen and Bezel Input for Accessible Smartwatch Interaction

Introduction

In Chapter 6, we adopted a participatory approach to explore gestures on the touchscreen and non-touchscreen areas of the smartwatch and to learn about accessible smartwatch interactions for people with upper body motor impairments. We found that while the body locations near the smartwatch were not preferred by people with upper body motor impairments, non-touchscreen areas (wristband and bezel) of the smartwatch closer to the body and the dominant hand were preferred. Previous studies have utilized the hard edges of handheld devices like mobile phones and personal digital assistants for target acquisition and stability in motion gestures [38,140]. Building on this body of work, we created an input system that utilizes the smartwatch bezel for interaction while also providing a potential solution to overcome the fat finger problem, a common issue with small interaction spaces (e.g., [5,52]). In this chapter we examine if expanding the interaction space to include the smartwatch bezel could potentially lead to an accessible input compared to the smartwatch touchscreen for people with upper body motor impairments who find precise touchscreen input difficult (e.g., [35,45]). More specifically, we investigated the following research question:

- Can input on the bezel of the smartwatch provide accessible control compared to input on the touchscreen for people with upper body motor impairments?

We examined the use of the smartwatch's bezel as a potentially accessible and alternative interaction space compared to the smartwatch touchscreen by conducting a study with 14 people with upper body motor impairments. We compared two interaction styles (bezel vs. a touchscreen control condition) and two target layouts (four targets vs. eight targets) in a controlled lab study by asking participants to do three sets of 16 trials for each condition. Our findings show that in terms of trial completion times the touchscreen was significantly faster compared to the bezel and the larger targets (4-target layout) were also significantly faster than the smaller targets (8-target layout). In terms of error rates, the bezel input had a significantly lower error rate compared to the touchscreen input for 8-target layout and the 4-target layout also had a significantly lower error rate compared to the 8-target layout for the touchscreen input. We also discuss participant's touchscreen and bezel location preferences and highlight challenges associated with bezel interactions. Lastly, we reflect on the bezel interaction technique and discuss ideas for improvement.

This research question contributes to the third thread of my dissertation research.

Background

To make mobile computing accessible, previous studies have leveraged the physical edges of devices like PDAs [38,140] as they offer several advantages over touchscreens like greater stability, greater speed, easy acquisition of targets along the edge (e.g., [137]). Other studies have adopted techniques that use touching and sliding the finger [135] for target selection, or analyzed touchscreen gestures to understand input performance and error rates of different target sizes and location preferences for people with motor impairments [35,45]. Anthony et al. [3] analyzed YouTube videos and found that people with motor impairments make several physical adaptations like using head and mouth sticks on touchscreens and physical guides to make existing technologies usable. For smartwatches specifically, the small interaction space results in fat finger problems (e.g., [5]) and people with upper body motor impairments may find precisely tapping on targets to be difficult (e.g., [35,45]). On the other hand, expanding the interaction space to include the smartwatch bezel may have the potential to mitigate these challenges. Consequently, we built touchpads of different sizes placed on different locations on the smartwatch bezel and compared tapping on these touchpads with tapping on the touchscreen for accessible smartwatch interaction. To determine the layouts (locations) of the targets to provide an efficient input, we use Shannon's index of difficulty [60] with choosing layouts with lower index of difficulty. This interaction technique was based on building accessible wearable interaction themes from Chapter 3: (1) a simple, manual input, (2) an easy to learn technique, (3) an input that supports use in a mobile context; and (4) input accessible to users with a range of upper body motor impairments.

Method

Participants

We recruited 14 participants (6 female, 8 male) with upper body motor impairments (see Table 7.1 for detail) through online advertising, mailing lists, local organizations and snowball sampling. All participants were volunteers and were compensated for their time. The study included a standardized Box-and-Block Test to measure gross manual dexterity in both hands [84]. Typical adult scores range from 60 for older adults

ID	Age	Sex	Reported Medical Condition	Uses wheelchair (WC)?	Dominant Hand	Box-and-Block Test	
						Dominant	Non-dominant
P1	41	F	Muscular dystrophy, SMA	Power WC	Right	19	21
P2	24	M	Cerebral palsy	No	Right	39	40
P3	29	F	Cerebral palsy	Power WC	Right	14	4
P4	51	M	Muscular dystrophy	No	Right	0	0
P5	34	M	Spinal cord injury	Manual WC	Right	29	18
P6	25	F	Arthrogryposis	Power WC	Right	14	15
P7	23	F	Cerebral palsy	Power WC	Left	2	1
P8	58	F	Essential and orthostatic tremors	No	Right	46	48
P9	47	M	C5-6 incomplete quadriplegic	Manual WC	Ambidextrous	42	32
P10	33	M	Cerebral palsy	Power WC	Right	25	19
P11	58	F	Multiple sclerosis	Power WC	Ambidextrous	27	0
P12	23	M	Radial nerve injury	No	Right	31	37
P13	21	M	Spinal muscular atrophy, Type 2	Power WC	Right	6	8
P14	50	M	Cerebral palsy	Power WC	Left	28	19

Table 7.1. Participant demographics, smartphone use, wheelchair use, and Box-and-Block Test results for both hands (higher values represent higher manual dexterity).

and 80 for younger adults [84]. Our participant scores ranged from 0 to 48 with higher scores indicating higher manual dexterity. All participants owned a smartphone. P2 and P6 owned an Apple watch. P2 reported experiencing challenges with wearing the Apple watch, precisely tapping on the touchscreen and pushing the crown button (also cited by P6) due to less strength. P4 owned a Garmin fitness tracker to track his steps and sleep but found pushing the button challenging and occasionally used his knee to press the button. P9 had limited experience using an Apple smartwatch for tracking wheelchair pushing.

Apparatus

We built two custom smartwatch applications, one for touchscreen tasks and another for bezel tasks. Both applications were written in Swift and were deployed on a 42mm Apple Watch Series 1 smartwatch (326 ppi). For the bezel tasks, we also used a smartwatch case (17mm × 15mm × 10mm) with fabric touchpads taped along the case

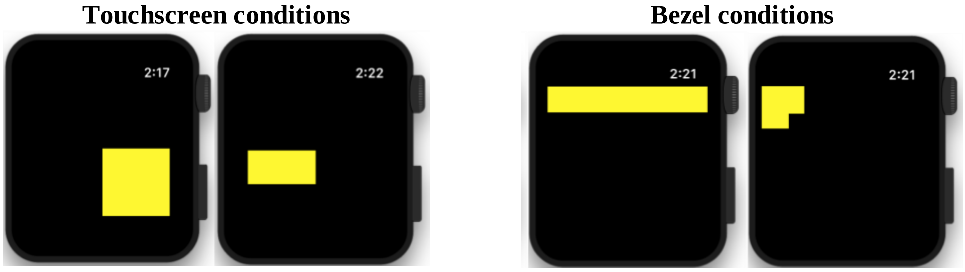


Figure 7.1. The figure shows the visual cues given to participants for the four tasks: 4-target and 8-target touchscreen and bezel (left to right).

on 4 and 8 locations. We used two smartwatches with cases to swap between the two bezel conditions.

