Toward Accessible Health and Fitness Tracking for People with Mobility Impairments

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ABSTRACT
Electronic health and fitness trackers have received substantial attention over the past decade, from new mobile and wearable technologies to evaluations of potential health impacts. These trackers, however, may not be accessible to people with mobility impairments, for whom activities such as running, walking, or climbing stairs can be difficult or impossible. To investigate the accessibility of wearable tracking devices and mobile apps, we conducted a study with 14 participants with a range of mobility impairments. The study included an in-person interview, evaluation of two off-the-shelf wearable devices, and a participatory design activity, followed by an optional week-long field evaluation of a mobile fitness app (to which 8 participants opted in). Our findings highlight widespread accessibility challenges with existing tracking technologies and provide implications for designing more inclusive solutions.

CCS Concepts
• **Human-centered computing → Human-computer interaction;** *Accessibility*; Ubiquitous and mobile computing;

Keywords
Accessibility, mobility impairments, wearable computing, health and fitness tracking.

1. INTRODUCTION
Activity tracking for health and fitness has received increasing attention over the past decade. In addition to commercial devices like the FitBit and Nike Fuelband, research projects have targeted areas such as food habits [40], sleep [25], physical activity [31], and mental well-being [29]. While these devices are not a panacea, they can act as facilitators to maintain or change health-related behavior [35]. Even the simple pedometer has been shown to increase activity levels and improve health outcomes [8].

Mobile and wearable activity trackers, however, may not be accessible to people with mobility impairments. In the United States alone, 15 million people find running, walking and climbing stairs difficult or impossible, and may use assistive aids like wheelchairs or walkers [15]. These impairments impact physical activity levels, in turn increasing the risk of obesity and other medical conditions [41]. Ambulatory young adults with cerebral palsy, for example, sedentary than their peers without cerebral palsy [33], yet an active lifestyle can have positive emotional and physical benefits for people with mobility impairments [30, 39].

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Movement tracking for people with mobility impairments has primarily focused on exergaming (e.g., [17]) and rehabilitation (e.g., [5, 22]), rather than everyday activity tracking. Specifically sensing manual wheelchair movement, however, is also an ongoing area of work [21], but the focus has been on technical aspects rather than user interface design. Most closely related to our work is a study by Carrington et al. [10], who interviewed five wheelchair athletes about wearable fitness trackers—three therapists were also interviewed but few findings are based on their comments. While none of the athletes had first-hand experience with wearable fitness trackers, their perception was that it would be useful to track wheelchair movement, breathing, heart rate and/or nutrition, but that these devices are not accessible. The authors identified three opportunities for future work: updating activity recognition algorithms, instrumenting the wheelchair with sensors, and generally making the interfaces more inclusive (e.g., not using the word "steps"). However, in addition to the small sample size (N=5) the findings are based only on user perception rather than actual experience.

Building on this body of work, we conducted a study with 14 participants who have a range of mobility impairments. The study included an interview and participatory design session, followed by a weeklong field evaluation of a mobile fitness app with eight of the participants. The first session focused on current tracking behaviors, perception of fitness trackers, assessment of the accessibility of two popular wearable trackers (*Fitbit One* and *Moov*), and design of a tracker tailored to the participant's needs. For the field study, participants installed an off-the-shelf mobile fitness app (*Pacer*) on their smartphone, reported daily on their physical activity and app use, and completed a second interview. Our study, though conducted prior to the publication of [10], thus employs a more in-depth and methodologically complete research approach than that used in [10].

Our findings both confirm the obvious perception (from [10]) that accessibility challenges exist with these trackers, yet also identify specific challenges, such as the difficulty of juggling paired devices, contrasting issues and desires with different groups of users (power *vs.* manual wheelchair users *vs.* walkers). Half of the field study participants were positive about their experience with the tracking app, feeling it worked at least to some extent—unexpected use cases included bicycle mode to track rolling and interpreting "steps" as an abstract quantification of activity rather than actual steps. Finally, the participatory design activity allowed us to identify common desired elements for future accessible tracking devices, such as using a wearable form factor instead of a mobile app (e.g., gloves were popular, in contrast to [10]), and additional features such as fall detection.

