RESEARCH-ARTICLE

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Exploring Accessible Smartwatch Interactions for People with Upper Body Motor Impairments

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ABSTRACT
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 wearables may pose challenges for people with upper body motor impairments. To investigate accessible smartwatch interactions for this user group, we conducted two studies. First, we assessed the accessibility of existing smartwatch gestures with 10 participants with motor impairments. We found that not all participants were able to complete button, swipe and tap interactions. In a second study, 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.

Author Keywords
Motor impairments; accessibility; wearables; smartwatches; interactions; elicitation study.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous; K.4.2. Social issues: assistive technologies for persons with disabilities.

INTRODUCTION
Mainstream wearables like smartwatches allow people to accomplish tasks in a mobile computing scenario and can track continuous health and fitness data. Compared to smartphones, smartwatches offer relatively hands-free interaction and may be able to overcome smartphone accessibility challenges like pulling the phone from a pocket or bag [30]. However, compared to smartphones, a smartwatch's small touchscreen interaction space and the need for bimanual interaction (i.e., bringing one hand to the opposite wrist) may be challenging for people with upper body motor impairments. Even physical button and bezel-based input on a smartwatch may be different than on a smartphone, both due to the bimanual interaction and because the watch is affixed to the body.

In this paper, we investigate the accessibility of smartwatches for people with upper body motor impairments and explore alternative solutions for supporting accessible smartwatch interactions. First, we conducted a lab study with 10 people with upper body motor impairments to assess the extent to which off-the-shelf smartwatch input is accessible to this user group—taps, swipes, button actions, text input, and voice dictation. We found perceived benefits to using smartwatches like overcoming situational impairments and reduced chance of dropping and damaging the device as compared to a smartphone. However, we also found that many participants encountered difficulties with manual text input and taps, and, for some, even with speech input due to dysarthria.

Second, we conducted an input elicitation study to explore the smartwatch input preferences of users with motor impairments, examining the touchscreen as well as other input spaces: the bezel and strap of the watch, and the user's own body (e.g., forearm or back of hand). These non-touchscreen areas provide a larger interaction space than the screen alone, which in turn could be more accessible to users who find precise touchscreen input to be difficult (e.g., [13,17]). In this study, 11 participants with upper body motor impairments were asked to create gestures for 16 common smartwatch actions on the touchscreen and non-touchscreen areas of a smartwatch. Previous work has employed gesture elicitation studies to create intuitive, easy-to-perform and easy-to-remember gestures (e.g., [4,23,37]). Building on the participatory nature of these studies, we instead adapt the method to learn about what types of gestures users consider to be accessible and why, when given the opportunity to imagine any input. We found that for the non-touchscreen areas, the on-body (i.e., skin) locations were not popular but areas closer to the dominant hand on the bezel and the strap were the most preferred. In some cases, participants also created more accessible alternatives to familiar touchscreen gestures that they felt were difficult on the small screen (e.g., two-finger zoom).

The primary contributions of this paper include: (1) empirical results from an accessibility assessment of

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existing smartwatch interactions; (2) physical properties of accessible gestures created by users, including interaction styles and finger inputs; (3) comparison of accessible interactions on the touchscreen and non-touchscreen areas around the smartwatch; (4) design guidelines to build accessible smartwatch interactions for people with upper body motor impairments.

RELATED WORK

We cover accessible mobile and wearable computing, and general smartwatch interactions.

Accessible Mobile Computing

Mobile computing devices using touchscreen technologies like smartphones and tablets have become ubiquitous. In addition to common benefits like access to information on-the-go, these devices also offer positive impacts on independence [22,30]. However, people with upper body motor impairments experience challenges performing multi-touch gestures and text entry (e.g., [2,22,35]), and are more prone to errors using touchscreens compared to people without motor impairments [12,29]. In terms of common touchscreen gestures like tapping Guerreiro et al. [17] found that targets located at the bottom of the screen and next to the gesture performing hand were the easiest to select. When touchscreen input was compared with mouse input for basic tasks (e.g., dragging), Findlater et al. [13] found that though touchscreen input was faster for people with motor impairments, it also led to a three-fold increase in pointing (tapping) errors compared to the mouse. For people with gross motor impairments, Irwin et al. [21] investigated the use of touchscreen technology and found longer dwell times associated with this user group.

Strategies to address existing touchscreen problems have included utilizing the screen edges to stabilize gestures [14,38], or utilizing a swiping ("swabbing") interaction rather than tapping, to stabilize finger interactions on the screen itself [36]. These studies highlight both the positive impacts and accessibility challenges that touchscreen devices can present for users with motor impairments. However, the focus has been on smartphones, tablets, or touchscreen kiosks rather than smartwatches, which offer a much smaller screen and require bimanual coordination.

