Sense and Accessibility

Understanding People with Physical Disabilities' Experiences with Sensing Systems

Shaun K. Kane
University of Colorado Boulder
Boulder, CO, USA
shaun.kane@colorado.edu

Anhong Guo
Carnegie Mellon University
Pittsburgh, PA, USA
anhongg@cs.cmu.edu

Meredith Ringel Morris
Microsoft Research
Redmond, WA, USA
merrie@microsoft.com

ABSTRACT

Sensing technologies that implicitly and explicitly mediate digital experiences are an increasingly pervasive part of daily living; it is vital to ensure that these technologies work appropriately for people with physical disabilities. We conducted on online survey with 40 adults with physical disabilities, gathering open-ended descriptions about respondents' experiences with a variety of sensing systems, including motion sensors, biometric sensors, speech input, as well as touch and gesture systems. We present findings regarding the many challenges status quo sensing systems present for people with physical disabilities, as well as the ways in which our participants responded to these challenges. We conclude by reflecting on the significance of these findings for defining a future research agenda for creating more inclusive sensing systems.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing**; **Accessibility**; • **Computing methodologies → Artificial intelligence**; • **Social and professional topics → People with disabilities**.

KEYWORDS

Sensors, sensor systems, ubiquitous computing, artificial intelligence, machine learning, data, disability, accessibility, inclusion, AI fairness, AI bias, ethical AI.

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1 INTRODUCTION

In his seminal 1991 article, "The Computer for the 21st Century" [60], Mark Weiser envisioned a future of ubiquitous computing, in which computing would be an "integral, invisible part of people's lives." Nearly 30 years later, many parts of that vision have come to pass, with the proliferation of a variety of sensors pervading our everyday interactions at home, at work, and in public places. This proliferation of *sensing systems* is likely to continue, with increasing interest in cloud-connected Internet of Things (IoT) devices [3, 50], Smart Cities [38], and rapidly emerging AI-powered technologies [51].

As explicit and implicit interactions with computing become increasingly interwoven with daily lives, it is important to examine the accessibility of computationally-mediated experiences for people with disabilities. In particular, in this article we focus on people with physical disabilities, since we hypothesize that many types of sensors embed *ability assumptions* [64] about end-users' physique and mobility.

In the U.S., the CDC reported in 2018 that 40.7 million adults have difficulty with physical functions, approximately 16% of the population [20]. A 2017 report from the University of New Hampshire's Institute on Disability found that overall about 6.6% of Americans have an ambulatory disability, rising to 22.5% when considering only those aged 65 and over [39], and the U.S. Census Bureau issued a 2019 report about workers who file for disability benefits, noting that 34.4% of disabled U.S. workers have ambulatory disabilities [56]. Researchers have recently issued calls-to-action to investigate whether AI systems properly recognize people with physical disabilities [29, 61]; in this paper, we contribute to the growing body of knowledge in this area by investigating the types of challenges that sensing systems pose for the substantial subset of the population comprised of people with physical disabilities.

In this work, we use the same definition of "sensing systems" as Bellotti et al. [4], who define sensing systems as including "ubiquitous computing (ubicomp) systems, speech and audio input, gesture-based input, tangible interfaces... and context-aware computing." Note that we include touchscreen interfaces in this definition of a "sensing system" since touchscreens enable many types of gesture-based input, and since touchscreen sensors have become ubiquitous since Bellotti et al. published their article in 2002. This definition encompasses both traditional, heuristic-based systems (e.g., a door that opens when an infrared distance sensor is triggered), as well as the emerging class of AI-powered systems (e.g., a door that uses face- or body-recognition to identify an approaching person). Increasingly, it is difficult to know whether a specific system uses heuristic or other methods, and systems that previously used heuristics to define the system's behavior (e.g., the time needed to press a button and the force used to press it) increasingly have the option of refining or replacing these heuristics with models based on prior user input.

This paper contributes qualitative survey findings from 40 adults with physical disabilities, describing the challenges they face with

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a variety of status quo sensor-based technologies, as well as the ways in which they respond to those challenges. We identify ten key challenge areas for sensing technologies for this demographic, including premature timeouts, poor device positioning, being "invisible" to sensors, mismatches of abilities to sensors' fidelity for range of motion, variability of users' abilities over time, difficulty setting up sensing systems, biometric failures, security vulnerabilities, incorrect inferences, and data validation problems. We also describe four patterns of response (assistance, adaptation, avoidance, and abandonment). These findings indicate that we are at risk of creating a digital divide between those for whom sensors work reliably and those for whom they do not; we reflect on how our findings suggest an agenda of research to address this challenge, to ensure that people with physical disabilities are not locked out of engaging with emerging technologies.

2 RELATED WORK

Our research builds on prior work in the areas of ubiquitous computing, touch and speech accessibility, inclusive design approaches, and fairness in AI systems for people with disabilities.

2.1 Ubiquitous Computing

The vision of ubiquitous computing is a future where computing is integrated throughout our environments and activities in a seamless and invisible manner [60]. Related paradigms like context-aware computing [18] expand the vision of how sensing infrastructures can support myriad implicit and explicit interactions; context-awareness has shown promise for supporting accessibility applications such as predictive text suggestions for AAC systems [36, 37]. The Internet of Things [3, 50] expands on this vision by adding cloud computing capabilities and connectivity to facilitate the creation of "smart" objects, buildings, and even cities [38]; smart buildings and cities have the potential to facilitate accessibility such as if beacons are embedded to support non-visual navigation (e.g., [1, 25, 26]) or better understandings of the accessibility of urban infrastructure for city planners or pedestrians (e.g., [30, 47]). New technologies such as 3D printing and other fabrication options enable embedding of sensors in a variety of materials and objects [63], which could have implications for accessibility (e.g., smart prosthetics [33]). Wearable technologies embed sensors directly into clothing or accessories, often with the goal of augmenting cognition (e.g., Google Glass's heads-up display) [58, 62] or health tracking (e.g., many smart watch systems [17, 42], some of which researchers have explored making more accessible [13, 16]); Carrington et al. have also explored expanding the concept of wearables to augment mobility aids [12]. Improved voice-based sensors are increasingly available as smart-speakers or phone-based virtual assistants (a category of sensor that may be particularly of interest to people with disabilities [10, 46, 59]). In this paper, we build on prior work at the intersection of ubiquitous computing and accessibility by exploring the ways in which modern sensing systems are and are not accessible to those with physical disabilities.

In 2002, Bellotti et al. [4] identified five aspects for designers of sensing systems to consider: Address, Attention, Action, Alignment, and Accident. We build on this work by presenting evidence that designers must consider a sixth aspect of sensing systems — Accessibility. As discussed in the Introduction, we use the definition of "sensing system" introduced by Bellotti et al. for the purpose of scoping our inquiry.

2.2 Access to Touch and Speech Interfaces

While our present work explores the proliferation of sensing systems, many of these systems include some form of user input via touch, speech, or physical buttons. These traditional input methods have existed for decades and have consistently presented accessibility challenges to people with physical disabilities [48]. Our findings confirm previously documented touch screen accessibility challenges, including problems related to the positioning of a touch screen device, difficulty providing the correct amount of force when touching, and slippage while touching or gesturing [35, 41, 55]. Similarly, our findings re-confirm previously documented speech accessibility challenges related to enunciation, speaking rate, and volume [46]. Our work expands upon this prior work by exploring additional environments and contexts in which these problems appear, and by identifying new accessibility problems found in these contexts, such as those related to failing to detect a user's presence or incorrectly inferring their age, gender, or physical fitness level.

