

“I Gave up Wearing Rings:” Insights on the Perceptions and Preferences of Wheelchair Users for Interactions with Wearables

Ovidiu-Ciprian Ungurean

MintViz Lab, MANSiD Research Center, Ștefan cel Mare University of Suceava

Radu-Daniel Vatavu

MintViz Lab, MANSiD Research Center, Ștefan cel Mare University of Suceava

Abstract—We report insights from structured interviews conducted with twenty-one adults with motor impairments to understand their perceptions about smart wearables, such as fitness trackers, smartwatches, smartglasses, smart earbuds, and smart rings. We document their preferences for accessible interactions with wearables and report high predilection for touch input. Our results also show high willingness to use wearables, including in public places, opportunities for cross-device input and, for wheelchair users, opportunities for conjoint use with chairable technology represented by devices designed for the workspace of the wheelchair. We highlight two key factors, ease of wearing and ease of donning/doffing devices, that affect adoption of wearables, and we draw recommendations for future work on accessible wearables.

■ Wearables come in many flavors, from fitness trackers that monitor health and activity to smartglasses enabling new experiences in augmented reality to smart rings used for fast payments and authentication. Some wearables, such as fitness trackers and smartwatches, have become largely adopted with about one-in-five Americans using them as of 2020 [1], while others, such as NFC rings, are forecast to generate new markets.

The variety of form factors, on-body locations, and use cases for wearables require effective interaction design. Prior work has examined touch and on-skin interactions for smartwatches [2], mid-air gestures performed with rings with built-in motion sensors [3], head gestures, eye gaze, and speech commands for interacting with content displayed on smartglasses [4], and touch-based interactions near the ears leveraged by the earbuds microphone [5]. However,

these interactions assume a variety of motor abilities, from the ability to move a finger to position it accurately on a target displayed on the small screen of a smartwatch to making a gesture with the finger wearing a smart ring and to raising the arm to touch the rim of a pair of smartglasses. For users with motor impairments, such interactions may prove challenging. For example, Malu and Findlater [6] found that conventional Glass interactions were not accessible to all users, and proposed on-body input alternatives, Carrington *et al.* [7] explored “chairables” as a new category of accessible devices for the workspace of the wheelchair, and Malu *et al.* [8], after evaluating the accessibility of existing smartwatch gestures, elicited more accessible alternatives from users with upper-body motor impairments.

Although this prior work has provided valuable information about the interaction perfor-

mance of users with motor impairments with smartwatches and smartglasses [6], [7], [8], research on accessible wearables has been limited compared to the large body of work on making other types of computer systems more accessible, such as mobile devices [9] and touchscreens [10]. For example, little is known about the accessibility of smart rings for users with motor impairments, except from side findings from rehabilitation research [11] that employed rings as sensors to monitor motor function. Also, little is known about the preferences of users with motor impairments for alternative input modalities for wearables, such as eye gaze and head gestures, compared to conventional speech and touch input.

In this context, more research is needed to understand (1) perceptions of users with motor impairments about wearables, (2) preferences for accessible input modalities, and (3) user willingness to wear devices in order to inform the design of more accessible wearable interactions. In this paper, we turn these needs into research questions and report insights from interviews conducted with twenty-one people with motor impairments about fitness trackers, watches, glasses, earbuds, and rings. We use our findings to propose future research directions for more accessible wearables.

STUDY

We conducted an exploratory study to evaluate and analyze quantitative measures about the use, perception, and adoption of a variety of wearables for people with motor impairments. The study was approved by the Ethics Committee of the University of Suceava, ref. 28/22.12.2020.