Accessible Wearable Computing

A survey by Zhou et al. [40] found that for people with motor impairments, wearable device research has largely focused on sensors for medical diagnosis or motor rehabilitation. In terms of accessible wearable interactions for information access, projects have investigated wearable touchpads at different locations to control Google Glass [26], explored the space around the wheelchair for potential input/output opportunities [7], and built arm-rest based pressure-sensitive input touchpads to control a mobile device [8]. Other interaction techniques have included wearable input to control wheelchair movement (e.g., using the tongue [20]) or to control desktop computers (e.g., inertial sensors [33]).

Specific to smartwatches, many accessibility applications have been explored. For people with low vision, arm movements recorded by smartwatches to perform a desired task on the smartphones have been investigated [32]. Informing people who are hard of hearing about environmental sounds [28], helping people with mild cognitive impairments overcome challenges related to employment [10], and helping people with ADHD overcome stress and anxiety and maintain focus via intervention techniques [9] are some other smartwatch applications for people with disabilities. The Apple Watch 2 also introduced manual wheelchair tracking, making their watch more attractive to users with motor impairments. While more work has leveraged the potential of smartwatches to support people with various disabilities, little is known about the overall accessibility of smartwatches for people with motor impairments.

General Smartwatch Interaction

Studies on smartwatch usage patterns (e.g., [34]) 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 [5]. However, the small input/output interaction space may result in fat-finger and occlusion problems [4]—problems that could be magnified for users with motor impairments. To overcome these problems, many research studies have explored alternative input techniques, such as wrist-based interactions to keep the hands free [16,18], mechanical input techniques using the watch faces [39], non-visual gestures like covering the watch face [31], utilizing the wristband for multi-touch gestures [1] and text entry [15], and utilizing the space above the smartwatch for finger input [19]. Kerber et al. also compared existing mechanical inputs (bezel rotations and digital crown) and touch interactions on a smartwatch [24] and found that users preferred the digital crown interaction over others. However, none of these studies have investigated interaction techniques 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. 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.

Method

Participants

Ten participants[1] (6 female, 4 male) were recruited through mailing lists and a local organization working with people with disabilities. They were on average 29.1 years old (*SD*

[1]Two additional participants did not complete the entire study and are excluded from our analysis because of insufficient data: one quit due to a lack of time and one quit due to difficulty in completing trials.

= 8.9). Eight reported daily smartphone or tablet use, while the remaining two used these devices "almost never". Two participants (P2 and P5) owned smartwatches, while the remaining eight had not previously used one. Eight participants' motor impairment was related to cerebral palsy, while the remaining two reported arthrogryposis and a coma, respectively. Half of the participants were righted-handed and half were left-handed. In terms of vision, one participant was blind in the left eye, one had amblyopia, one was far-sighted, two were near-sighted, and the remaining five had normal or corrected-to-normal vision. More detail on participants is in the Supplemental Material. Participants were volunteers and were compensated $25.

Procedure

The procedure took up to 90 minutes and was video recorded. Video captured a view of the watch surface, hands and elbows of the participants. After a demographic questionnaire, participants were given a five-minute introduction to smartwatches, including the following demos on a 42mm Apple Watch Series 1: composing and sending a message both with voice and manual input (i.e., drawing letters on the touchscreen), and setting an alarm using both voice and manual input.

The smartwatch was then placed on the participant's non-dominant wrist and they completed basic input tasks using 19 interaction techniques native to the Apple Watch. Figure 1 shows the input areas on the watch. Interactions were completed within the native text messaging app, watch home screen, or within a custom app that we built. Although our goal was to preserve a degree of ecological validity, the custom app was necessary to isolate interactions and eliminate input ambiguity in some cases (e.g., regular swipes and edge swipes often cause the same outcome but can be unique). The interaction techniques were organized into the following four *interaction groups* and basic input tasks for each were specified as follows:

• *Taps (4 interaction techniques):* one-finger single tap, double tap, and hard press, and two-finger double tap. For one-finger single and double taps, target size (52 × 312 *px*) in the custom app was set in accordance with Apple's *watchOS* human-interface guidelines [3]. For two-finger double tap and hard press, the target was the entire screen to reflect *watchOS* zoom and force-touch target sizes.

• *Swipes/flicks (8 interaction techniques):* directional swipes left/right/up/down, left/right edge swipes, and up/down flicks. "Edge swipes" are swipes that must start at the curved edge of the touchscreen (Figure 1). Flicks require greater velocity than swipes. These interactions were performed in the custom app.