Application for Touchscreen Tasks

The touchscreen application supported two target layouts: one with four targets and one with eight targets. For each trial, the application displayed a yellow target on the touchscreen along with an audio cue, played the appropriate audio upon a successful or an erroneous tap and recorded all touchscreen interactions (Figure 7.1). The application advanced to the next trial after a successful tap or a 10-second timeout. The actual active touchscreen area of the smartwatch was 24mm × 27mm but we restricted the active touchscreen area to a 24mm × 24mm box (the smaller of the two sides) for both layouts, a total of 96mm perimeter. The goal was to maximize the target sizes on both the touchscreen and bezel areas. This resulted in target sizes of 12mm × 12mm for the 4-target layout and a 12mm × 6mm for the 8-target layout. The layouts for the touchscreen tasks were chosen based on theoretically calculated *Index of Difficulty (ID)* values with the goal of maximizing efficiency (i.e., minimizing movement time as predicted Fitts' Law IDs). Layouts with lower *IDs* were chosen where $ID = \log_2(D/W + 1)$ [60]. The theoretical *IDs* were 1.0-1.2 for the 4-target layout and 1.0-2.2 for the 8-target layout.

Application for Bezel Tasks

As with the touchscreen application, the bezel application supported two tasks: one with a 4-target layout and one with an 8-target layout. We built a custom reconfigurable system consisting of conductive fabric taped on 4 and 8 locations on a smartwatch (Figure 7.2). These fabric touchpads were connected to an Arduino Uno via insulated conductive threads, and taps were sensed using the CapSense library. The sensed information (i.e., the tapped touchpad and the start and end times of the touch) was then sent to an iPhone 5S via an nrf8001 Bluetooth module. The iPhone then forwarded this information to the paired Apple watch.

For each trial, the smartwatch application displayed a thick, yellow target along the edge of the touchscreen to indicate which bezel location should be tapped, played the appropriate audio upon a successful or unsuccessful tap, and recorded the start and end times (in milliseconds) of the trials. The target sizes were 24mm for the 4-target layout and 12mm for the 8-target layout. Similar to touchscreen tasks, the sizes and layouts for the bezel tasks were chosen based on theoretically computed *IDs* with the goal of maximizing the target sizes and efficiency given the constraint of using only as much space as the total length of the perimeter of the touchscreen (96mm) and keeping the sizes equal on all sides of the bezel for both layouts. The theoretical *IDs* were 1.1-1.5 for the 4-target layout and 1.3-2.5 for the 8-target layout.

Procedure

All sessions lasted up to 90 minutes. The session started with a background questionnaire followed by technology experience survey and a 5-minute Box-and-

Figure 7.2. This figure shows P7 and P4 performing the bezel task: 4-target (left) and the 8-target (right).

Block test. The participants then completed four tasks which were presented in a balanced Latin Square order and the session ended with a semi-structured interview about the overall use and experience of using bezel and touchscreen taps.

Tasks

For each of the four tasks, participants first completed a practice block followed by three test blocks. The practice block consisted of 8 trials (2 taps × 4-target layout and 1 tap × 8-target layout) and the test blocks consisted of 16 trials (4 taps × 4-target layout and 2 taps × 8-target layout). At the end of each task, participants were asked to rate on a 7-point Likert scale the ease, physical comfort, perceived accuracy and perceived speed of performing the taps.

In each trial, a yellow rectangle was displayed on the touchscreen and an audio cue played. Upon tapping on the correct target (touchscreen or bezel), a success audio played followed by a 3-second countdown timer and another target was displayed on or along the touchscreen. The countdown timer was used to allow participants to reposition their hands and fingers and to avoid having the hand occlude the next target prompt. In case the participant tapped the incorrect target, an error sound played. We used the lift-off strategy for selection, where a successful tap occurred when a participant successfully lifted their finger off from the intended target on the touchscreen or bezel. A trial moved forward only upon a successful tap on the target or a 10-second timeout. The order of trials was randomized per task such that consecutive taps were not on the same target. A 30-second break was enforced between the three test blocks and participants were allowed to take breaks between the tasks.

Study Design and Hypothesis

We used a 2 × 2 within-subjects design: *interaction technique* (bezel *vs*. touchscreen) × *layout* (4-target *vs*. 8-target). The goal of the study was to compare the bezel interactions with the touchscreen interactions in terms of efficiency and error rates. Our hypotheses were derived based on the findings from Chapter 6 and also previous work that utilized the hard edges of devices for target acquisition [38,140]:

- H1: Bezel interactions are faster than touchscreen interactions.
- H2: Larger targets (4-target layout) are faster than smaller targets (8-target layouts).
- H3: Bezel interactions are less error prone than touchscreen interactions.
- H4: Larger targets (4-target layouts) are less error prone than smaller targets (8-target layouts).

Semi-structured Interview

The session concluded with a semi-structured interview on the participant's overall experience of using the bezel touchpads compared to the touchscreen, the advantages and disadvantages of both interaction techniques, and, lastly, a discussion on ideas for improving the bezel technique.

Counterbalancing and Data Analysis

For the order of conditions, we used a balanced Latin Square design where an equal number of participants were randomly assigned each of the four orders.

A total of 14 (participants) x 4 (conditions) x 3 (blocks) x 16 (trials per block) = 2688 trials were collected. The primary dependent variables were time and error rate. We also collected subjective rating data (7-point Likert scale) on the ease and physical comfort of performing taps, perceptions on speed and accuracy of performing taps. We checked for the normality assumption per condition via Q-Q plots and Shapiro-Wilk's W test and found that time and error both violated the assumptions. We also checked for learning effects using one-way repeated measures ANOVA with ART with a single factor of *block* for each condition and found statistically non-significant results. The block was then collapsed, and the analysis included only two factors. Hence, we used the 2x2 repeated measures ANOVAs with Aligned Rank Transform (ART) [138], with Wilcoxon signed rank tests and a Bonferroni correction for posthoc comparisons for trial completion times, error rates and subjective feedback.

Results

We report on performance evaluation results in terms of trial completion time, error analysis and subjective ratings for all four conditions. We also discuss location preferences for all the conditions.

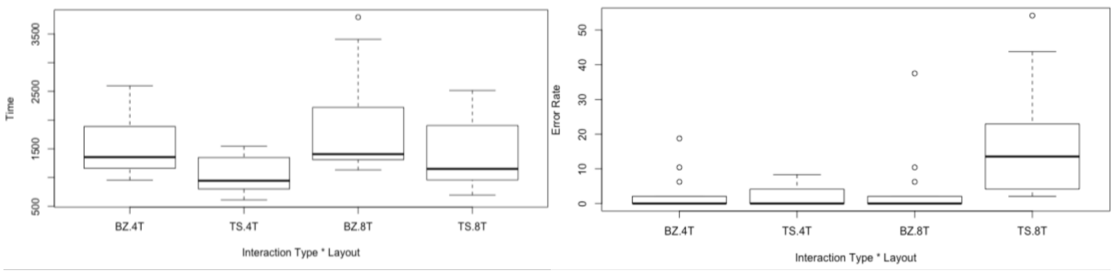


Figure 7.3. This figure shows boxplots of average trial completion times (left) and error rate results (right) for the 4-target bezel (BZ.4T), 4-target touchscreen (TS.4T), 8-target bezel (BZ.8T) and 8-target touchscreen (TS.8T) conditions (left to right). Lower values are better in both graphs. Error bars are standard error.