2.3 Inclusive Design

Inclusive design approaches consider how to create technologies that consider accessibility as a fundamental feature, rather than a post-hoc fix. Ability-based design [64] is an example of a popular inclusive design approach, in which designers are encouraged to consider the abilities of end-users when designing software. One approach to incorporating abilities into the design of software is by supporting customization or personalization of user experiences; the SUPPLE++ system for customizing touchscreen UIs [22, 23] and the GPII system for customizing Windows PCs [57] are examples of this approach. Our findings explore the extent to which sensing systems have been inclusively designed; in the Discussion section we reflect on the implications of our participants' experiences for future innovation in inclusive design, including questions of whether and how inclusive design approaches can be adapted for ubicomp scenarios.

2.4 AI and Disability

Although some sensing systems are powered by simple indicators and heuristics, many are powered by AI algorithms, and even simple sensor readings may feed into AI systems, particularly as sensing devices are increasingly networked (e.g., the IoT). Recently, researchers have issued calls-to-action to investigate how various AI technologies (such as vision, speech, text, and integrative AI systems) might require scrutiny regarding their impacts on people with disabilities, including issues such as whether such technologies are trained on inclusive datasets, whether they have reasonable accuracy for people with disabilities, and whether they might further societal biases against disadvantaged groups [6, 19, 29, 32, 53, 61]. This paper adds to our understanding of issues at the intersection of AI and disability by providing evidence of the ways in which status quo sensing systems pose challenges for people with physical disabilities.

3 STUDY DESIGN

The goal of our study was to obtain qualitative examples of how people with physical disabilities may experience challenges with the variety of sensing systems that are increasingly prevalent in modern life. By better understanding users' experiences with these systems, researchers and practitioners can begin to proactively address these concerns in the design of improved technologies. Because of the large variety of physical disabilities and the diversity of experience users may have with different sensing technologies, we chose to conduct an online survey — this would allow us to reach a larger (and therefore more diverse) audience than an interview study, and would also support participation by a larger sample of people with physical disabilities since many people from this group experience mobility challenges that may make travelling to an in-person interview challenging or that may require taking frequent breaks due to fatigue.

3.1 Participants

To identify study participants, we used a professional recruiting service focused on participants with disabilities (AURC[1] / Shepherd Center[2]). This recruiting service also included an institutional review board (IRB) evaluation of our consent form and survey materials. The service recruited participants in the U.S., and aged 18 or over, to take our online survey, with inclusion criteria of participants self-identifying as having a physical/mobility impairment or difference. Participants who relied on a screen reader to interact with a computer were excluded from the study due to anecdotal reports that the survey software did not reliably function with all screen reader software/hardware combinations despite being rated as screen reader compliant by the survey company.[3] Pilot-testing indicated the survey took about an hour to complete, and participants were paid a $50 gratuity by the recruiting service based on this one-hour time estimate. Participants were anonymous to us (only the recruiting agency had their contact information, in order to provide gratuity payments).

In total, 56 participants engaged with our online survey, of which 40 completed the entire survey instrument (spending a mean of 46.2 minutes to complete it). We consider the data from the 40 complete surveys in our analysis. The surveys were completed over a three-week period spanning from July 15 - August 5, 2019.

Participants ranged in age from 18 to more than 75. We did not collect exact age for privacy reasons, but rather participants reported age in buckets: 18 - 24 (5%), 25 - 34 (20%), 35 - 44 (32.5%), 45 - 54 (7.5%), 55 - 64 (25%), 65 - 74 (7.5%), and 75 or older (3%). Participants' self-reported gender identities were: woman (53%), man (45%), and non-binary (2.5%). Participants reported a range of occupations including geologist, IT project manager, communication consultant, student, homemaker, attorney, day trader, investment banker, emergency planner, non-profit/advocacy worker, writer, and secretary; 28% of participants reported being unemployed either due to disability or retirement. When asked to self-rate their knowledge of computers and IT compared to other people, none described their knowledge as "much less than average," 5% described it as "somewhat less than average," 30% as "about average," 47.5% as "somewhat more than average" and 17.5% as "much more than average."

We asked participants to self-describe their disability status using the following prompt: *Please briefly describe your disability, using whatever language you prefer. For example, you might simply list a medical diagnosis (e.g., "spina bifada") or you might prefer to more specifically describe your particular abilities/disabilities (e.g., "I use a power wheelchair for mobility and also experience tremor in my upper limbs.")* Participants reported a range of physical disabilities, including: limited motion in the upper limbs; limited fine-motor abilities and dexterity; use of mobility aids such as canes, crutches, walkers, scooters, manual and power wheelchairs; paralysis, paraplegia, and quadriplegia; impaired balance; differences in gait, spasticity, and/or muscle tone (such as due to cerebral palsy or muscular dystrophy); and amputation of limbs.

In addition to these free-form self-descriptions, we also asked a series of multiple-choice questions about participants' abilities. 57.5% reported difficulty using their arms, 75% reported difficulty using hands or fingers, 90% reported difficulty walking or climbing stairs, 40% reported fatigue or limited stamina, 10% reported difficulty being understood by others when speaking, 7.5% reported difficulty reading, none reported learning disabilities, 17.5% reported difficulty concentrating or remembering, 12.5% reported difficulty hearing, 5% reported difficulty seeing, and 5% reported difficulty with sensory integration.

We also asked multiple-choice questions about body shape and size differences, since we hypothesized these might impact interactions with many status quo sensing technologies. 47.5% reported that they are much shorter than most people (i.e., due to growth differences or due to being seated in a wheelchair), 12.5% reported being much taller than most people, 15% reported weighing much less than most people, 32.5% reported weighing much more than most people. 2.5% reported having facial differences, 42.5% reported having upper limb differences, and 52.5% reported having lower limb differences. 37.5% reported that they move more slowly than average, 15% report experiencing tremor, 67.5% experience muscle spasms, 55% experience muscle weakness, 77.5% experience difficulty walking, and 60% experience difficulty reaching or holding objects.

We also asked about participants' use of assistive devices, mobility aids, and support people or animals. 2.5% reported using upper-limb prosthetics, 5% reported using lower-limb prosthetics, 22.5% reported using a walker or cane, 40% reported using a manual wheelchair, and 70% reported using a power wheelchair. 12.5% reported using a mouthstick, reacher, or other alternative to hand use, 7.5% reported using an accessible keyboard (e.g., one-handed

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[1] https://accessibilityuserresearchcollective.org/

[2] https://www.shepherd.org/resources-healthcare-professionals/research

[3] While we would have preferred to use a more screen-reader-compliant survey tool, we have encountered anecdotal reports of screen reader problems with several major survey software providers (whose products claim full accessibility compliance), and have been unable to find full-featured survey software that is fully accessible. Indeed, the challenges of survey software providers believing they comply with accessibility guidelines but then discovering that adjustments and updates need to be made as they introduce new features or as new accessibility hardware or software are adopted by end-users exemplifies Bennett et al.'s observation that "access requires continuous work" [7]. In this case, since visual impairment was not the focus of the study, we decided to report the accessibility bug to the software provider but to proceed with the study without waiting for the bug patch, although there is the possibility that this caused us to overlook interesting findings about intersectional identities (i.e., vision impairment plus physical disabilities).

keyboard, key guards), none used switch input or eye gaze input, 5% reported using a speech generating device (e.g., AAC), 35% reported using dictation technologies (i.e., speech to text). None of our participants reported travelling with a service animal, but 42.5% travel with a personal care assistant vs. 47.5% who primarily travel independently.