• *Physical buttons (5 interaction techniques):* single press, double press, long press, and rotate of the crown button, and single press of the side button. Button tasks were done on the watch home screen as most native button actions mapped to cross-app outcomes (e.g., single press closed an

Figure 1. The figure shows screens for the right-edge swipe trial before (left) and after a successful attempt (right).

app and opened the app menu). Crown rotate was performed in our custom app to scroll a vertical list.

• *Text input (2 interaction techniques):* Manual input by "scribbling" the letters "T", "A", and "i" (3 separate input tasks), which span varying input complexity, and speech input of the phrase "Hi Siri". We used the messaging app and the three manual input letters were always presented in the same order.

In total, there were 21 input tasks (including the three manual input letters) spanning the 19 interaction techniques. The four *interaction groups* were randomly ordered per participant, with individual techniques randomly ordered within each group. For each technique, the experimenter demonstrated how to complete the basic task, then participants completed up to three trials of that task (with the exception of manual text input, for which they repeated up to three trials of each letter). A trial ended upon successful completion or after 45 seconds (3 times the maximum time taken by a user without motor-impairments in a pilot session). 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. At the end of each interaction group, participants rated the *ease of use* of the group as a whole using a 7-point scale (1 – very easy to 7 – very difficult). For text input, manual and speech input were rated separately because they require substantially different physical abilities. Participants also specified the easiest and most difficult technique within each group and provided rationale for those choices.

Finally, the session closed with open-ended questions about the overall experience of using the smartwatch, how it compared to other devices (e.g., smartphone), projections on utility, and suggestions for improving the device.

Data Analysis

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. We thematically analyzed the open-ended interview responses. Two team members independently coded a randomly chosen participant video on eight dimensions as shown in Table 1. Two conflicts arose (out of 140 codes) and were resolved with discussion. The coding scheme was refined based on discussion with the research team members.

Findings

We describe performance and subjective feedback with the basic input tasks, followed by the video analysis and open-ended responses.

Task Completion

The task completion rates demonstrate the overall accessibility issues of smartwatches for users with upper body motor impairments. Out of 630 possible trials (21 × 3 × 10), 75 were automatically skipped due to a previously timed out trial; had they been attempted, these skipped trials would likely have reduced completion rates further. Of the remaining 555 trials, 489 (88%) were successfully completed. The 66 unsuccessful trials included attempted and voluntarily skipped trials (*N*=26) and attempted and timed-out trials (*N*=40).

Among all *interaction groups*, Swipes/flicks and Buttons had the highest completion rates. Overall, the number of participants who completed all three trials successfully for each *interaction group* were: Text (speech) – *N*=9, Swipes/flicks – *N*=7, Buttons (excluding *crown double press*) – *N*=7, Taps – *N*=3, Text (manual) – *N*=2. This lattermost result shows the difficulty of manual text input. The *crown double press* was particularly difficult, with no participant successfully completing it. Excluding *crown double press*, only one participant (P2) successfully completed all trials for the remaining input tasks.

Ease of Use 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).

Swipes/flicks. There were no clear trends with the swipe and flick preferences. *Regular swipes*, specifically up and down, were found to be easy (5/10) and difficult (5/10) by an equal number of participants. Similarly, *flicks* were deemed easy (2/10) and difficult (2/10) by an equal number of participants. Two participants each found *edge swipes* to be the most difficult.

Taps. The easiest interaction choices were as follows: *single tap* – *N*=5, *hard press* – *N*=4, *two-finger double tap* – *N*=1. Nine participants chose the *two-finger double tap* as the most difficult interaction, while one specified the hard press. Successive taps within a time duration (speed) and also having to use two fingers made the former difficult for the participants. P10 elaborated: *"two-finger double tap. You had to use two fingers and that was kind of hard."* The pressure level control required by the hard press was stated as a reason for it being difficult. P6 expressed caution while performing the hard press: *"…I'm kind of heavy handed. So, I am not trying to break it"*. Conversely, P9 emphasized that the increased pressure requirement of the *hard press* made it the easiest: *"I press hard. It's really hard to press soft. Since I was in my accident, it's harder to press soft."*

Physical orientation
User posture: upright, reclining, leaning forward
Non-dominant wrist position: resting on table, body, arm-rest, etc.
Dominant wrist position: resting on the table, suspended in air, etc.
Watch position: top, bottom, sides of the wrist
Watch screen orientation: flat, vertical, angle with ground/table surface
Interaction method
Finger preference – single touch gesture: thumb, index, etc.
Finger preference – multi-touch gesture: thumb + index, etc.
Watch stability during gesture: Held only by strap, additional support

Table 1. List of eight dimensions and codes used to conduct video analysis in Study 1.