Participants

Twenty-one adults (17 male) between 28 and 59 years old ($M=43.3$, $SD=8.2$) volunteered for our study; see Table 1 for their demographics. We used convenience sampling to recruit participants from a non-profit association that provides technical support to people with disabilities of many kinds. Our inclusion criterion was people with clinical conditions of motor impairment for a period of at least one year before the study so that they had had the time to adapt to their motor impairment and create their own coping strategies to use objects and devices. All of our participants were wheelchair users. Fifteen had

tetraplegia (*i.e.*, partial or total loss of use of all of the four limbs), two had paraplegia (they were wheelchair users, but the arms were not affected by the motor impairment), while four had hemiplegia (they were able to use only one of their arms). The number of years since our participants lived with the motor impairments varied between 3 and 47 ($M=23.1$, $SD=10.7$). Most of the participants reported poor coordination (15/21), difficulty gripping and holding (15/21 and 16/21), rapid fatigue (15/21), and difficulty controlling the direction and distance of movement (15/21 and 13/21). Their WHODAS scores [12] ranged between 22.9 and 85.4 ($M=52.4$, $SD=17.3$).

Method

We conducted one-to-one interviews to evaluate perceptions of *fitness trackers*, *smartwatches*, *smartglasses*, *earbuds*, and *rings*, representing the conditions of the WEARABLE independent variable in our study. We measured nine dependent variables, described in the next section. The interviews (about one hour per participant) were conducted by the first author over the phone because of social distancing measures enforced in 2020, and were structured using a Google Forms document with fixed-choice questions corresponding to our dependent variables. The form was convenient for the interviewer to easily record participants' responses, but also to make sure that the questions were presented identically to all of the participants. Each question was accompanied by video examples, sent to the participants via WhatsApp at the convenient moment during the interviews. Occasionally, the interviewer also made transcripts of participants' free comments.

A few days before the interview, participants were primed about the five categories of wearables by asking them to watch YouTube videos presenting features and use cases for smartwatches ("Top 10 best smartwatches," https://youtu.be/v2Z0DU_jQsI), smartglasses ("Six best smart glasses to make your life easier," <https://youtu.be/KUs7ZH5uWl4>), rings ("Top 10 best smart rings," https://youtu.be/hoZF_yRZYxs), fitness trackers ("Top five best fitness trackers," https://youtu.be/tqmvM_iaoDg), and smart earbuds ("Nine best smart earbuds," <https://youtu.be/7TOlbgUJf3k>). We employed priming, a widely used technique in psychology research, so that

Table 1. Demographic details of our participants with motor impairments, their self-reported impairments using the eleven categories of [13], and the WHODAS 2.0 health and disability scores [12].