The primary contributions of this paper include: an assessment of the accessibility of mobile and wearable fitness tracking for users with mobility impairments, based on use (1) in the lab and (2) in the field; (3) specific guidelines for how to design more inclusive, activity tracking devices for people with mobility impairments.

2. RELATED WORK

We discuss three areas related to activity-monitoring devices for people with mobility impairments.

2.1 Electronic Health and Fitness Tracking

In a survey of mobile-health interventions, Klasnja and Pratt [27] 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 [27]. Issues, however, include people's perceptions about how activities are tracked [43], dealing with tracking errors, visualizing large amounts of data, and respecting users' privacy [27]. The ultimate goal of these technologies is often to impact long-term behavior change but Harrison et al. [19] describe the challenges associated with long-term studies, including unreliability of devices and engagement with them. Hence, Klasnja et al. [26] 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. [13] combined wearable activity sensing with ambient mobile phone displays to promote fitness. Focusing on older adults, Davidson et al. [14] 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. The closest work to ours comes from Carrington et al. [10], as discussed in the Introduction. Although not studying people with mobility impairments specifically, Beevi et al. [6] 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 [21]. However, custom sensing algorithms that primarily use accelerometer data have provided high accuracy in detecting wheelchair activities [22, 36, 38]) 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 [34]. Simple classification of floor surfaces has also been examined [16]. 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.

2.2 Accessible Exergaming

Accessible exergames have been explored to some extent for users with motor impairments [20]. As with fitness tracking, making exergames accessible can require movement sensing not supported by off-the-shelf technologies. For example, Gerling et al. [17] built the KINECTWheels toolkit for Microsoft Kinect to classify wheelchair-accessible gestures such as clapping hands, moving forward, and raising an arm. Exergames are also used to engage people in physical rehabilitation exercises, particularly for repetitive exercises like reaching or balancing [9]. While movement sensing in this context must meet specific rehabilitation needs [5], some sensing approaches may still be useful for more general fitness and activity tracking.

2.3 Mobile and Wearable Accessibility

Designing health and fitness trackers for people with motor impairments is not just a matter of appropriate activity sensing—the user interface must also be accessible. Both phone-based and wearable trackers are common; our study evaluates both. Mobile phones can provide a sense of independence for users with disabilities [24], yet accessibility challenges range from retrieving the device from a pocket [32] to using multitouch gestures [2]. Recommended target sizes [18] and techniques to stabilize the user's input (e.g., [42]) can address some of these challenges. Increasing attention has also been paid to the use of wearable technologies to support people with disabilities. For people with motor impairments, specifically, recent work has examined wheelchair-based input [11, 12] and accessible control of head-mounted displays [28]. Wearable devices have also been employed for therapeutic purposes, such as to visualize [1] or gather data for rehabilitation therapy [23].

3. 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 into a week-long field evaluation of a mobile app. The initial session captured health and fitness attitudes, and use and perception of tracking tools, while the field portion captured challenges encountered in practice.

3.1 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 1. 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.

3.2 Fitness Trackers

Participants evaluated three complementary fitness trackers: Fitbit One and Moov, wearable devices and Pacer, a smartphone app (Figures 1 and 4). 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 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.