Buttons. Participants' easiest interaction choice varied: *crown single press* – *N*=3, *side button single press* – *N*=3, *crown long press* – *N*=2, and *crown rotate* – *N*=2. In a clearer trend, most participants (*N*=7) found the *crown double press* to be the most difficult action due to the speed needed for two successive presses. P5 specified: *"Because you got to hold your hand in an awkward way and press it [crown button] twice."* The size of the button also impacted ease of use, as explained by P10, *"I guess because the [side button] press was bigger than the crown button."*

Text. Nine participants preferred to dictate text compared to manual input. Participants' lack of familiarity with the manual input method, and the speed and complexity of the strokes influenced this choice. P4, for example, said, *"…when I tried to do [scribble input], it was too fast and it wouldn't let me do it"*. Interestingly, P10 preferred Text (manual) as he found it useful for improving hand-eye coordination and motor skill. P8 was unable to complete voice input tasks due to dysarthria but still found Text (speech) easier compared to Text (manual).

Video Analysis

We focus on user posture and input characteristics.

User Characteristics and Posture

The posture of participants influenced the resting position of the dominant/non-dominant arms and wrists, which in-turn could affect input difficulty. Eight participants used wheelchairs, one (P8) used a walker, and one (P9) did not use a mobility aid. While interacting with the smartwatch, most participants (*N*=6) sat in an upright position, two leaned forward, one reclined, and one alternated between a forward and reclined posture. Posture depended on the participant's preferred position while not using a watch, a fastening harness to the wheelchair, or use of a wheelchair tray.

The non-dominant wrist, on which the smartwatch was worn, was most often held mid-air (N=5), while two participants rested the wrist on the table or wheelchair tray, the remaining three varied between mid-air and resting on the body. The dominant wrist was either held mid-air (N=5) or varied between mid-air and resting on a table or the body (N=5). Nine participants positioned the watch such that the dial was on top of the wrist. P10 preferred to wear the watch with the dial resting on the inside of the wrist because his arm was naturally oriented with the wrist side up. He also continued to perform gestures after the watch dial slipped from the side to bottom of the wrist.

Physical Interaction Methods

Collectively, our participants' finger preference spanned across all five fingers, varying in accordance with nature of the gesture and the participant's dexterity. Overall, for 170 single-touch tasks (17 × 10), participants' finger preference varied as follows: index (61.8%), thumb (11.8%), multiple fingers but only one touch at a time (10.6%), ring (7.6%), and little (7.1%). We found the index finger being used the most for high-precision tasks like Taps (66.6%) and Text (Manual) (80%). Thumbs were more common, however, for pressure-reliant Button interactions (75.0%), including single press of crown and side button, crown long and double press. Ring and little finger usage was entirely from only two participants (P2 and P10). Participants switched to another finger after unsuccessful attempts using the previous finger. A variety of finger pairs were used for *two-finger double tap*: index and middle (N=8), middle and ring (N=4), and ring and little (N=1). To keep the watch stable during the gesture, especially for button interactions, four participants sometimes used other parts of their dominant hand (e.g. additional fingers to hold watch dial) for support.

Post-evaluation Interview

On being asked about their overall experience, four participants reported a neutral experience in using the watch, including the two who already owned a smartwatch: P2 found her smartwatch to be *"fine"*, but preferred to use her smartphone, whereas P5 preferred his Samsung Gear S over the Apple Watch due to familiarity. The remaining six participants reported an overall positive experience, indicating potential for current and new users.

Participants generally felt they would be able to use smartwatches as well as smartphones. Five participants said their abilities would allow them to use both, two participants found the watch easier to use because of compactness, and three participants chose the phone. P5, a daily smartwatch user, commented that there were better accessibility features on the phone.

Seven participants reported specific advantages of smartwatches over smartphones – compactness (P1), voice commands (P3, P9) and support to overcome situational impairments (P1, P4, P5, P6 and P10) by always being on the wrist. There were mentions of not having to retrieve the phone and less risk in dropping the device. For example, P5, who is a daily smartwatch user, explained: *"Most of us don't pull out our phones in a moving van because quite frankly in a van, we might drop it usually. We just keep our smartwatches on."* Disadvantages included the screen size (P5) and text entry (P1, P4, P5). For example, P4 said, *"Because you know like when I did that writing part it was kind of hard. That was hardest."* Four participants found no disadvantages, while two participants (P2, P8) preferred the smartphone and did not provide specific rationale.