Performance

Trial Completion Time

The touchscreen trials were faster than the bezel trials with averages of 1194ms (*SD* = 229) and 1707ms (*SD* = 242), respectively (Figure 7.3). This difference was statistically significant with a main effect of *interaction technique* ($F_{1,13}$ = 22.60, $p < .001$, η_p^2 = .63). These results contradicted our hypothesis H1 that the bezel interactions are faster than the touchscreen interactions. Additionally, the 4-target layouts were faster than the 8-target layouts with averages of 1284ms (*SD* = 356) and 1617ms (*SD* = 370), respectively, thus supporting H2. This difference was also statistically significant with a main effect of *layout* ($F_{1,13}$ = 50.50, $p < .001$, η_p^2 = .79). However, the interaction between the *layout* and the *interaction technique* was not significant ($F_{1,13}$ = 1.22, p = .289, η_p^2 = .08).

Error Analysis

The error rate for the touchscreen interactions was higher than the bezel interactions with averages of 10% (*SD* = 11.25) and 3.5% (*SD* = 0.95) respectively (Figure 7.3). These findings supported our hypothesis H3 with a main effect of *interaction technique*

($F_{1,13}$ = 18.62, $p < .001$, $\eta_p^2 = .58$). Similarly, average error rate for the 4-target layout was 2.46% (*SD* = 0.53) and for the 8-target layout was 11.1% (*SD* = 9.79), a main effect of *layout* ($F_{1,13}$ = 26.54, $p < .001$, $\eta_p^2 = .67$), also supporting hypothesis H4. There was also a statistically significant interaction effect of *interaction technique* and *layout* ($F_{1,13}$ = 37.20, $p < .001$, $\eta_p^2 = .74$).

Posthoc pairwise comparisons among touchscreen 8-target layout and bezel 8-target layout using Wilcoxon signed-rank tests revealed that the *interaction type* significantly impacted the error rate in the 8-target layout, with fewer errors in the bezel condition ($p < .01$) compared to the touchscreen condition. However, pairwise comparison between touchscreen 4-target layout and bezel 4-target was not significant. Additionally, pairwise comparisons among touchscreen 4-target layout and touchscreen 8-target layout was significant ($p < .01$), with fewer errors in the 4-target condition compared to the 8-target condition. But pairwise comparisons among the 4 and 8-target *layouts* and bezel conditions was not significant. Based on these results, the bezel interactions have a lower error rate compared to the touchscreen interactions when the targets are of smaller sizes (8-target layout). Similarly, the 4-target layout have a lower error rate compared to the 8-target layout for the touchscreen conditions.

Subjective Feedback

At the end of each condition, participants rated the physical comfort, ease of use, perceived speed and accuracy using the 7-point Likert scale. We ran separate 2x2 repeated measures ANOVAs with ART for each of the measures.

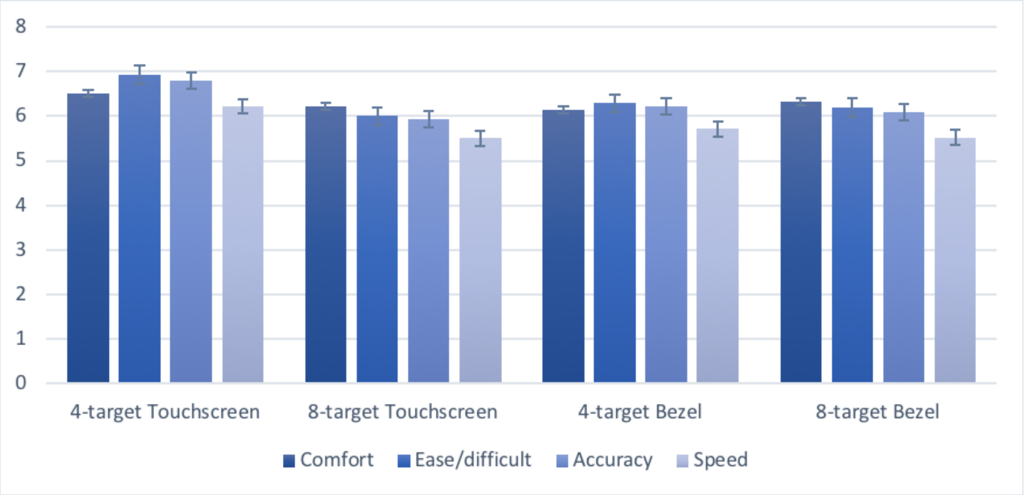


Figure 7.4. Physical comfort, ease of use, perceived accuracy and speed ratings for all 4 tasks. (1 = very uncomfortable/difficult/inaccurate/slow and 7 = very comfortable/easy/accurate/fast). (N=14). Error bars are standard error

Physical comfort. There were no statistically significant main or interaction effects for physical comfort. Average rating for the 4-target touchscreen was 6.5 (*SD* = 1.40), 8-target touchscreen was 6.21 (*SD* = 1.48), 4-target bezel was 6.14 (*SD* = 1.35), and the 8-target bezel was 5.92 (*SD* = 1.44), as also shown in the Figure 7.4.

Ease of use. The *layout* significantly impacted the ease of use ($F_{1,13}$ = 13.47, $p < .01$, $\eta_p^2 = .50$) with averages of the 4-target layout and 8-target layout as 6.60 (*SD* = 0.45) and 5.96 (*SD* = 0.05) respectively. There was no significant main effect for the *interaction type* and no interaction effect.

Perceived Speed. Similar to ease of use, the 4-target layout was perceived to be faster compared to the 8-target layout ($F_{1,13}$ = 7.67, $p < .05$, $\eta_p^2 = .37$) with averages of 5.97

(*SD* = 0.35) for the 4-target layout and 5.46 (*SD* = 0.05) for the 8-target layout. No significant main effect for *interaction type* or interaction effect was found.

Perceived Accuracy. For perceived accuracy also, a significant effect of the *layout* was observed with 4-target layouts perceived as being more accurate compared to the 8-target layout ($F_{1,13} = 12.76$, $p < .01$, $\eta_p^2 = .49$) with average ratings of 6.5 (*SD* = 0.40) for the 4-target layout and 6 (*SD* = 0.10) for the 8-target layout. No significant main effect for *interaction type* or interaction effect was found.

Summary. Our results supported hypotheses H2, H3, and H4 but contradicted hypothesis H1. The touchscreen interactions were significantly faster than the bezel interactions but were more prone to errors for smaller targets. As expected, our results also showed that the larger targets (4-target layouts) were perceived to be easier, faster and more accurate compared to the smaller targets (8-target layouts).

Qualitative Comparison of Touchscreen and Bezel Input

Overall, all participants found the 4-target touchscreen task to be the easiest. Seven participants thought the bigger target sizes on the touchscreen made this task the easiest and two (P1, P10) thought it was easy to use their fingers or thumb for this task. P4 talks about how this task provided more control based on performing the taps and the feedback received,

> *"There's also psychological reward, if you will, on touching what I can see versus tapping on the bezel on the side. I can touch the target and make it disappear, it's hard to describe. It felt more controlling, touch the color and it disappears. And*

> *that was, maybe, more psychologically rewarding than touching the side of something to make it appear or disappear."*

P8 felt the familiarity of using touchscreens with her smartphone made it easy for her and P2 thought there was less room for error when tapping on targets in this task.

While the majority (12/14) of the participants thought that 8-target bezel was the most difficult, P3 reported the 8-target touchscreen as the most difficult because of small targets and the need for precision and P8 felt the 4-target bezel was the most difficult as corner locations in the 8-target bezel task were easier for her,

> *"It's funny, its probably the 4-target bezel, that was harder than the 8-target bezel and I have no idea why. I think because the corners were easier to hit with the bezel."*

Reasons for the 8-target bezel being difficult included: smaller targets (5/14), need for precision (3/14), need to twist the wrist (3/14), need for coordination between the finger and the wrist (2/14), and lastly, P4 felt that the targets were furthest from the tapping finger.