Participant (age, gender)	Health condition	Functioning of limbs	Years with imp.	Self-reported impairments [†]											WHO- DAS 2.0 score [‡]
				Mo	Sp	St	Tr	Co	Fa	Gr	Ho	Se	Dir	Dis	
P ₁ (46 yrs., male)	Spinal Cord Injury (C5-C6)	Tetraplegia	26	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	62.5
P ₂ (57 yrs., male)	Spinal Cord Injury (C5-C6)	Tetraplegia	22	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	70.8
P ₃ (43 yrs., male)	Traumatic brain injury	Hemiplegia	24	✓	-	-	-	✓	✓	-	-	-	-	✓	43.7
P ₄ (36 yrs., male)	Spinal Cord Injury (C5)	Tetraplegia	20	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	56.2
P ₅ (43 yrs., male)	Spinal Cord Injury (C6-C7)	Tetraplegia	22	✓	✓	-	-	✓	-	✓	-	✓	✓	✓	54.1
P ₆ (49 yrs., female)	Spinal Cord Injury (C6-C7)	Tetraplegia	17	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	68.7
P ₇ (48 yrs., male)	Multiple sclerosis	Tetraplegia	21	✓	-	✓	-	✓	-	✓	✓	-	✓	-	39.5
P ₈ (41 yrs., female)	Spinal Cord Injury (C6-C7)	Tetraplegia	17	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	62.5
P ₉ (31 yrs., male)	Spinal Cord Injury (C5-C6)	Tetraplegia	3	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	56.2
P ₁₀ (46 yrs., female)	Spina bifida	Paraplegia	46	-	-	✓	-	-	✓	-	✓	-	-	-	39.5
P ₁₁ (55 yrs., male)	Spinal Cord Injury (T6-T7) & right brachial plexus injury	Hemiplegia	32	-	-	-	-	-	✓	-	✓	-	-	-	41.6
P ₁₂ (28 yrs., male)	Spinal Cord Injury (C6-C7)	Tetraplegia	12	-	-	-	-	-	-	✓	-	-	-	-	27.0
P ₁₃ (59 yrs., male)	Spinal Cord Injury (T3-T4)	Paraplegia	32	-	-	✓	-	✓	-	-	-	-	-	-	22.9
P ₁₄ (47 yrs., male)	Osteogenesis imperfecta	Tetraplegia	47	-	-	-	-	-	✓	-	✓	-	-	-	35.4
P ₁₅ (40 yrs., male)	Spinal Cord Injury (C5)	Tetraplegia	18	-	✓	-	-	-	-	✓	✓	-	-	-	43.7
P ₁₆ (32 yrs., female)	Spina bifida	Paraplegia	32	✓	-	✓	-	✓	✓	✓	✓	-	✓	✓	81.2
P ₁₇ (47 yrs., male)	Spinal Cord Injury (C3-C4)	Tetraplegia	23	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	85.4
P ₁₈ (45 yrs., male)	Spinal Cord Injury (C4-C5)	Tetraplegia	14	-	✓	-	-	-	-	✓	✓	✓	✓	✓	68.7
P ₁₉ (43 yrs., male)	Spinal Cord Injury (T6-T7)	Paraplegia	30	-	-	-	-	-	✓	-	-	-	✓	✓	29.1
P ₂₀ (34 yrs., male)	Spinal Cord Injury (C5)	Tetraplegia	11	-	-	✓	-	-	✓	✓	✓	-	✓	✓	58.3
P ₂₁ (40 yrs., male)	Spinal Cord Injury (C4-C5)	Tetraplegia	17	-	✓	✓	-	-	✓	✓	✓	✓	✓	✓	54.1
Summary				11	11	13	1	12	15	15	16	10	14	14	52.4

[†]Mo = Slow movements; Sp = Spasm; St = Low strength; Tr = Tremor; Co = Poor coordination; Fa = Rapid fatigue; Gr = Difficulty gripping; Ho = Difficulty holding; Se = Lack of sensation; Dir = Difficulty controlling direction; Dis = difficulty controlling distance. The self-reported impairments were collected at the beginning of the interviews. The code in the parentheses from the “Health condition” column denotes the affected vertebra(e), e.g., C6 and T7 indicate traumatic injury at the 6th cervical and 7th thoracic vertebrae, respectively.

[‡]Calculated by administering the 12-item version of WHODAS 2.0 [12] at the start of the interviews. WHODAS is an instrument developed by WHO that produces standardized disability profiles with numerical scores between 0 and 100 (larger values indicate more advanced disability).

participants could form perceptions about wearables they had not used before our study, to appreciate wearables through the perspective of their motor impairments, and be ready to use the corresponding concepts during the interviews. To make sure that the participants watched and understood the videos, they were asked before the actual interview to describe briefly the characteristics of the devices featured in those videos. The interviewer admitted all the participants based on their answers, but did not provide any feedback to prevent bias of the actual interview that followed.

Measures

We evaluated the following measures:

(1) *Experience with smart wearables.* Participants reported wearables they were using at the moment of the study or had used in the past, and rated any experienced difficulties on a 5-point Likert scale from 1 (not difficult to use at all) to 5 (very

difficult or impossible to use for me).