3.2 Apparatus

The online survey questionnaire contained 76 questions; however, not all participants encountered all of the questions — for example, free-text boxes asking participants to describe an experience with a particular sensor type would only appear if they indicated in earlier multiple-choice questions that they had encountered that class of sensor. The questionnaire combined multiple-choice items and free-text responses, in order to gauge whether a respondent had encountered a particular scenario and, if they had, to collect qualitative data on their particular experience. Progress on completing the online questionnaire could be paused and resumed to support fatigue-related breaks. Quality-control checks included verifying that free-text responses contained meaningful data, and recording of the time spent completing each survey page (i.e., to ensure participants spent a reasonable amount of time rather than racing through with random clicks).

We iteratively refined the survey questions through pilot-testing with members of our organization who had a variety of motor disabilities (pilot participants were compensated with a gift card for their time). For instance, we decided to add specific examples following each question illustrating each sensor scenario (see Appendix A) after feedback from pilot participants that indicated this would help jog their memory and clarify the intended scope of each scenario, particularly for less technical participants. We considered that providing specific examples for participants might influence their responses, but decided this to be a worthwhile trade-off; we discuss this further in the Limitations section. Examples were drawn from one of the authors' own experiences with sensors as a person with physical differences and from another author's disabled mother's experiences, as well as from examples provided by pilot participants.

The first section of the survey consisted of questions about participants' demographic traits, physical abilities and limitations, and use of assistive interventions. These responses are summarized in the prior sub-section describing our participants (Section 3.1).

The next sections provided prompts about scenarios that participants may have encountered when interacting with various classes of sensing technology. The instructions for this portion of the survey stated: *For each scenario, you will be asked whether you have had a similar experience. Note that we are particularly interested in examples of experiences that you know or suspect may be related to your mobility limitations, physical differences, disability status, and/or use of assistive devices. If you answer yes, we will ask you to provide further details about your experience. If you are unsure about whether your experience matches the description, please answer "unsure" and provide details in the text box about any experience you think might be related. If you have never used a particular class of technology, please answer "not applicable."*

Each question in this main part of the survey followed the same format — a statement about a scenario (e.g., "Technology fails to recognize that I am present in a location") followed by a set of examples (e.g., "Examples: An automatic door fails to open for me; automatic lights turn off when I am in a room.") followed by a multiple-choice prompt ("Have you had a similar experience?") where the five choices were: *yes, frequently; yes, sometimes; unsure; no; not applicable.* If participants selected "yes" or "unsure" they were then shown a free-text prompt that said: "If so, describe briefly how this has happened before" as well as a second free-text prompt asking: "When this happens, are you able to overcome the problem? What have you tried to do to overcome this problem?" Appendix A contains the full set of scenarios and associated examples.

4 RESULTS

We employed the qualitative data analysis technique of affinity diagramming [31] to identify themes in the the free-text survey responses. Three researchers participated in the affinity diagramming exercise, iteratively refining groupings of responses according to thematic similarity. The Results section is organized based on these emergent themes, and uses quotes from the survey responses to illustrate each theme. Where applicable, we also report quantitative data (e.g., percent of participants who indicated experiencing a particular category of challenge relevant to the current theme); note that we do not have quantitative data related to all themes, since the themes were developed post-hoc. We first present findings regarding the challenges our participants encountered with sensing systems, followed by findings regarding the strategies they employed to mitigate these challenges.

4.1 Challenges with Sensor Systems

Our survey asked participants whether they had encountered twenty-two different scenarios involving sensing systems (Appendix A), and an additional write-in question where respondents could describe any additional scenarios that we hadn't inquired about. For each scenario they had encountered, participants provided a free-text description of their own experience. Our qualitative analysis of these responses identified ten high-level themes with regards to the types of challenges sensing systems pose for people with physical disabilities: *premature timeouts*, *poor positioning*, *being "invisible,"* *mismatched range of motion*, *variability of abilities*, *setup difficulties*, *biometric failures*, *security vulnerabilities*, *incorrect inferences*, and *data validation problems*.

4.1.1 Timeouts.

Sensor systems timing out because they are programmed with defaults that do not account for the slower movement speeds of people with physical disabilities were common among the anecdotes relayed by our participants. In response to the prompt, "I am unable to move quickly enough to complete a task," 72.5% of respondents indicated that they had had this type of experience, 25% had not had this experience, and 2.5% were unsure.

Sensors that control the timing of doors, such as entrances to stores and workplaces, public transit, and elevators, often failed to allow long enough for someone with mobility challenges to enter or exit. P3 noted, "Automatic doors or elevator doors closed before I got to them. Subway doors closed before I could get completely inside." P8 also experienced challenges with door timings on public transit: "An entry system to a subway closed too quickly and I got stuck halfway." P9 related how "Automatic doors close before I can walk to them because I am very slow." P19 also said that, "I've had times where automatic doors do not open or close before I've been able to move through." P15 observed, "Automatic doors definitely close quickly sometimes, but the worst one is definitely elevators. I've gotten caught in elevators so many times because I don't have time to get in them." P32 also highlighted elevator sensors as a problem: "... elevators quickly close without allowing the time for a wheelchair user to go inside."

Sometimes the challenges with automated doors occur only in particular configurations. For instance, P28 noted that doors positioned at the top of inclines should have longer default opening times, since it takes more time to move uphill, saying "This [door closing prematurely] only happens to me when an automatic door is located at the top of an incline. When I am in my power chair, it is not a problem, but I am very slow going up the hill in my manual chair because I do not have a lot of strength to push." P16 observed that doors should stay open longer in smaller elevators, because their small size makes the act of turning around in a wheelchair in order to exit more challenging: "[problem with a] small elevator with quick door. Could neither turn nor backup fast enough."

In addition to doors, other types of sensors, such as for speech recognition systems or other apps, may time out too quickly for users with physical disabilities. As P3 observed, "I have been disconnected by automation on phone if I didn't answer quickly enough..."

"Smart" sensors can also be a problem, such as if the timeout period for motion controls to identify presence is not calibrated for the time it may take people with limited mobility to perform actions. P22 described how, "... automatic sensor lights, I mostly use them in bathrooms at certain public places. Sometimes I take longer in the bathroom due to disability-related issues and I've had the lights turn off on me because I was still in the stall."

Physical kiosks such as ticket machines and ATMs are another problematic category; in this case, timeouts impact two parts of the transaction — the time needed to enter data into the system using buttons or touchscreens, as well as the time needed to perform physical components of transactions such as swiping credit cards or withdrawing tickets or cash. P14 shared how, "One example is when I used to have to purchase train tickets on the automated ticket system for the train. It was hard for me to reach from the wheelchair and would time out." P22 also shared that "This [timeout] happens to me all the time. It's to the point where I don't even want to withdraw money from an ATM because I'm afraid the door will close before I can pull the cash out. I also sometimes can't pull my card out at the end fast enough before the machine pulls my card back in. It's incredibly frustrating." P19 said, "I specifically have encountered this with timers for locks in automatic doors that require a key-card or pass code. By the time I'm able to put back the key-card or grab my belongings, the door has re-locked."