Location Preferences

To understand if there were locations on the touchscreen and bezel that were perceived as easier or more difficult to tap compared to others, we asked participants about their preferences at the end of each condition.

Touchscreen Location Preferences

4-target Touchscreen. While the majority (10/14) of the participants reported that there was no perceived difference in tapping between the four locations in this task, P1 and P7 stated that targets closer to the bottom of the touchscreen were easier to tap compared to other locations. On the other hand, P1, P12 and P14 reported targets closer to the top of the touchscreen as being marginally difficult,

> *"Just because you have to turn the watch a little bit or bring it closer to hit it. The bottom is closer to you. It's (points to the top of the watch) not far but every now and then you have to like turn if you have mobility issues." (P1)*

8-target Touchscreen. Similar to the 4-target touchscreen task, six participants reported that there was no perceived difference in tapping between the eight locations in this task. P8 said that the smartwatch touchscreen *"is such a small area already,"* that it did not matter. Others mentioned specific areas on the touchscreen but there was no clear trend. In terms of difficulty too, participants preferences varied based on their motor abilities and there was no clear trend. P7 said that the physical positioning of her arms made it harder for her to reach locations that were too close or too far,

> *"The topmost row and the bottom most rows were hard cause of my arm. The bottom most row was the hardest. I guess cause my hand (non-dominant hand) was not high up."*

While P10 felt that he had to hit the targets twice that were close to his non-dominant side to ensure he was tapping. But, P3 thought she had more control reaching targets that were on her non-dominant side.

Bezel Location Preferences

4-target Bezel. Eight participants reported tapping on the bottom bezel as easy, five reported the top bezel, three the non-dominant and three the dominant side as easy. For P5, both the sides (dominant and non-dominant) were easy to tap as he did not have to worry about the finger angle,

> *"They were easier to tap because one, there's more area and two, I didn't have to worry about the angle of attack. I was using my middle finger, but I was using it from the side or straight on. So, I was able just to sort of, I didn't have to worry about the angle in which I was touching it [...] the side closest to the hand I seem to touch it straight on. On the side furthest from me I didn't have to worry about any sort of angle of attack, I just used the side of my finger in that situation."*

Participants' rationale also included the proximity to the finger used for tapping (P4, P8) and the natural position of their hands (P13, P14),

> *"Like I'm sitting here like this and my thumb is quick to that one (the bottom bezel) as opposed to the other three where I had to move my finger around." (P14)*

For P1, the top and bottom locations would cause the least interfere with her wrist movement,

> *"Yes, the top and the bottom are easier than the sides. They just seem to stick out more. If you have like, you know, your wrist, you have to really keep it down, it really pushes the bezel out. If you go like that (raises her wrist towards the hand) then it's hard to get on the sides cuz your hand is blocking. No matter which way you go, the top and the bottom will always be sticking out as opposed to crunching the sides."*

On the other hand, in terms of difficulty, six participants said the non-dominant side, three said the dominant side and three said the top bezel were difficult. However, none of the participants found tapping on the bottom bezel difficult. Participants rationale included the need to turn the wrist (4/14), locations prone to accidental tapping (3/14), and hard to reach locations (P10). P5 describes turning his wrist to tap,

> *"Yes, the top ones are difficult to tap. Again, because it sort of strains my arm the most when I am making that turn to see the face of the watch which I feel as though I need to do in order to touch the top button and so it's more uncomfortable in the hand in my arm, whatever muscle is right there just immediately gets strained." (P5)*

P1 compared accidental tapping to a "butt" call,

> *"Just that your hand can get in the way, your wrist can get in the way of the sides. And your wrist here, if you raise it up, can tap the side accidently when you might not mean to, like a "butt" call." (P1)*

8-target Bezel. The eight locations in this task included the 4 sides and 4 corners of the bezel. Participants had varying preferences for locations on the bezel. Six participants reported the bottom bezel was easy to tap, four said the top bezel was easy, three said the corners were easy and three said the dominant side was easy. For P4, both the sides were equally easy and for P5 only the corners on the bottom bezel were easy. P13 also mentioned the corners on the dominant side were easy and P14 said the bottom corner on the dominant side was easy. Participants rationale were similar to the 4-target bezel condition: the natural position of the hand (4/14), locations that were easy to reach (2/14), closer to the pointing finger (2/14), could fit the finger (P1) and lastly could see where the finger was while tapping (P5). P2 talks about the natural position of hands as,

> *"Because with my hand position the thumb could reach the corners or could reach these two corners (corners on the bottom bezel) quickly and my index fingers could reach these two corners (corners on the top bezel) quickly."*

On the other hand, the locations that were difficult to tap followed the same trend of mixed preferences that depended on each participant's motor abilities including: the dominant side (3/14), the non-dominant side (3/14), all corners (2/14), top corners (2/14), top bezel (P5), bottom bezel (P2), dominant side corner (P9) and non-dominant side corner (P13) of the bottom bezel. For six participants, tapping on bezel locations required repositioning of hands or twisting of the wrist,

> *"I think because the way I would approach it my hand over the watch is like my fingers are further past those buttons, so I have to like pull them back to touch them because I had a position where I could instantly touch as opposed to like having it back here and having to reach forward. Like I would have to pull it back and touch, so it took longer." (P2)*

For P4, all the corners were difficult because,

> *"It was difficult to be accurate. The target was not as large and not as tactile cuz it's a corner, there's not as much surface* as on the sides. *You had to hit the bezel and not the color (on the touchscreen). There's no visible target on the bezel. There is one on the watch face and not the bezel. It made a little more difficult."*

For P1 and P11, the fingernails got in the way of tapping on the dominant side,

> *"I think cuz you have a finger nail it can be hard to tap things. Cause I was trying to turn my finger for this one (dominant side) and the finger nail is really in my way. Like I'm trying to get the pad of my finger on it […] It's hard to get your pad on the sides whereas these (corners), I feel like are sticking out." (P1)*

Summary. In terms of location preferences for all four conditions, while participants did not find any major differences between the target sizes for the touchscreen conditions, location preferences varied for the bezel conditions. The most common reason for the variation included the need for more movement of the arms, wrist and fingers which depended on the participants' motor abilities. However, many participants in the touchscreen and bezel conditions said that the bottom areas were easier to reach compared to other areas.

Overall Use and Comparison of Touchscreen and Bezel

We asked participants about their overall preference between touchscreen or bezel, in terms of physical comfort, ease of use, perceived accuracy and speed.

Physical Comfort

All participants except P3 reported that the touchscreen was physically more comfortable to use compared to the bezel. Participants reasons included no requirement of twisting the wrist (P4, P13), familiarity with the touchscreen (P8), and that the touchscreen offered an overall consistent experience (P5). P1 also talks about how it was easier to avoid other locations on the touchscreen compared to the bezel,

> *"Let's say this whole thing was lined with 6 squares, now that might be difficult because you may accidently hit the wrong one. So, they weren't all on the screen at the same time there was only one option [..] if they all were together at the same time, that would be more difficult and frustrating. The bezel again it was only one choice to make and I find 8 too many too close together. It's just so small, tight space"*

For P3, the bezel locations were more comfortable as she did not have to worry about her taps on the bezel being recognized as some other gesture compared to when she used a touchscreen that was capable of recognizing multi-touch gestures.