(2) *Perceived characteristics of smart wearables.*

We selected several constructs of interest for the perceptions of wearables from the perspective of *interacting* with wearable devices (how easy, fun, and accessible interactions are), the *comfort* [14] of wearing them, including how easy it is to don and doff devices, but also aspects of *desirability* and *social acceptance* [15] for wearables. To this end, we employed the following six measures, which we evaluated using 5-point Likert scales with items from 1 (strongly disagree) to 5 (strongly agree): DESIRABILITY (in response to the statement “*I would like to use or I would need this wearable device*”), EASE-OF-ACCESS (“*This wearable will be easy for me to put on and take off*”), EASE-OF-WEAR (“*This wearable will be easy for me to wear*”), EASE-OF-USE (“*This wearable will be easy for me to use*”), FUN (“*This wearable will be fun to use*”), and

UNWANTED-ATTENTION (“*This wearable could draw unwanted attention to my disability, if I were to wear it in public places*”).

(3) *Preferences for input modalities to interact with wearables.* We asked participants to express their preferences for the following input modalities for wearables: *direct touch, hand gesture, head gesture, eye gaze, speech input, brain-computer interface (BCI)*, input via *chairables*, and using a *smartphone app*. We compiled this list by considering modalities employed in prior work on accessible wearables [16] involving various body parts. We organized these categories as conditions of the INPUT-MODALITY independent variable in our study. Participants specified their preferences for each modality with a rating on a 5-point Likert scale from 1 (not suitable at all) to 5 (very suitable), which the interviewer recorded in the Google Forms questionnaire. The *eye gaze* option was not evaluated for earbuds, the only device for which direct eye contact is not possible. For other wearables, such as watches or rings, that are used in front of the body and, thus, have a direct view of the user’s face, we considered eye gaze input as realistically possible [17].

(4) *Social acceptability of wearables.* Participants specified *locations* where they would not be willing to use wearables and *audiences* in front of which they would not use them. Following Rico and Brewster [15], we considered five locations (*home, sidewalk, passenger on a bus or train, pub or restaurant, and workplace*) and six audiences (*alone, with partner, friends, colleagues, strangers, and with family members*), constituting the independent variables LOCATION and AUDIENCE. We did not use the *driving* condition [15], since it did not apply to most of our participants.

Analysis and Statistical Tests

We report medians as the conventional measure of central tendency for Likert scale variables, which we complement with histograms and means to provide a comprehensive picture of our participants’ ratings. Since our data are ordinal and normality assumptions were violated (according to Shapiro-Wilk tests), we employed the Aligned Rank Transform for nonparametric factorial ANOVAs from the ARTool package (<https://cran.r-project.org/package=ARTool>). To analyze

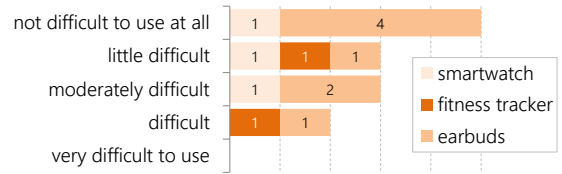


Figure 1. Participants’ prior experience with wearables reported with Likert-scale ratings; *e.g.*, two participants found earbuds moderately difficult to use.

the binary nominal data representing responses about the social acceptability of wearables, we fit binomial generalized linear mixed-effects models (GLMMs) with the lme4 package (<https://cran.r-project.org/package=lme4>). Our dataset (2,625 data points) and R code are available at the web address <http://www.eed.usv.ro/~vatavu/projects/WearablesPreferencesMIDataset>.

RESULTS

We organize the presentation of our results according to our three research questions about (1) perceptions of wearables, (2) preferences for accessible input modalities, and (3) willingness to use wearables. We start with our participants’ prior experience with such devices.