4.1.2 Positioning. In response to the prompt, "I am unable to reach a button, control, or sensor," 62.5% indicated having had this experience, 25% had not experienced this, 2.5% were unsure, and 10% felt this scenario was not applicable to them.

Several participants described how buttons (such as those used to trigger the opening of automated doors) were often positioned too high for wheelchair users to reach. P3 (an attorney who self-described as an incomplete quadriplegic and uses a manual wheelchair) describes that "courthouses frequently have interior door-open buttons placed too high so I ask for assistance."

In addition to height, placement location was also a problem — for example, buttons placed in tight corners or with obstacles in front made them difficult to reach for people using wheelchairs. P13 described how he cannot reach buttons if they are "... placed too high or there was an obstacle in front, preventing access" and P29 described how a challenge in reaching buttons and switches is "... not so much height as awkward placement - too far into a corner, for instance." P22 mentioned how "... sometimes I can't reach the button because it's in a corner or awkward angle that I can't pull my wheelchair up to." Another placement challenge was when sensors were positioned distant from the object they controlled (e.g., if the button to open an automated door is far from the door itself, then one must move very quickly between them or ask for help, illustrating how *positioning* issues can be intertwined with *timeout* issues); as P32 described, "doors that have to be open with the pushbutton, the pushbutton is far away so my personal assistant has to go far away from me in order to push it."

The positioning of sensors at heights or angles incompatible with wheelchair use contributed to rendering participants "invisible" to many computing systems. For instance, P20 complained about how often the mounting height and angle meant that "Door bell cameras... cannot see a wheelchair person." P30 (who uses a manual wheelchair) encountered a similar issue in her workplace: "At my work, there are cameras to be buzzed into a secure area; however, the cameras are too high and I have to lift myself up or back far away enough that the camera can see my face." P19 experienced issues with another class of security scanners: "I've had issues where at airports and train stations where the security scanner uses an eye retina and it's too high and can't be lowered further to reach me."

This positioning problem extended beyond security and motion sensors to other classes of sensor, such as in P39's case: "In my own home due to the height placement of my thermostat connections, the activity sensors in my thermostat often do not detect me." P28 noted that her gaming system also had this challenge: "The Wii motion bar must be set at the right height or it cannot read me because I am seated in a wheelchair." P29 shared that "Detection devices occasionally fail to detect my presence in the wheelchair. This is certainly height related. The chair is capable of elevating to eye level, and I am in the habit of keeping it elevated when out in public so as not to be overlooked by sensors (and people!)."

In some cases, a challenge with positioning was not merely a limit to providing input, but also resulted in the inability to see feedback from digital systems. For instance, P26 noted, "I will try to reach buttons to use the payment terminal in the grocery store. I just cannot see it when I am in a manual chair."

Additionally, P28 shared an example of how user-positioned sensors (e.g., cameras) could not always be maintained in the designer's intended position by end-users with limited mobility. She said, "I struggle at times with holding the camera high enough and pushing buttons at the same time. If they are random shots where I can just snap at a lower level, it is better. If I have to hold the camera higher than my head, or hold it in the air for any length, I am not able to do that because of my arm strength."

4.1.3 Invisibility. In response to the prompt, "Technology fails to recognize that I am present in a location," 55% of respondents indicated that they had had this type of experience, 40% had not had this experience, and 5% felt it was not applicable to them. While in many cases this theme of *invisibility* relates closely to the prior theme around sensor *positioning* (i.e., poor positioning can be one of the causes of functional invisibility), we call this theme out separately, as it relates to the feeling of "othering" created by technology not recognizing one's humanity, as highlighted in the writings of disability studies scholar Karen Nakamura [45].

Participants described being invisible to a range of smart technologies, such as automated doors, lights, and thermostats. P4 described how "automatic door won't open, or closes early and traps/hits me... automatic lights don't sense that I'm in the room," and P39 complained that, "In my home the activities in my Nest thermostat have trouble detecting whether I am home or not." P15 shared that "I definitely had lights in bathrooms not recognize me, so I have to keep moving my wheelchair to try to get to turn the lights on." Even in venues that might anticipate many users with physical disabilities, respondents still reported being invisible, such as P16, who found that the "automatic door sensor in [the] hospital was too high to sense me."

P40 noted that sometimes "invisibility" was context-dependent. She noted, "I cannot speak very loudly due to a throat problem, so I have trouble speaking loudly enough for my phone's Google Assistant voice recognition to hear me while I'm driving, since the car is noisy. This isn't a problem in a quiet space."

4.1.4 Range of motion. Participants described how sensors sometimes did not work properly for them because they expected motions beyond their range of possible or comfortable physical motion. This included challenges regarding gross motor interactions (e.g., needing to wave hands around to remind a motion sensor that you are present) as well as fine motor interactions (e.g., the ability to effectively use game controllers, touchscreens, and cameras). For instance, P13 observed that "... technology at the workplace requires multiple hand gestures or an unlimited range of motion which I do not have." Attempting to match one's abilities to the expected range of motion for sensors can have negative consequences; as P4 observed, "[I] stretch [to reach buttons], which is uncomfortable and dangerous."

Range of motion concerns were often intertwined with the aforementioned *positioning* challenges (e.g., needing to wave one's hand around to remind a highly-placed motion sensor that one is present), as well as with some of the *biometric* challenges we discuss later (e.g., difficulty finely adjusting one's hands to align to a fingerprint scanner).

4.1.5 Variable abilities. Another theme in our data concerned how participants' abilities were often not constant, but rather changed over time (or even within the course of a single day) due to factors such as fatigue, medication side-effects, progression of degenerative conditions, etc. While participants' abilities varied, sensing systems expected normative inputs regardless, creating a mismatch.

For instance, P29 (who has multiple sclerosis), described how his ability to use a touchscreen changed over time, since "some pinching/swiping gestures can be tricky on touch screens, especially on 'bad hand days'."

P22 (who has muscular dystrophy) noted that she found vision- and motion-based sensors used as inputs to gaming systems to be too tiring to use: "I don't use motion controls such as the Kinect or the Wii because I can't use my body that much to play due to fatigue."

Additionally, P22 described how physical sensors such as buttons to open an automatic door may also become difficult to use, since they require a consistent strength threshold: "Sometimes I am not strong enough to push the button because it needs a more forceful push than I can do."

4.1.6 Setup. Understanding how to configure "smart" devices posed a barrier to their use. For instance, P5 mentioned how she was unable to take advantage of new technologies: "[I] have no clue how to set up my phone bluetooth in my van. Also we have Alexa in our home but no clue how to use it."

In addition to initial device setup, participants also indicated difficulty in restarting "smart" devices when they got into an error state. For instance, P38 reported a problem with speech input systems crashing, which required a hard reboot of the underlying computer system; however, P38 (who is paralyzed from the neck down) is not able to "[press] Ctrl+Alt+Del at the same time... so I have to get assistance about once a week [to reboot]."

In addition to the digital aspects of configuring technology, our participants reported additional concerns around physically configuring devices, beyond those that may have been anticipated by the designers. For instance, P1 (who has cerebral palsy) notes that he uses "heavy duty Velcro for keyboard and joystick so they stay in place."