Ease of Use

In terms of ease of use, all except P3 found the touchscreen easier to use compared to the bezel. The main reasons included touchscreen tasks had visual targets (P4, P8, P10), the flat surface of the touchscreen (P1, P11) and the touchscreen provided a bigger area to tap (P1, P5, P12, P13). P4 describes tapping on the visual target as,

> *"because it was a visual target. It's easier to tap where you are and where you want to tap. In touching the bezel, you didn't touch the visual indication whereas on the touchscreen you did."*

Other reasons included, the targets were all grouped closer (P5), familiarity with touchscreens (P14), there was no need to twist the wrist (P2) and the touchscreen locations were not narrow for the fingers (P1). But, for P3, the touchscreen interaction needed precision and hence she felt the bezel was easier to tap.

Perceived Accuracy

For accuracy, 11 participants said touchscreen was more accurate. While P8 and P10 reported bezel interactions more accurate compared to touchscreen, P11 reported both interactions as equally accurate. Fewer error sounds (audio feedback) in bezel interactions made P8, P10 and P14 believe that they were more accurate in the bezel interactions. But, P11 was confused by the error sounds, perhaps due to concurrent touches of other parts of the finger or hand. Other reasons included touchscreen targets were bigger (P1, P3, P4, P5) and could fit the fingers (P1) and the tap was directly on the visual cue (P4).

Perceived Speed

Lastly, in terms of speed, twelve participants said touchscreen interactions were faster, P3 said bezel was faster and P8 felt both interactions were the same. Touchscreen interactions did not require reaching around the watch (P2, P9, P14), fingers and wrist needed less movement (P1, P2, P4) and that the targets were grouped closely together (P9, P13).

Advantages and Disadvantages of Bezel

Compared to the touchscreen, participants reported several advantages of bezel interactions: increased functionality (P4, P9, P12), possibility of using multiple fingers (P8, P14) or different angles of attack (P5), the possibility of being less accurate but more confident in the touch (P5), the sense of touch (P2), no requirement to look down on the watch (P2), no interference with touchscreen (P1, P13) and that the bezel offered more space which allowed touching anywhere (P5). P2 says,

> *“You know for sure what you tapped as you can feel it as opposed to the touchscreen where you have to be looking at it.”*

P5 describes his less accurate but more confident touch as,

> *“One advantage is that I can use different sides of my finger […] the 3 of the 4 sides are sides where I can be less accurate but more confident in the orientation of the finger. The bottom side and the left and the right side. And there's more real estate. So specially with the bezel 4 target, I can touch anywhere. And in that way, I could be less accurate in where my finger landed and how my finger landed but still feel like I was touching the bezel.”*

P8 says how using multiple fingers can be an advantage,

> *“I found myself using only the index finger for the touchscreen but for the bezel I was using multiple fingers. I think it’s an advantage to be able to use multiple fingers.”*

On the other hand, participants thought bezel locations required to orient themselves in certain ways like twisting the wrist or turning the finger (P2, P4, P5, P13, P14) and they may have a hard time mapping the locations to the functionality (P1, P9) if it existed. P1 also said that interacting with the smartwatch in general will need both hands, a disadvantage when driving,

> *“if you are driving, you can use your phone with one hand and touch buttons like I do because I drive with my right hand and I can still be on the phone when I make a call driving. I won’t be able to do it on the watch unless I had Alexa or something. You have to be very precise, so the touchscreen may have 4 options but if it’s on*

> *the bezel there may be more options and it may be harder. It's going to take you longer to figure out which bezel button to use as opposed to looking at the screen."*

P5 also thought that he had to put in more effort to make an accurate contact on the 8-target bezel taps.

Participants also discussed situations or scenarios where they would prefer the bezel taps over the touchscreen taps. P1, P9, P10 and P13 thought bezel taps would be preferable for quick tasks, P1, P5, P12 thought when there's something already on the touchscreen that you need to maintain continuous contact (e.g., maps) or in tasks where touchscreen touching would take longer like using a timer or stopwatch (P9, P11, P12) or in case of emergencies (P10),

> *"When you have an emergency. Because sometimes the touchscreen is good but you gotta work on the bezel and get used to the bezel. Probably the bezel is faster than the touchscreen." (P10)*

P9 describes several use-cases of using bezel taps,

> *"Maybe if it was a stopwatch where you didn't have to touch the screen to start and stop to where you could just touch the bezel to do it. If you are timing something, it could take an extra second to touch it and see it and then touch it again to start it and stop it. Again, maybe on a program if it's like a smart device, again I'm using an example like your living room lights, to what you can program it to touch the top of the bezel to turn on the living room lights where now you have to touch the screen, pull up that app and turn that stuff on."*

P2 thought touching on the bezel did not require him to look down on it as he could just touch and feel and know where the finger is. P3 also says that she may use bezel taps for existing gestures like pinching as they are difficult for her. P11 thought the bezel locations are the most intuitive and logical for tasks like timer and stopwatch. P13 talks about a case,

> *“Perhaps answering a call or changing volume. Those are things that I don’t need to do with a lot of precision. They are just momentary touches to the watch. If my arms are apart, when I bring them together, the bezel is closer than the touchscreen and in order to reach the touchscreen I have to turn my left (non. dom. hand) wrist to bring the screen closer to me but if I had to quickly answer or quickly lower the volume I could reach the bezel quickly.”*

Advantages and Disadvantages of Touchscreen

When asked about the advantages and disadvantages of touchscreen tapping, participants listed various advantages like it was easy (P6, P9, P11, P13), no need to twist the wrist (P2, P7, P14), familiar (P8), grouping of targets was closer (P5, P14), could see the targets being tapped (P4), less movement was needed (P2), felt that the accuracy was better (P11) and that it could be used with long fingernails too (P1).

Some disadvantages, however, included the touchscreen needed precision (P7, P8), finger obscured the screen (P4, P5, P13), was prone to accidental tapping (P9, P14), tapping on the touchscreen felt less accurate (P5), P2 felt he needed to look at where he was tapping and P1 thought it may be difficult for people who tap with their knuckles,

> *"With the 8-target touchscreen one, you never really know for sure, I felt less accurate with that. This is a common thing with touchscreens in general you are never quite a 100% sure where you should tap because your finger might be visually covering it up and if you are looking it from an angle you can, sort of, there's a little bit if room where you can go above or below the button, you are not quite sure if you are touching where you should be […] You always know where the bezels are cuz they are always on the outside."(P5)*

P9 describes a problem he's experienced with his smartphone and fears he may experience it with the smartwatch too,

> *"I had a problem with my phone when I first started playing with it. If it's too sensitive, if you get too close to the screen or something maybe you can activate something else."*

When we asked participants about scenarios when they would prefer touchscreen taps over bezel taps, six said they would prefer touchscreen taps for everything. Others mentioned specific cases like when a series of button presses are needed like for texting purposes (P3, P5, P10), P4 thought it would be difficult to use the bezel when the watch is sitting on the charger and P2 thought in cases when he was not busy and could look down on the watch.