Prior experience with wearables

Twelve participants were using wearables at the time of the study: *smartwatches* (4 participants), *earbuds* (8), and *fitness trackers* (2). Their difficulty ratings for these devices ranged between 1 (not difficult at all) and 4 (difficult); see Figure 1. All the earbuds models (*e.g.*, Jabra Talk 35 and Plantronics Explorer 55) featured external ear hooks and physical buttons, which rendered them easier to put on and take off compared to in-ear designs with touch buttons. Prior experience with smartglasses and smart rings was not reported because of the little availability of these devices compared to smartwatches, fitness trackers, and earbuds. This result suggests that participants’ answers for some of the WEARABLE conditions were informed by their prior experience with those devices and, where longitudinal exposure was not available, perceptions were formed based on the videos used for priming.

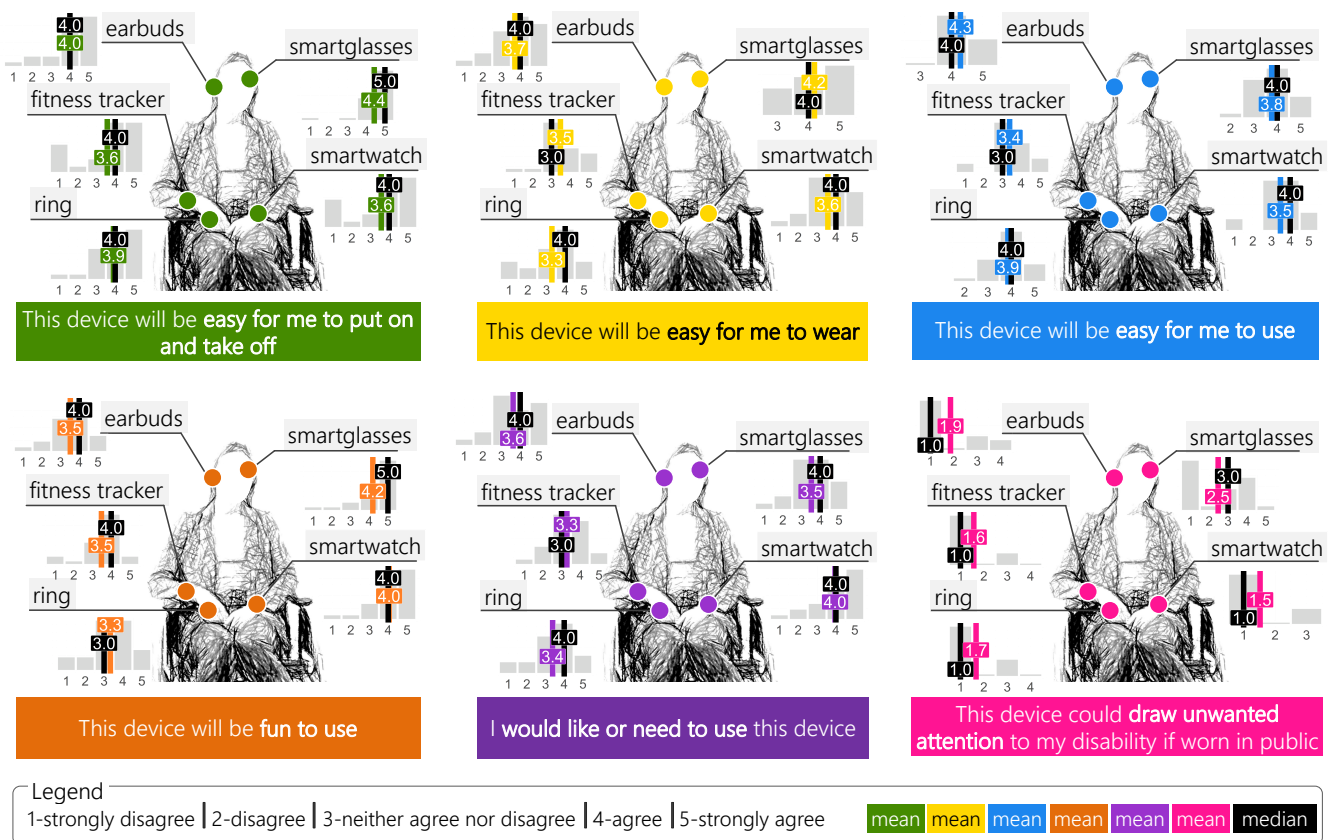


Figure 2. Participants' ratings of smart wearables across the six dimensions considered in our study. *Notes:* means are highlighted in various colors and medians in black on top of each histogram (N=21 responses).