4.1.7 Biometrics. Our participants' survey responses indicated that biometric sensors posed a particular challenge for people with physical disabilities. In response to the prompt, "A computer system recognizes me as someone else, or fails to recognize me," 37.5% responded yes, 50% responded no, and 12.5% felt this question was not applicable to them.

Participants reported challenges using face verification software for logging into computer systems. P26 sarcastically observed that, "When I use the 'Hello' [face verification software] on Windows to open my computer, it won't recognize me but it will recognize my cat"; she noted that, "if I have time to get out of my [wheel]chair and get on the floor I can usually get it to recognize me." P12 experienced a similar problem with a security system used by her healthcare provider, "The intranet program that Mass General Hospital uses, frequently doesn't recognize me." P8 commented, "I know people with ventilators that cover their noses which could cause a problem with recognition."

Voice recognition systems also created challenges for our respondents. As P13 described, "Because I use a ventilator, my voice does not naturally come across to answering services or things of that nature like in instances of calling a bank or some other service and using automated voice prompts." P39 (who has cerebral palsy) asserted that, "Voice recognition fails to understand my speech, printing the wrong words."

Fingerprint scanning systems posed a particular challenge for many of our participants, since many physical disabilities prevented participants from maintaining the posture or angle needed for a successful scan. P15 commented, "Because I can't always put my finger on my iPhone button the same exact way depending on my position, it often won't open my phone." Similarly, P22 observed, "I think my main problem is fingertip recognition because my hands have to move to a weird angle in order to touch it. I recently got a front door lock that uses a code or a fingerprint to open. My finger just doesn't work unfortunately." And P14 described how her "... fingers also have joint contractures so I cannot flatten them, which prevents me from using fingerprint recognition." P28 mentioned that in addition to posture producing a challenge for fingerprint scanning, circulatory system problems may also impact this class of device: "I deal with being cold all the time, so my fingers are always very cold. Fingerprint recognition struggles to read my fingerprints when they are cold."

4.1.8 Security. One emergent theme was the way in which the need to work around failures of sensing systems often required people with physical disabilities to make tradeoffs regarding digital security. For example, due to challenges entering text on touchscreens, P8 indicated that often "someone else inputs passwords" for her, requiring her to trust someone else not to abuse or share her password information. P15 similarly indicated that when sensing systems fail to allow them to enter text successfully, they "just have to wait till somebody I trust can log me in."

As mentioned in the prior section, biometric security system failures were common for this demographic, and we note there that these biometric errors also compromise security for this demographic, or require assistance from others to achieve correct body positioning to pass biometric prompts. For instance, P33 noted, "I have trouble because I can't move my fingers so using fingerprint is out of the question unless someone helps and the same as facial recognition unless someone holds the phone up to my face."

Finally, poor positioning of sensors in the physical world often creates security challenges. For instance, P16 (who uses a power wheelchair) is positioned low with respect to the checkout kiosks in stores, and so he allows others to "forge" his signature as an expedient for checking out, as he described: "Someone has to sign for me when checking out at the grocery store, using the tablet-like mounted system, because I can't reach it." Participants also recounted similar difficulties in reaching sensitive input devices such as the keypads of ATMs for banking services; P14 (who has rheumatoid arthritis) notes that she "can't reach ATMs... because my arms are too short and contracted."

4.1.9 Incorrect inferences. In response to the prompt: "A computer system incorrectly recognizes my age, gender, height, or weight," only 7.5% of respondents indicated experiencing this, 2.5% were unsure, 60% had not experienced this, and 30% felt this question was not applicable to them.

Incorrect inferences about a user's physical position were part of this theme; unlike the *invisibility* challenge discussed earlier (in which the user is not detected at all), in the case of an *incorrect inference* the user is detected, but in an erroneous fashion. P15 (who has spinal muscular atrophy and often uses his computer while laying in bed) observed that a vision-based input for a gaming system "always [mis]recognized [me] as [doing] a squat."

Fitness and health trackers were a major source of incorrect inferences described by participants. P22 noted, "I wish I could use fitness apps but it's not possible because there isn't anything that is customizable enough to work for motorized wheelchair users. There are some for manual chairs I believe." P2 (who has cerebral palsy) notes that her fitness tracker "doesn't register my steps when I am hanging on to something [for support]." Similarly, P9 (who walks with a cane) observed that she "... can't use a fitness tracker or pedometer because it doesn't register my steps because I am very slow and sometimes shuffle my feet."

Another type of incorrect inference involves making incorrect assumptions about a user's demographic traits. For example, P13, who is male, notes that speech input systems misgender him: "My voice is usually identified as female, probably because of my ventilator."

4.1.10 Data validation. Participants also described challenges associated with computing systems perceiving data about them as invalid, because aspects of their physical experience were not anticipated by system designers. For instance, P28 (who self-described as a C5-C7 incomplete quadriplegic), noted that health and fitness-related sensors and apps did not work for her since her height-weight ratio was atypical: "when you do not walk or use many muscles in your body, then they atrophy and you lose a lot of muscle mass. I have yet to find ANY nutritionist or system that takes that into account while determining calories or BMI." P19 (who has spina bifada) experienced a similar challenge of "... some apps not allowing my height/weight combo for my age." Sometimes these data validation problems resulted in participants falsifying data, as P22 relates: "I'm much shorter than other people my age so I've lied about my height before in health and wellness surveys I've taken..."

P3 (who is quadriplegic due to a C5-6 spinal cord injury) noted that questionnaires used for registering for or calibrating sensing applications often do not offer responses that are applicable to her personal circumstances. For instance, she noted, "I frequently see closed-ended questions on programs that give me no possible way to answer. 'Do you take the steps versus the elevator?'... So, my answer must be 'no' but it's because of my disability, not because of my choice."

As discussed in the prior section on *incorrect inferences*, step-counters (such as Fitbit) that did not account for data produced by wheelchairs or scooters (rather than walking) also created circumstances where participants generated "invalid" data.

4.2 Mitigation Strategies

Whenever survey respondents indicated they had experienced a particular challenge with sensing systems, we asked them to describe what (if any) steps they took to mitigate that challenge. This section synthesizes our qualitative analysis of these responses, which found four high-level themes: seeking *assistance* from others, developing custom *adaptations* to make technologies work correctly, *avoidance* of sensing technologies, and *abandonment* of technologies.

4.2.1 Assistance. Our participants described many situations in which they relied on family, friends, colleagues, or caregivers to assist when sensor systems failed to detect them properly. For instance, P4 described how "for the restroom [lights going off], I either have my wife come in or try waving my hand in the air," and P5 mentioned that, "Our office door on occasion closes too fast even though it a push button. I will push it open manually or a coworker helps if they are close by." P19 also described relying on colleagues for assistance, because he is unable to enter key-codes in the time permitted by the automated system on the door at his workplace: "I often try to time it where I'm entering the same time as someone else, sometimes I've had to just wait hoping someone comes along or if I have a peer or friend available inside I will call them on my cell to help me get access inside."

Participants also described having to rely on strangers and passers-by for assistance at times. For instance, P8 (who uses a power chair) described a time when she "waited till a walking person entered" in order to trigger automatic lights that didn't detect her due to being seated low in her wheelchair. P8 also noted that when the door sensors on her local subway system (consistently) fail to recognize her, she must "wait for help" from other train riders or transit employees.