Feedback on the Bezel Interaction Technique

We asked participants about the general feedback they had about the bezel tasks they used and ways to improve the interaction technique or make it accessible. Five participants mentioned the need to be able to customize the different area of the bezel based on their impairment. On the positives, P9 mentioned that the bezel provided more options and the sizes and locations were on locations that were easy to reach. P6, who owns a smartwatch said that bezel taps could potentially replace the side buttons and make the watch accessible,

> *"People that don't have motor skills, it's hard for them to push the buttons. They have to ask people to push the buttons for them. If we replace the buttons with the bezel taps, it would be more easy."*

P6 also said that she occasionally rested her thumb on the bottom bezel for support to be able to reach and tap the top bezel which caused accidental tapping. P5 discussed the idea of using the inner side of the wristband, that was closer to him, to replace the top bezel to make it more accessible. P5 also reflects on the corner bezels as being a little odd,

> *"You know any smaller than these 8 I guess would be problematic. I would prefer the bezel with the 4 targets. The corner bezels are a little odd. Just that. I think it's probably just an unusual thing to touch a corner or something, just historically you don't really have corner buttons a lot"*

P3 and P5 also talk about introducing more gestures on the bezel locations like double or triple taps or scrolling gestures. P10 spoke about increasing the size of the bezels and making the full side touch sensitive. Lastly, P8 said the 3-second timer between the trials made it harder for her to perform tasks,

> *"I guess the hardest thing for me for all the taps was the waiting the 3-seconds in between. I guess for me when I get a rhythm going with things like writing my name*

> *as opposed to printing me name, like if I have like a pattern going or speed going its easier than stopping and starting and stopping and starting."*

P13 also wanted physical feedback from the bezel.

Discussion

The goal of this chapter was to investigate if expanding the existing interaction space of smartwatches to include the bezel could offer an accessible interaction compared to touchscreen interactions for people with upper body motor impairments. In this chapter, we compared bezel interactions with touchscreen interactions in terms of trial completion times and error rates. We also compared the physical comfort, ease of use, perceived speed and accuracy for both interactions. We found touchscreen interactions were significantly faster compared to bezel interactions, contradicting hypothesis H1, which we discuss below. We also found that bigger targets (4-target layout) were significantly faster compared to smaller targets (8-target layout), supporting hypothesis H2. In terms of error rates, our study supported hypothesis H3 and H4 and demonstrated that smaller targets (8-target layout) were prone to significantly fewer errors for the bezel interaction compared to touchscreen interactions and bigger targets (4-target layout) were prone to fewer errors compared to smaller targets (8-target layout) for the touchscreen interactions.

Speed-accuracy tradeoff: The findings from this study showed that there is a speed-accuracy tradeoff for the touchscreen *vs.* bezel tapping: while bezel interactions were slower compared to touchscreen interactions, they were also less error prone for smaller targets. Some potential reasons for this finding emerged in the study. The touchscreen targets had lower Fitts' law *indexes of difficulty (IDs)* as the targets were grouped closer together compared to the bezel targets where the targets were further from each other and hence needed more hand movement. Despite the Fitts' law ID advantage offered by the touchscreen targets, we had expected that the bezel locations would still offer an advantage due to the benefit of "target overshoot," where target acquisition on physical edges are easier compared to targets on a touchscreen because the edge catches any overshooting movement [140]. Ultimately, however, the touchscreen offered faster input, likely due to a combination of the lower touchscreen target *IDs*, participants' familiarity with touchscreens, and lower demand for gross hand movements. For errors, the bezel targets had physical spacing between them, which allowed for some imprecision in touch without causing the system to recognize an incorrect input, unlike the touchscreen targets that were immediately adjacent to each other. Additionally, the touchscreen error feedback may not have been as perceptible to participants, perhaps due to occlusion or concurrent touches, a common problem with touchscreen interaction (e.g., [95]).

An additional important question for future work is how information throughput compares for the touchscreen versus bezel input. Information throughput (e.g., [77]) is a single measure that combines both speed and accuracy, may be useful to examine in future work. While our study was not setup to be able to support a robust throughput analysis (e.g., based on Fitts' law), the measure may help in understanding the optimal choice of interaction technique and layout for accessible smartwatch interaction.

Design Reflections

Location customization. In our study, while all participants were able to use the bezel interactions, only one participant (P3) preferred bezel interactions over touchscreen interactions. Participants bezel location choices indicated a preference of locations closer to the body but also included locations like the non-dominant side, contrary to the findings from Chapter 6. These location preferences depended on participants gross and fine motor skills (e.g., range of motion) and the natural state of their hands (e.g., thumb resting near the bottom areas of the touchscreen and bezel), highlighting the need for locations to be customizable. Practical issues like accidental tapping of the bezel touchpads by other parts of the body (e.g., by wrist movement in case of P1) also arose which likely could be avoided if participants could customize their choice of locations, shutting off the touchpads on the sides of the bezel for P1.

Touch behavior on non-flat surfaces. While previous studies (e.g., [57,94]) have investigated touch behaviors on flat surfaces like touchscreens, not much is known about the touch behavior on non-flat surfaces. The primary goal of this study was not to understand how people with upper body motor impairments touch on non-flat surfaces like the smartwatch bezel, but our study offers insights into factors that impacted participants' bezel interaction experience. Bezel interaction required dexterity required to reach to different locations on the bezel to tap (point): twisting of the wrist (e.g., to reach the non-dominant side of the smartwatch), and the twisting and using different parts of the finger (e.g., using the pad of the finger for touching the bezel). While the bezel touchpads could also work by tapping using the side of the finger as P5 used, some participants (P1, P9) had an implicit assumption that they had to touch the bezel with the pad of the finger similar to existing touchscreen interactions. For tasks that need fine motor skills (e.g., text entry as also cited by P3, P5), using bezel interactions may make tasks even more challenging for people with motor impairments. Future studies should consider the users' touch behaviors on non-flat surfaces for building such interaction systems.

Practical implications. Our findings indicated a speed-accuracy tradeoff and highlighted the benefits and limitations of bezel and touchscreen interactions in different contexts. Based on participants' responses about bezel and touchscreen preferences, bezel interactions are preferred for tasks that require maintaining continuous eye contact on the touchscreen (e.g., manipulating a map), for performing time-related gestures (e.g., starting or stopping a stopwatch) that were perceived as more logical on the bezel, and, lastly, when looking at the smartwatch was not possible (e.g., reflection due to sunlight) or desirable (e.g., in settings like in class or at work). On the other hand, touchscreen tasks were preferred for most other tasks, especially for tasks that needed continuous or a series of tapping (e.g., text entry) interactions, and tasks that needed less precision.

The practical implication of these findings is to use touchscreen interactions for performing continuous actions and to use bezel interactions for quick tasks and tasks that need less precision, and when maintaining eye-contact with the touchscreen is necessary. Based on the findings from this study, the bezel interactions could be used in combination with the touchscreen interactions to overcome existing problems with touchscreen precision and allow for accessible smartwatch input for people with upper body motor impairments.

Limitations

The bezel interaction approach presented in this chapter is applicable to rectangular smartwatches only. While we leveraged the already existing sides and corners of the rectangular smartwatch for interaction, these sides and corners may not be available in circular smartwatches. Different approaches like discrete markers may be used to adapt the current technique to provide accessible smartwatch interactions. The bezel targets were narrower compared to the touchscreen targets. This may have influenced the participants' overall preferences in terms of interaction and location of the bezel. Additionally, the experiment displayed visual cues on the touchscreen for all conditions. The demand to map these visual cues to the appropriate bezel targets may have impacted the bezel conditions. In this chapter, we only explored tapping (pointing) interactions for bezel locations. To fully understand the impact of expanding the space for accessible smartwatch input, other interactions (e.g., swiping) and locations (e.g., wristband) should be explored. Our study was done in a lab setting with all participants resting their hand either on the table in front of them or on their wheelchair tray. To truly understand the impact of bezel interactions, more work needs to be done to investigate their use in settings beyond the lab. Lastly, our goal was to investigate if expanding the current interaction space of smartwatches to include the bezel location would have the potential to improve accessibility for people with mild to moderate upper body motor impairments. While the results and findings from this work are applicable to people with mild to moderate upper body motor impairments, we recognize that more work needs to be done to generalize the results and findings to a broader population.