Perceptions of wearables

Figure 2 presents an overview of our results regarding participants' perceptions of the five categories of wearables examined in our study.

We found a significant effect of WEARABLE on EASE-OF-ACCESS ($F_{(4,80)}=5.807$, $p<.001$) with *smartglasses* being rated the highest ($M=4.4$, $Mdn=5.0$) and *smartwatches* and *fitness trackers* equally the lowest ($M=3.6$, $Mdn=3.6$). Post-hoc contrasts (with Tukey adjustments of p -values for comparing a family of five estimates) revealed significant differences between *smartglasses* and *smartwatches* ($p<.001$), *smartglasses* and *fitness trackers* ($p<.001$), and *smartglasses* and *rings* ($p<.05$), respectively.

We also found a marginally significant effect of WEARABLE on EASE-OF-WEAR ($F_{(4,80)}=2.478$, $p=.051$), for which *smartglasses* were rated the highest ($M=4.2$, $Mdn=4.0$) and *rings* the lowest ($M=3.3$, $Mdn=4.0$, $p=.005$). Perceptions of EASE-OF-USE were also affected

by WEARABLE ($F_{(4,80)}=8.292$, $p<.001$) with *earbuds* scoring the highest rating ($M=4.3$, $Mdn=4.0$), significantly larger than the ratings of *fitness trackers* ($M=3.4$, $Mdn=3.0$, $p<.001$), *smartwatches* ($M=3.5$, $Mdn=4.0$, $p=.002$), and *smartglasses* ($M=3.8$, $Mdn=4.0$, $p<.01$).

There was no effect of WEARABLE on DESIRABILITY ($F_{(4,80)}=1.543$, $p=.198$, $n.s.$), but wearables were perceived differently in terms of their potential for being FUN ($F_{(4,80)}=3.951$, $p<.01$): *smartglasses* were rated the highest ($M=4.2$, $Mdn=5.0$) and *rings* the lowest ($M=3.3$, $Mdn=3.3$, $p=.021$, Tukey adjustments for comparing a family of five estimates).

We also found a statistically significant effect of WEARABLE on UNWANTED-ATTENTION ($F_{(4,80)}=5.350$, $p<.001$). The device that participants believed could draw the most attention to their disability was the *smartglasses* ($M=2.5$), while *smartwatches* and *fitness trackers* ranked at the opposite end of the scale ($M=1.5$, $p=.001$).