Eight participants demonstrated interest in using a smartwatch in the future, whereas P2 (a current smartwatch owner) and P8 preferred to simply use their phones. P10, for example, said: *"I am very interested, but it would take me some time to get used to it. Because my hands are less efficient than what it needs to be to use a smartwatch."*

Overall, participants predicted that they would use smartwatches for a range of tasks: calling, texting, listening to music, monitoring health, internet access, social media, and watching videos. In terms of suggestions, participants mentioned a video player (P7, P10) and theft alarm apps, and an auto-fastening strap for older adults and wheelchair users to ease putting on the watch (P10). Participants also wanted to be able to adjust touch sensitivity (P4, P5), and have larger physical buttons (P3).

Summary and Discussion

Only one participant was able to complete all input tasks (excluding *crown double press*). Manual text entry was particularly difficult, but at the same time speech input did not work for one participant due to dysarthria. Previous work has shown that tapping small touchscreen targets is highly error prone for users with motor impairments [13]. A small smartwatch screen likely magnifies the problem of tapping, which our results demonstrate – despite subjective reports that taps were easy. Despite these accessibility challenges, 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 [14,38])—that could ultimately improve accessibility. To achieve these goals, we adapted an input elicitation method [37] whereby we asked 11 participants to create gestures for common smartwatch actions like *view notification*.

ID	Age, Gender	Reported Medical Condition	Uses wheelchair (WC)?	Box-and-Block Test		Physical Ease and Good Match Ratings (7-point Likert Scale)					
						Touchscreen		Non-touchscreen		Mixed	
				Right	Left	Ease	Goodness	Ease	Goodness	Ease	Goodness
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	Power WC	10	5	7	7	7	7	7	7
*P4	28, F	Cerebral palsy	Power WC	13	0	6.25	6.37	6.12	6.06	6.06	6.37
P5	49, M	Spinal cord injury	Power WC	0	10	6	6	6	6	6	6
P6	34, M	Spinal cord injury	Manual WC	29	21	7	6.68	6.87	6.81	7	6.62
P7	40, F	Muscular dystrophy	Power WC	18	21	6.75	6.93	7	6.56	7	7
P8	58, F	Multiple sclerosis	Power WC	0	25	7	7	7	7	7	7
P9	27, F	Osteogenesis imperfecta	Power WC	44	47	7	6.87	7	6.81	7	6.93
P10	44, F	Juvenile rheumatoid arthritis	Power WC	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 2: 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.

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 2). 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 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 [27]. For context, average adult scores for this test are around 80 for young adults and 60 for older adults [27].

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

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 [4,11,25], 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 3) 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 3 shows the 16 actions, which include a subset from [4] as well as *view notification* and *dismiss notification* because these two are common smartwatch tasks [34].

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 they 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 [6]. 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 [37], 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.

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.

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

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 4). 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)

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 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 [4,37], participants also created gestures that mimicked real world

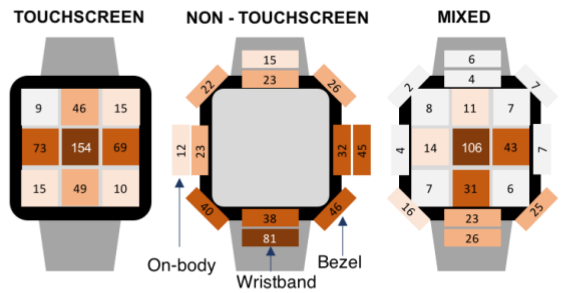

Figure 2. Areas touched during the three tasks for all 16 actions for all participants. In the mixed task, no participants chose to touch the skin locations. (Darker colors represent a higher frequency of gestures).

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 2, 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. [17] with handheld devices. 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 4). 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 5).

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 5. 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).

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 2, 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., [26]). 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., [13]).

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 2), 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 4), 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 2, 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 5).

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 [4], 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., [13]) or multi-touch gestures on smartphones (e.g., [2]). Our work also highlights similar problems with *taps* and *pinch-to-zoom* for smartwatches. Given that smartwatches have a smaller touchscreen 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 [14,38] 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. 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

We presented two studies to explore accessible smartwatch interactions for people with upper body motor impairments. In the first study, we assessed the accessibility of existing smartwatch interactions and found that participants experienced challenges performing existing gestures, including taps. In the second study, we explored alternative smartwatch interactions by asking participants to elicit gestures on the touchscreen and non-touchscreen areas for 16 common smartwatch actions. 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 more accessible smartwatch input.

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