In some cases, participants described engaging assistance in a cooperative manner, reminiscent of Bennett et al.'s notion of interdependence [5]. For instance, P1 reports dividing up responsibilities for input when gaming, since he cannot operate all of the controls himself but can operate a subset of them: "My aide usually has to play FIFA [a soccer video game] for me. But I can still shoot the ball while he runs down the field. And manage the team!"

Additionally, some participants indicated they asked for assistance from authorities, i.e. to get to the root of a problem so that it would be solved not only for them but for others. For instance, P13 commented on how he reaches out to seek improvements when sensors for automatic doors in public places are positioned too high to recognize people seated in wheelchairs, noting, "I have reported issues like this." P39 also described seeking assistance from powerful entities, saying that he has "... reached out and complained to the manufacturers" of sensors that fail to detect people seated in wheelchairs, including light sensors, door sensors, and smart home control systems.

4.2.2 Adaptation.

Our survey respondents also discussed how they adapted their behavior and/or environments in order to force sensing technologies to better recognize them.

For example, several participants discussed performing exaggerated gestures so that sensors would notice them, in particular people seated in wheelchairs often found they needed to raise up or wave their hands in order to be noticed. For instance, to stop restroom lights from turning off, P4 (who uses a power chair) needed to "try waving my hand in the air" and P28 (who uses a wheelchair) notes that, "I have to wave in the air for motion sensors when I am too short to activate it."

Some participants with power chairs described using features for adjusting the height of their chair itself in order to make sensors notice them. For instance, P16 related how when an automatic door sensor was too high up to notice them, they "had to raise chair using its controls. The seat rises vertically till I'm about 5' tall." However, sometimes wheelchair height adjustments are insufficient to surmount problems — P22 noted that "even though my wheelchair lifts up I still have trouble reaching [buttons]. My arms don't lift up past my shoulders due to muscle weakness so I reach up very little."

Other participants described using low-tech adaptations to trigger sensors or buttons. P4 says he "improvise[s] an extension like a book or cane." P14 described how, "my husband cut down a dressing stick that I keep on my wheelchair so I can use it to hit the buttons [in public places]" and she also noted that she permanently modified switches throughout her home "I use a child light switch extender so I can turn the light on or off."

Some participants also attempted to modify their physiology, such as P28 who has poor circulation that results in fingers not being detected on various touchscreens and scanners: 'I blow on my fingers or try to warm them up to get [recognized]."

4.2.3 Avoidance.

When asked about workarounds in the face of challenges with sensing technologies, a common response was that participants simply avoided using certain classes of technology, either because of prior negative experiences or because of anticipated negative experiences (i.e., having low expectations that a novel technology would work correctly for them).

When asked, "Are there technologies that you avoid using because you know or suspect they will not work for you due to body differences, mobility differences, assistive device use, etc.?", 62.5% of respondents answered "yes," 32.5% answered "no," and 5% answered "unsure," which suggests that avoiding entire classes of technology is a common experience for people with physical disabilities.

For instance, P21 (a power chair user with spinal cord injury and no fine finger movement) reported that he had tried using VR devices for gaming, but that such devices tended to "require fine motor skills or wearing of gloves" and that therefore he "just avoid[s] using those systems." Another gaming enthusiast, P22 (who has muscular dystrophy) noted "I only use specific consoles and controls due to the limited hand strength I have. I don't use motion controls such as the Kinect or the Wii because I can't use my body that much to play due to fatigue... recently there was a game I tried to play but couldn't because it required motion controls... I can't do much to work around these problems except avoid those games."

While the aforementioned gaming examples illustrate cases where participants simply avoided engaging with particular classes of technology, some technologies were not possible to choose not to interact with, but rather required a change in routine in order to actively avoid them on a regular basis — for instance, P30 (a T-4 paraplegic who uses a manual wheelchair) indicated that at her workplace some doors did not have automatic sensors to admit her and the buttons to trigger manual opening of the door were broken or unreachable. In this case, she learned to "avoid having to use said door" to enter the building, instead rerouting to another entrance.

P8 (who is paralyzed below the shoulders and uses a motorized wheelchair via chin control) indicated that she "avoid[s] taking pix" with a digital camera/phone because she assumes these devices will not work via chin control. P16 (a power wheelchair user with partial use of arms and hands) also avoids digital cameras, noting "I have never purchased a digital camera because I suspect I could neither hold it steady nor manipulate the controls." P19 (who has spina bifada and uses crutches) also noted that he has avoided purchasing certain camera technologies due to assumptions about their compatibility with his abilities: "I have strongly considered getting a GoPro due to the hands-free aspect of the device, but I've had concerns that the video would come out extremely shaky since I have limp and archaic movements to my walking."

P5 (who is a power a chair user due to paraplegia) observed that she "Don't [sic] own a Fitbit because I don't think it would work since I don't walk." P9 (who has multiple sclerosis) noted that she assumed fitness trackers wouldn't accommodate her gait: "I won't buy a fitness tracker because of how I walk." Similarly, P30 noted, "I avoid buying fitness technology [Fitbit tracker]... because it is not set for a wheelchair user." P13 (who is quadriplegic) observed, "I have never considered buying any health monitoring device because of the exact notion that I doubt it will track my body correctly."

4.2.4 Abandonment. Some participants described ceasing to use certain categories of technology due to frustration with failed sensing; this differs from *avoidance* (in which participants never tried a technology at all due to assumptions that it would not work with their disability), since in these cases participants attempted to engage with a class of technology before deciding to abandon it.

P12 (who self-described as having a T-4 Complete injury and using a wheelchair) indicated that many touchscreens do not recognize his gestures (i.e., because he does not touch the screen in the expected style, a common challenge for people with physical disabilities as described by Mott et al. [44]). As a result, he often abandons touchscreens that do not match his abilities, including personal devices like his iPad ("I usually become frustrated/irritated and give up") and touchscreens in public locations ("At public kiosks I give up and leave.").

Fingerprint scanning technologies to support biometric login to devices were frequently abandoned by participants who expressed frustration that they could not consistently log into these devices due to limited abilities to position their fingers against the scanner in the manner required by the device. For instance, P9 noted that she gave up logging into her iPhone in this manner ("I don't use the fingerprint scanner"), and P22 also abandoned this method of login since she "can't do anything about these issues [with the fingerprint scanner] unfortunately." P29 (who has multiple sclerosis) related a similar experience, describing how he "... can't use fingerprint recognition as hands won't reliably touch the right spot at the right angle... I learnt [sic] not to waste time activating fingerprint identification on my tablet."

P22 (who has muscular dystrophy) described abandoning software applications, rather than abandoning hardware, noting that she sometimes cannot pass implicit CAPTCHAs that observe mouse movement patterns to determine if someone is human or a bot, and therefore must abandon her attempts to access websites: "Some CAPTCHA requires movement of the mouse, which can be difficult for me... Sometimes I give up but many times I can just try a few times to get it to work."