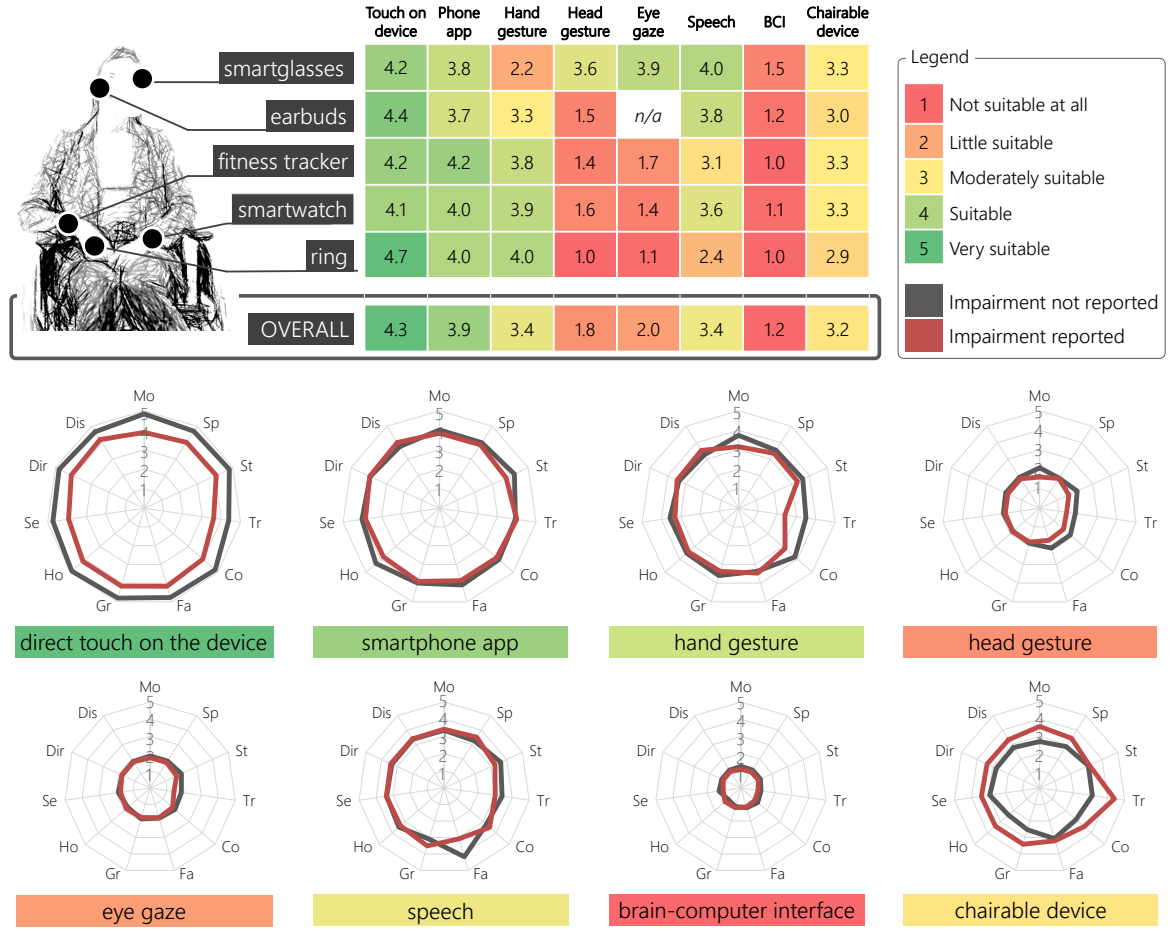


Figure 3. Participants' preferences for accessible input modalities to interact with wearables. *Notes:* means are presented from a total of 819 ratings; the combination *earbuds* and *eye gaze* input was not evaluated; self-reported impairments, e.g., Mo for "slow movements," are described in the footnote of Table 1.

and $M=1.6$, $p=.002$). However, the mean ratings were between 1.5 and 2.5, showing our participants not concerned overall about this aspect.

Preferences for input modalities for wearables

We detected statistically significant effects of WEARABLE ($F_{(4,780)}=18.144$, $p<.001$), INPUT-MODALITY ($F_{(7,780)}=164.509$, $p<.001$), and an interaction between WEARABLE and INPUT-MODALITY ($F_{(28,780)}=11.323$, $p<.001$) on participants' preferences for accessible input with wearables. Contrasts for WEARABLE (Tukey adjustments) showed significant differences ($p<.001$) between *smartglasses* and all of the other wearables. Contrasts for INPUT-MODALITY showed many statistically significant differences ($p<.05$), e.g., between *direct touch* and all of the other modalities, *head gestures* and all of the

modalities except *eye input*, and between *BCI* and all of the other input alternatives.