Conclusion

We present findings from the design and evaluation of an alternative interaction technique utilizing the bezel for accessible smartwatch interaction for people with upper body motor impairments. All participants performed all the four tapping tasks. We found that while bezel interactions were slower than touchscreen interactions, they were also less error prone compared to touchscreen interactions. We also found that a majority of the participant preferred the touchscreen interactions compared to bezel interactions and the locations closer the body (bottom the touchscreen and bezel) were perceived to be the easiest, also confirming findings from Chapter 6. Our results also highlighted the speed-accuracy tradeoffs between touchscreen and bezel interactions. Lastly, we reflect on the design of the bezel taps highlighting some challenges and specifying a few directions for further research.

Chapter 8 : Conclusion and Future Work

The goal of my dissertation was to investigate emerging wearable technologies for people with motor impairments and to design, build and evaluate alternative input mechanisms to make these wearables accessible. More specifically, my dissertation comprises three threads of research: (1) assessing the accessibility of three common classes of wearable devices—head-mounted displays (HMDs), smartwatches, and fitness trackers; (2) understanding the potential impacts for people with mobility impairments of sharing fitness data from existing activity-tracking wearables; and (3) implementing and evaluating accessible interactions for HMDs and smartwatches. In this chapter, I summarize the steps taken to investigate the three threads of research, outline the main contributions of this dissertation and, lastly, provide directions for future work.

To investigate the three threads of research, we conducted four exploratory studies to examine the potential benefits and accessibility challenges, if any, of emerging wearable technologies via semi-structured interviews, participatory design activities, design probes activities, and a week-long field study (Chapters 3, 4, 5, 6). Based on the findings and design guidelines from these studies, we built an alternate, accessible input mechanism for HMDs (Chapter 3) and smartwatches (Chapter 7) and evaluated the new input mechanism via controlled lab studies. Finally, we also reflected on the design of these input mechanisms in Chapters 3 and 7 and discussed future directions to improve the same.

Reflections

From the first thread of my dissertation research, we found that wearable technologies offer advantages that could potentially mitigate existing challenges experienced by people with upper body motor impairments with smartphones. However, accessibility challenges existed with these wearables. The strategies adopted in this dissertation towards building accessible interactions included utilizing the hard edges of handheld devices, expanding the current interaction space or supporting customization of locations to accommodate people with varying motor impairments. These strategies, already existing, when used to make wearable technology accessible have made interaction with HMDs and smartwatches possible for people with motor impairments. However, it is important to note that these strategies are not the only ways to make interactions with existing wearables accessible. It is possible to adopt other strategies or build an entirely new wearable primarily for people with motor impairments or other disabilities. But, the goal of my dissertation was to investigate if existing technologies can be made accessible without the need for sophisticated hardware. This, in turn allowed equal access to mainstream wearable technologies instead of specialized devices for people with motor impairments.

Thesis Contributions

Thread 1: Accessibility of Existing Wearable Technologies

To investigate the potential advantages and accessibility of emerging wearable technologies we conducted a series of exploratory studies. In the first semi-structured interview study with six people with upper body motor impairments with an HMD

(Google Glass), we learnt that Glass offered several benefits like not having to hold the device or look down at it and not having to worry about dropping and damaging the device, but half the participants were not able to use the Glass because of their impairment (Chapter 3). In a second study, 14 people with mobility impairments participated in an in-person interview study evaluating two wearable fitness trackers followed by a participatory design activity, and a subset also participated in a week-long field trial assessing a fitness tracking mobile app (Chapter 4). We learnt that participants experienced problems like irrelevant tracking, inaccessible form factor, small size of the display and buttons. In the participatory design activity, all participants opted in for an easy to put on wearable form factor and wanted tracking that would be embedded in existing mainstream technology. We also presented design guidelines to build accessible HMDs and fitness trackers. The specific contributions of this thread are:

- **C1:** Empirical evidence demonstrating the extent to which an existing interaction mechanism (built-in touchpad) of an HMD is accessible to people with upper body motor impairments (Chapter 3).
- **C2:** Potential benefits of HMDs for people with upper body motor impairments (Chapter 3).
- **C3:** Empirical evidence demonstrating the extent to which existing mobile and wearable fitness trackers are accessible for users with mobility impairments, based on use (1) in the lab and (2) in the field (Chapter 4).
- **C4:** Guidelines for how to design more inclusive activity tracking devices for people with mobility impairments (Chapter 4).

Thread 2: Implications of Sharing Activity Data

Based on the findings from Chapter 4, we learnt that people with mobility impairments wanted the ability to share their data with peers with similar impairments. We investigated the impact of sharing automatically tracked activity data from wearables on people with motor impairments and therapists via semi-structured interviews and a design probe activity (Chapter 5). While we learnt that people with mobility impairments were interested in learning about new activities from others or finding peers based on different parameters, the study also brought to light several questions about privacy, sharing of mental health related data and demotivation by looking at the data of others. The specific contributions of this thread are:

- **C5:** Identification of opportunities for building tools to help therapists make personalized therapy decisions about their patients using data from activity-tracking wearables (Chapter 5).
- **C6:** Characterization of attitudes and concerns about sharing health and fitness data from the perspective of both therapists and individuals with mobility impairments (Chapter 5).
- **C7:** Design recommendations to build tools that support inclusive sharing of fitness-related activities with peers who have similar mobility impairments (Chapter 5).

Thread 3: Designing, Implementing and Evaluating Accessible Wearable Interactions

Toward the last thread of my dissertation, we built and evaluated alternative input mechanisms to allow for accessible control of HMDs (Chapter 3) and smartwatches (Chapters 6 and 7). Findings from the first part of Chapter 3 revealed that half the participants were not able to use the HMD. To this end, we built wearable touchpads of three sizes that participants could place anywhere on their body or wheelchair to control an HMD. In a controlled lab study with 12 participants, all participants were able to control the HMD using the wearable touchpad input technique and participants placed the touchpads at locations on their body or wheelchair based on their own individual motor abilities.

In a participatory study with smartwatches with eleven participants with upper body motor impairments, we also explored the touchscreen and non-touchscreen areas of the smartwatch for accessible smartwatch interaction (Chapter 6). Results from this study indicated participants' preferences for non-touchscreen areas closer to the body and dominant hand, but no preference for on-body locations near the smartwatch. Based on the design guidelines from Chapter 6, we built touchpads of two sizes mounted on the bezel of the smartwatch and compared tapping on these bezel touchpads with touchscreen in a controlled experiment (Chapter 7). Fourteen participants performed taps on the touchscreen and bezel locations in four tasks. We compared the trail completion times and error rates of bezel interactions with touchscreen interactions and found that touchscreen interactions were significantly faster compared to bezel interactions but were also more error prone for the smaller targets. We also reflected on the bezel interaction design and discuss improvements for future work.