5 DISCUSSION

Our survey of 40 people with physical disabilities about their experiences with sensing systems revealed a rich picture of the challenges that emerging "natural," "smart," and "ubiquitous" forms of interaction pose for this demographic. These challenges pose a pervasive barrier to accessing both digital content and various aspects of the (increasingly digitally-mediated) physical world. As P15 observed, "I think it [sensors failing to respond properly to me] happens so frequently I don't even recognize that they [sensors] are problems... They [the problems] are just basically life for me." We hope these findings serve as a call-to-action for the community, to consider the need for inclusive design of sensing technologies, particularly with respect to the needs of people with physical disabilities, so as to avoid creating a digital divide in terms of who can interact with emerging systems.

Certainly, solutions to these challenges are not straightforward. Indeed, our findings highlight many of the tensions researchers and practitioners are likely to encounter. For instance, many of our participants' experiences highlighted tensions between security and accessibility (tensions between usability in general and security have been a well-documented problem for years, see [24] for a review). Intersecting with the security tensions in many situations is the tradeoff between designing for independence vs. interdependence [5]; are some classes of technology (e.g., biometric sensors) fundamentally in conflict with the concept of interdependence for accessibility? Whether to pursue universal vs. personalized technology solutions is another challenge — is personalization the solution for making sensing systems work well across individual differences in body shapes and motor abilities, or is personalization a post-hoc "band-aid" that allows technologists to avoid designing inclusive technologies? From the point of view of sensing systems, in particular, is personalization in opposition to Weiser's vision of interchangeable ubicomp technology [60]? Can methods like ability-based design [64] be extended from software systems to sensor systems in a straightforward way, or is new research required to extend design methods and philosophies for emerging interaction paradigms? How might disabled participants' low expectations that novel technologies will work for them create biases in responses to user studies — for instance, do people with disabilities rate accessible technology probes overly favorably on subjective scales (a hypothesis supported by some preliminary evidence in the domain of visual impairment [54]), and, if so, how must evaluation methods change to account for this?

While many of the accessibility barriers discussed in our findings necessitate technical solutions (e.g., improved hardware and software solutions, improved design and evaluation processes), some require socio-technical considerations. For example, a lack of knowledge about technologies' capabilities led some participants to avoid them, such as the avoidance of fitness trackers by people who use wheelchairs, even though some systems (such as Apple Watch [2]) have deployed adaptations to support wheelchair users following research on this issue [13]. Similarly, a lack of awareness of existing accessibility functions for mainstream technologies like phones [21, 43] and web browsers [9] has been documented in prior studies. The broader socio-technical context of marketing materials, setup instructions, system defaults, and accessibility options for systems may need to be reconsidered in order to ensure that existing solutions are utilized effectively.

For those aspects of our participants' challenges that can be addressed by improved technology, we see promise in emerging approaches such as general-purpose, personalizable sensor models like Zensors++ [28, 40], though the setup and training processes may need simplification for widespread deployment to non-technical end-users. Personalized ML approaches, such as Project Euphonia [27] (which explores making voice-activated systems work better for people with disabilities that impact their speech), also show promise, though such efforts are in early stages and the trade-offs of personalized vs. universal approaches must be considered carefully. Notably, some researchers have begun to specifically explore designing sensors for people with physical disabilities, such as wheelchair-athlete fitness tracking tools [13, 15, 16] and "chairable" computing tools (i.e., wheelchair-mounted "wearables") [12, 14]. Efforts around inclusive making may also provide opportunities for people with disabilities to modify, hack, and invent personalized or novel sensing approaches [8, 49]. Investing in new modalities of interaction, such as sensors for brain-computer interaction, may also be particularly relevant for this user group; P29 commented, "And the minute brain implanted control interfaces become safe and viable, sign me up."

5.1 Limitations and Future Work

To our knowledge, this paper is the first to systematically investigate the myriad challenges people with varied physical abilities encounter with sensing systems. While our approach of conducting an online survey with 40 participants with physical disabilities provided an informative and rich sample of data on this topic, all methodological choices include trade-offs, and it is important to keep in mind these limitations when interpreting our findings.

One issue to consider is the sample size and variety. Recruiting participants from specialized sub-populations can be challenging, and participation in online surveys can be particularly challenging for people with severe physical disabilities, who typically rely on assistive technologies for using computing devices, which results in longer completion times [65]. In light of these considerations, 40 is a large sample size for an HCI study of people with motor disabilities [11], and was sufficient to reveal a rich and varied set of challenges for us to learn from. However, the range of physical disabilities is quite large, and our 40 participants certainly do not embody all possible configurations of body differences, motor abilities, etc. Further, our participants were only located in the United States, and people in other regions of the world may have more varied experiences with sensing technologies. Also, there may be some self-selection bias among our sample (e.g., people uninterested in the topic of the survey may have turned down the recruiting agency's invitation to participate, or people who have limited mobility or physical differences but do not identify as "disabled" may have also opted out). Indeed, one type of self-selection bias is that our participants all had sufficient motor abilities and technical literacy to complete an online survey, and hence may experience fewer sensor-related challenges (or be better-equipped to mitigate them) than people who were not able to complete a survey such as this.

While we learned a great deal from the open-ended survey responses, other methods, such as interviews, ethnography, diary studies, environmental instrumentation, and/or technology audits, may be valuable avenues to pursue in future work, in order to obtain different perspectives and depths of information on this topic.

Further, while we focused specifically on people with physical disabilities, studying the experiences of other groups with sensing technologies is also an important avenue for future work, as is investigating the unique challenges that may result from intersectional identities (i.e., physical disabilities combined with other classes of disability such as sensory or cognitive, or the intersection of physical disabilities with other marginalized statuses such as gender identity, race, socioeconomic status, etc.).

One challenge in studying this topic is that many participants may not be aware of the large variety of sensing systems they interact with (indeed, one of the goals of ubiquitous computing is for sensors to be invisible and fade into the background [60]). In particular, if systems silently fail (or silently succeed), participants may not be aware of these interactions or think to report them in our survey instrument. We also note that participants did not mention interactions with sophisticated AI or machine learning systems; it is unclear whether this is because such systems are not yet widely deployed and therefore were truly un-encountered by our respondents, or whether participants did yet not have a mental model of when they were interacting with AI-powered systems. For example, some technologists have reported challenges with self-driving car technologies [52] and robots [34] with respect to recognition of people with physical differences, or other types of AI systems misrecognizing input from this demographic [29], but these issues were not surfaced in our study; re-visiting these topics over the next few years as more sophisticated ML systems become widely deployed in society is an important avenue for future work.

Participants may also have been biased by the examples we provided in our survey (i.e., perhaps being less likely to share anecdotes related to classes of technology not specifically mentioned in our examples). We chose to include examples (see Appendix A) based on pilot-testing, because we found that non-technical participants often didn't understand the meanings of broad classes of technologies (e.g., IoT devices, smart speakers) without concrete examples, and because participants often had difficulty recalling anecdotes with generic prompts. It is quite likely that our findings therefore under-represent the diversity of devices that cause challenges for our participants, since responses may have coalesced around the examples used in the survey prompts.

A related challenge is in validating participants' mental models of why sensor systems may have failed. While we encouraged participants to specifically share anecdotes of sensor challenges that they believed were a result of their physical differences, it is difficult to ascertain from self-report data whether such difficulties were disability-specific or more widespread. Of course, there is also a continuum wherein some problems may impact all users, but are exacerbated by disability status; for instance, most people have probably encountered a motion-controlled light turning off when they have sat still for a long time, but this experience may be more frequent (and more difficult to remedy) for people with physical disabilities. While it may not be possible to verify whether some of our participants' anecdotes about sensor failures were the result of disability versus other factors, collecting and sharing these experiences is useful as a starting point for more systemic investigation such as lab studies, system audits, or other techniques for pinpointing causality more clearly. Further, the need to create sensor systems that help end-users form correct mental models about system failures is an important area for concentrating future efforts in HCI and AI research.