3.3 Procedure

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

ID	Age	Gender	Diagnosed Medical Condition	Mobility Aid(s) Used	Fitness Rating[a]	Frequency of Fitness Activity (days/week)	Activity Duration
P1	26	Female	Cerebral palsy	Power wheelchair	3	Rarely (1-2 days)	30 – 60
P2*	26	Female	Cerebral palsy	Power wheelchair	2	Occasionally (3-4 days)	30 – 60
P3*	22	Male	Cerebral palsy	No assistive aids	3	Rarely (1-2 days)	30 – 60
P4*	56	Male	Spinal cord injury, L1, T12, paraplegia	Manual wheelchair	2	Occasionally (3-4 days)	60 – 90
P5*	62	Female	Hemiplegia, stroke	Cane (home); manual wheelchair (long distances)	3	Almost everyday (5-7 days)	30 – 60
P6*	37	Male	Cerebral palsy	Power wheelchair; manual wheelchair (home)	4	Never	N/A
P7	72	Female	Osteoarthritis; knee replacement	Walker (home); another walker with a seat	3	Rarely (1-2 days)	30 – 60
P8*	32	Male	Spinal cord injury, C6	Manual wheelchair with power assist wheels	3	Rarely (1-2 days)	< 30
P9*	31	Female	Spinal cord injury, T6	Manual wheelchair; walker occasionally (home)	1	Almost everyday (5-7 days)	60 – 90
P10	63	Male	Spinal cord injury, T11, paraplegia	Manual wheelchair; leg braces (sometimes)	2	Occasionally (3-4 days)	60 – 90
P11*	38	Female	Muscular dystrophy type 2	Power wheelchair	3	Rarely (1-2 days)	< 30
P12	47	Male	Spinal cord injury, C5, tetraplegia	Power wheelchair	3	Rarely (1-2 days)	< 30
P13	56	Female	Multiple sclerosis	Power wheelchair	4	Almost everyday (5-7 days)	30 – 60
P14	23	Male	Cerebral palsy	No assistive aid; power & manual wheelchair; crutches	2	Almost everyday (5-7 days)	60 – 90

[a] Self-reported fitness ratings: 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

Table 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.

Figure 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.

3.3.1 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 1) but participants could also sketch or describe new ideas.

3.3.2 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.

3.4 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 [7]. 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 [3]: 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).

4. 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.

4.1 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 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

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

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 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.

4.2 Current Use 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 [10]).

4.2.1 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."*

4.2.2 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." (P11)*

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 [4], 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.

4.2.3 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 [10] 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."*

4.2.4 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 [10]'s smaller study), thus we now turn to a hands-on evaluation of two wearable trackers.

4.3 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.

4.3.1 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 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*

Figure 2. P8 (left) stowed the Fitbit One in a pouch under his seat and P10 (right) clipped it on the seatbelt.

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." (P12)*

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).

4.3.2 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 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 [32], 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."*

4.3.3 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.

4.4 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 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 [28]), 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 [10], where participants wanted a wrist-based tracker but had no first-hand experience using one.

Similar to [10], popular tracking targets were vitals, calories burnt and duration, all desired by half of the participants. Several participants also wanted dietary information 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.

Figure 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.

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." (P5)*

4.4.1 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).

4.5 Field Evaluation of a Mobile Fitness App

During the field study, eight participants made 48 diary entries and shared screenshots (Figure 4); 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! :-)" (P3)*

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."*

Figure 4: P3's log showing more activity than expected (left) and P9's log showing much less activity than expected (right).

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." (P9)*

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." (P5)*

Summary. In contrast to [10], 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.

5. 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 [10]—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 [10], 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 [10] 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.

5.1 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 [10], 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 [10] 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. [10] 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 [6] 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 [37], 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. [10], "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 [10] were open to considering "steps" as an abstract measure of movement, others were understandably strongly against it.

Social 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). 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.

5.2 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.

6. CONCLUSION

Our interview and design sessions with 14 participants and week-long field evaluation with eight of those participants explored problems with existing health and fitness trackers and opportunities to make fitness tracking relevant to people with mobility impairments. The 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). Among other guidance for how to improve the accessibility of these devices, future work needs to focus on wearables as opposed to mobile apps and on personalized tracking to accommodate a wide range of human movement.

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