The specific contributions of this thread are:

- **C8:** A simple, customizable input solution to allow users with upper body motor impairments to control an HMD via switch-based touchpads (Chapter 3).
- **C9:** Empirical results from a performance and subjective comparison of three sizes of touchpads, and, secondarily, between these touchpads and the default manual control on an off-the-shelf HMD (Chapter 3).
- **C10:** Characterization of personalization patterns and design considerations to support accessible wearable input for users with motor impairments (Chapter 3).
- **C11:** Guidelines to build accessible smartwatch gestures by including the touchscreen and the non-touchscreen (bezel, wristband and skin near the watch) areas of the smartwatch based on input created by people with upper body motor impairments (Chapter 6).
- **C12:** Empirical results from a performance and subject comparison of bezel interactions with existing touchscreen interactions for smartwatches (Chapter 7).

Future Work

The research from this dissertation opens possibilities for future projects, some of which I present below.

Use in settings beyond the lab and longer evaluations

All of the studies in this dissertation were lab-based, with the exception of a week-long field study in Chapter 4. To truly understand the impact of the wearable technologies evaluated and proposed in this dissertation, and to provide greater external validity, longitudinal evaluations in the user's everyday environments and in public settings should be considered. Several studies (e.g., [3,62,92,98,132]) have investigated interaction behaviors with smartphones and tablets in the wild for people with motor impairments; however, less is known about the use of wearable devices in field settings. The user's social settings (e.g., [108,124]) or different contexts like walking and running (e.g., [91]) or pushing the wheelchair (Chapters 3, 6 and 7) may impact factors such as the location of where the wearable is worn or interference with everyday activites. In Chapters 3 and 4, participants chose locations of wearable touchpads used to control Google Glass (Chapter 3) and of their ideal fitness tracker (Chapter 4) by taking into account wheelchair pushing or interference with assistive aids. In Chapter 3, specifically, some participants also considered social scenarios when selecting where to place their wearable touchpads. More questions related to use in settings beyond the lab may arise: To what extent are the interaction techniques implemented in this dissertation appropriate for use in social settings and to what extent are bystander perceptions important (e.g., [108,109,115])? How do people's motor impairments impact the use of a wearable device over time?

Extending to broader audiences

The input mechanisms introduced and evaluated in this dissertation offer unique features such as location personalization based on use in social settings, participants' motor ability and interference with wheelchair or clothing (Chapter 3) and also applicability to people with varying physical strengths in hands and arms (Chapters 3 and 7). The target user group of this dissertation primarily involves people with mild to moderate upper body motor impairments, ~20 million people in the United States [17]. However, these interaction techniques may also benefit people who may or may not have motor impairments but who are situationally impaired such as use in inclement weather (e.g., [119]), restrictive clothing (e.g., [121]), in-motion (e.g., [41]), divided attention (e.g., [62]) or when the phone is in the bag or pocket (e.g., [98]) or people with temporary physical impairments or older adults who have difficulty using their hands and arms. Future work should evaluate these techniques to understand how such interactions can be applied to the above-mentioned groups either directly or with minor adaptations.

Extending to other wearable technologies.

In this dissertation, we focus only on some of the most popular wearable technologies – head-mounted displays, activity trackers and smartwatches. However, as the wearable technology landscape expands with the inclusion of technologies like wearable cameras for photos and videos or AR/VR technology, it may be worthwhile to explore the accessibility of these wearables. The interaction techniques implemented in Chapters 3 and 7 may be adapted to make these wearables accessible, in case of existing interactions being inaccessible. For example, the wearable touchpads implemented in Chapter 3, could potentially be adapted to take pictures and record videos using Snapchat's smart glasses, Spectacles[1] which currently uses a button on the glass for this purpose.

Exploring other interaction techniques

In Chapter 3, we built switch-based wearable touchpads that supported location personalization to control Google Glass and in Chapter 7, we attached fabric touchpads on the smartwatch bezel to make the non-touchscreen area interactive. While these techniques are only a few potential solutions to make existing wearables accessible by instrumenting the wearable itself, other techniques may also be explored. Some examples include 3-D gestures (e.g., [54,116]) or interactions utilizing the space around the wheelchair [21,22]. Exploring speech input can also be a possibility (e.g., [8,9,23,51,83,90,106,141]) but speech has its own limitations: it can be awkward in public places, it needs trigger phrases to activate which that can potentially be used by anyone, and speech also has privacy issues as anyone in the environment can hear. Lastly, some people with motor impairments also have slurred speech which can make speech interaction problematic, as was the case with one of our participants in Chapter 3. In addition to exploring alternative interaction techniques, wearable interfaces that would automatically adapt to the user's abilities would be an interesting avenue to explore.

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[1] https://www.spectacles.com/

Investigating activity tracking and systems to support sharing of this data

Findings from Chapters 4 highlighted the need for tracking activities relevant to users who use assistive aids like walkers, wheelchairs and canes, which, with the exception of the Apple Watch 2 [4] that now tracks manual wheelchair pushing, still remains an unexplored area. While we assessed the overall accessibility of the Apple Watch (Chapter 6), little is known about the accuracy of tracking of wheelchair pushing and the potential utility of this feature by people with mobility impairments. Additionally, we also explored the potential impacts of sharing health and fitness-related data tracked by these wearables in Chapter 5. While the findings from Chapter 5 are based on perceptions of people with motor impairments and therapists and are preliminary, we offer guidelines to advance this research to build systems to support sharing of this data with peers and therapists and to make informed decisions about the same.

Overall Limitations

The goal of this dissertation was to explore the potential impacts and accessibility of emerging wearable technologies like head-mounted displays, fitness trackers and smartwatches for people with mild to moderate upper body motor impairments. While we discuss the limitations of each study in its respective chapter, a few overall limitations are important to mention. The work presented in this dissertation limits the generalizability of the findings to people with mild to moderate upper body motor impairments. Our participants also self-reported their impairment, were relatively tech-savvy, and may also have been socially well connected since they were recruited via local organizations, on-campus listservs and other listservs in organizations that work with people with disabilities. All our participants were from the US only.

Lastly, all of the studies in this dissertation were short evaluations or interviews done in the lab or other controlled settings (with the exception of the field study in Chapter 4), and Chapters 3-6 were based on participant perceptions. Longer evaluations and use of fully functional technologies may change opinions, hence more work needs to be done to extend the findings of this dissertation to a broader population and other use cases.

Final Remarks

The work presented in my dissertation provides evidence to support my research statement,

"Popular wearable technologies like head-mounted displays, fitness trackers, and smartwatches can be made accessible for people with upper body motor impairments by improving input accuracy over default input mechanisms and supporting custom input for wearable interaction thus providing quick access to information and enabling independent use of technology."

As mobile computing trends shift from smartphones and tablets towards wearable technologies that are worn on the body or clothing, it will be important to investigate their potential impacts and accessibility for a broad group of users. This dissertation is the first step towards investigating the accessibility of emerging wearable technologies like head-mounted displays, fitness trackers and smartwatches for people with motor impairments. In this work, I also implemented and evaluated alternate, accessible interaction techniques by allowing customization of wearable input locations for head-mounted displays and by expanding the interaction space of smartwatches. These techniques offered improved accuracy when compared to the default inputs, built-in Google Glass touchpad and the smartwatch touchscreen. By making existing wearable technologies accessible via improved accuracy and custom input, all our participants were able to independently use the wearable technology, especially in the case of Google Glass. Additionally, the interaction techniques in this dissertation also supported the design goals we defined based on exploratory studies: simple manual input, interaction should be socially acceptable, should support use in mobile context, be easy to learn and be accessible to people with varying levels of physical strengths. As the wearable technology landscape expands to include different interactions and form factors (e.g., smart clothing), it will be important to investigate if the techniques implemented in this dissertation can be used for accessible input, either directly or with minor adaptions for people with motor impairments.

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