Finally, this research faces the challenge of determining when the user is interacting with an AI system or a simpler, heuristic-based system, which may make it difficult to direct research findings to the appropriate audience (e.g., to AI system developers or sensor designers). This uncertainty affects everyone's interactions with technology, but may be especially confusing when the system acts incorrectly or fails to activate, as described in this study. As this study has documented our participants' history of experiencing problems with, and inventing workarounds for, these systems, we believe this research presents opportunities to address these problems at multiple points, either by overcoming long-standing problems related to accurately sensing users and their actions, or by building inclusive AI systems that can anticipate and respond to these challenging usage scenarios.

6 CONCLUSION

In this paper, we present the first systematic study of the challenges posed by a variety of emerging sensing technologies for people with physical disabilities. We present the findings from a survey of 40 adults with varied physical disabilities, which collected open-ended, qualitative responses describing participants' experiences with sensor-based systems. We identified an array of challenges, including premature timeouts, poor device positioning, being "invisible" to sensors, mismatches of abilities to sensors' fidelity for range of motion, variability of users' abilities over time, difficulty setting up sensing systems, biometric failures, security vulnerabilities, incorrect inferences, and data validation problems. We also identified the ways in which people with physical disabilities react to the limitations of status quo sensor systems, including soliciting assistance, designing adaptations, avoiding certain classes of technology, or abandoning devices. These findings contribute to our understanding of the ways in which emerging technologies risk creating new digital divides that exclude people with physical disabilities, and point the way toward opportunities for future research in understanding and remedying the hardware, software, and socio-technical challenges of designing and deploying inclusive sensing systems.

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A SCENARIO PROMPTS FROM SURVEY

As described in Study Apparatus (Section 3.2), the survey provided participants with a series of scenarios and a few examples that illustrate the intent behind each scenario. Participants then selected from a multiple-choice prompt whether (and how often) they had experienced this type of situation, and, if they had experienced it, they then answered two free-text questions asking them to describe an example of the challenge they faced as well as any steps they attempted to overcome the challenge. Here, as in the original survey, we group the scenarios by related themes. Participants were also reminded to "... please keep in mind that we are particularly interested in examples of experiences that you know or suspect may be related to your mobility limitations, physical differences, disability status, and/or use of assistive devices."

A.1 Passive and Active Interactions with Sensing Systems

- Technology fails to recognize that I am present in a location. *Examples: An automatic door fails to open for me; automatic lights turn off when I am in a room.*
- I am unable to move quickly enough to complete a task. *Examples: A timer on a web page, ATM, or automated ticket machine times out before I can complete a task. An automatic door closes before I can use it.*
- I am unable to reach a button, control, or sensor. *Examples: A button is placed too high or too low for me to reach.*
- I am unable to perform a specific gesture needed to interact with some technology. *Examples: I cannot perform a gesture on a touchscreen. I cannot hold a computing device in the preferred way.*
- I am unable to complete a task that requires me to perform multiple actions at the same time. *Examples: I cannot press multiple buttons or keys at the same time. I cannot hold a computing device and press buttons at the same time. I cannot use a device while standing, walking, or otherwise moving.*
- A computer system recognizes me as someone else, or fails to recognize me. *Examples: A motion sensor does not recognize my presence or movement. Face recognition, voice recognition, or fingerprint recognition does not work correctly.*
- A computer system incorrectly recognizes my age, gender, height, or weight. *Examples: A photo sharing app incorrectly identifies something about me. A health or fitness tracking app provides incorrect information.*

A.2 Issues with Specific Technologies

- I experience accessibility challenges with technology in my home or in someone else's home. *Examples: I have difficulty using smart home technology or appliances.*
- I experience accessibility challenges using voice recognition systems. *Examples: I have difficulty using smart home speakers such as Alexa or Google Home. I have difficulty using voice commands on my mobile phone, in the car, or during telephone calls.*
- I am unable to control a gaming system or virtual reality system. *Examples: I have difficulty using a game or virtual reality control. I have difficulty using "motion controls" in video games such as the Xbox Kinect or Nintendo Wii. I have difficulty using virtual reality devices.*
- I experience accessibility challenges using technology when in a car or other vehicle. *Examples: I have difficulty using information technology in a car. A car does not recognize when I am present, or performs some other action incorrectly.*
- I experience technology-related accessibility challenges when traveling. *Examples: I have difficulty using technology at the airport, on an airplane, at a train or subway station. I have difficulty using automated ticket machines or other technology when traveling. Security scanners or other biometric technologies at airports or train stations generate errors when I use them, or do not recognize me at all.*
- I experience technology-related accessibility challenges using technology at my school or place of work. *Examples: I have difficulty entering my school or place of work, traveling around my school or place of work, or using technology that is necessary for school or work.*
- I experience accessibility challenges related to a computing device's security features. *Examples: I have difficulty using face recognition or fingerprint recognition. I have difficulty typing passwords or using keys. I have difficulty completing CAPTCHA or "Are you a human?" tests in my web browser.*
- I experience accessibility challenges related to eye gaze tracking or face recognition. *Examples: I have difficulty using eye gaze input with my computer. I have difficulty using face recognition-based security systems.*

- I experience accessibility challenges related to digital cameras or photography. *Examples: I have difficulty operating a camera and taking good pictures. I am not detected by someone else's camera.*
- I experience accessibility challenges related to health or fitness tracking systems. *Examples: I cannot use step counting or other physical activity tracking systems. My physical activity is not tracked accurately by these systems. A health or fitness app does not accurately track my height, weight, or other information. A health or fitness app provides incorrect or confusing information because it misunderstands something about me.*

A.3 General Opinions and Strategies

- Do computer systems misinterpret who you are or what you are doing because they misunderstand something about your disability, mobility limitation, or use of assistive devices? *Examples: A computer system recognizes a very small adults as a child. A computer system asks a person using a wheelchair to stand up because it thinks they are seated on a sofa.*
- Do you have to use any technologies in a way that is different than most other people? *Examples: Needing to place a handheld device onto a table to be able to reach the buttons. Making exaggerated motions to trigger an automatic light switch. Modifying technologies by adding cases, mounts, lanyards, etc.*
- Do you ever have to falsify information that you provide to a computer system to overcome an accessibility problem? *Examples: Providing a false name, age, height or weight to a system to overcome some problem with that system.*
- Do you ever rely on a friend, family member, coworker, or another person to perform some technology task on your behalf? *Examples: Giving a mobile device to a friend to complete some task that is difficult for you to complete alone. Asking a coworker to perform some task on your behalf using some technology in the workplace.*
- Are there technologies that you avoid using because you know or suspect they will not work for you due to body differences, mobility differences, assistive device use, etc.? *Examples: You have never purchased a fitness tracker such as a Fitbit because you suspect it will not properly count your steps since you use a scooter for mobility.*
- In general, we are interested in how computer systems that are not trained to recognize people with atypical physical abilities, body shapes, or movement, may create accessibility problems. If you have other examples of this problem that you would like to share, or additional thoughts on this subject, please share them here.