The lowest rated input modalities were *BCI* ($M=1.2$), *head gestures* ($M=1.8$), and *eye gaze* ($M=2.0$), but the significant interaction between WEARABLE and INPUT-MODALITY reveals more information, as follows; see Figure 3. *Head gestures* and *eye gaze* were consistently rated low for all of the WEARABLE conditions, except for *smartglasses* ($M=3.6$ and $M=3.9$, respectively), for which they were found suitable. Also, *speech* was rated above 3 for all of the wearables, except for *rings* ($M=2.4$), for which *direct touch* was largely preferred ($M=4.7$).

Figure 3, bottom also shows the effect of specific motor impairments or symptoms, self-reported by our participants, e.g., slow movements or rapid fatigue (see Table 1), on their

	locations					audiences					
	Home	Sidewalk	Passenger train/bus	Pub or restaurant	Work place	Alone	Partner	Friends	Col-leagues	Strangers	Family
smartglasses	0	2	7	4	4	0	0	1	1	8	1
earbuds	3	1	1	2	5	2	2	3	3	2	3
fitness tracker	2	1	1	1	1	1	1	1	1	1	1
smartwatch	2	1	1	1	1	1	1	1	1	1	1
ring	2	2	2	2	2	2	2	2	2	3	2
OVERALL	9	7	12	10	13	6	6	8	8	15	8

Legend

1 One participant

5

11 Half of the participants

16

21 All of the participants

Figure 4. Number of responses (out of 21 per condition) specifying locations and audiences where participants would not wear or use wearable devices.

preferences for accessible input modalities for wearables. Two radar plots are shown for each INPUT-MODALITY with mean ratings computed for each of symptom from the participants who reported those symptoms (in red) compared to the participants who did not (gray). For the majority of the input modalities, preferences almost coincide for the participants with and without specific symptoms, as indicated by the superposition of the two radar plots. Differences can be observed for *direct touch* that received lower preference from the participants that reported specific symptoms compared to those who did not ($M=4.02$ and $M=4.75$). Also, we found a higher preference for *chairables* for the participants reporting symptoms ($M=3.47$ vs. $M=2.83$). We resume on these results in the Discussion section.

Willingness to wear and use wearables

Overall, our participants showed high willingness to use wearables in mostly all of the *locations* and in front of all of the *audience* types considered in our study. Only few locations (9.7% of 525 responses) and audiences (5.5% of 630 responses) were indicated as not appropriate; see Figure 4. We did not find any significant effect of WEARABLE, LOCATION, or AUDIENCE on WILLINGNESS to use wearables ($p>.05$).

Qualitative findings

We designed our study to evaluate quantitative measures about people's preferences and perceptions of wearables. We did not plan to

elicit free-form feedback as part of our structured interviews, but some of our participants voluntarily provided comments. Next, we present these comments as they provide useful insights that complement the numerical findings obtained with our quantitative measures. By analyzing participants' comments, we identified a common theme: one key advantage of devices designed to be worn, *i.e.*, their always-availability, is often counterbalanced by challenges experienced when donning, doffing, and wearing those devices.

A few participants remarked the advantage of wearables being always there for them to use unlike other mobile devices, such as smartphones. For example, P₂₀ said he liked using the smartwatch instead of the smartphone, because current phone models have become too large and heavy for him to operate effectively, and P₁₃ witnessed: “my smartwatch is very useful because I can answer phone calls when my phone is not near me or when I’m already in bed and the phone is not close to reach. This way, I don’t have to get up and into the wheelchair to go and fetch my phone.” However, the utility of smartwatches was counterbalanced by P₃ with watches not being always comfortable to wear: “[smartwatches are] useful to monitor the quality of your sleep, although for me regular watches are uncomfortable and I am taking them off before going to sleep.”

Comments about the comfort of wearing devices came from several other participants. For example, P₁ said that “if the earbuds are not stable in my ear, I cannot adjust them,” although he

had tried several models over the years, and P₂₁ told us the following story: *“I received a pair of smart earbuds as a gift, but I could not get them to stay in my ears, so I had to send them back. They were falling off my ears all of the time, and I was running the risk of losing them or driving over them with my power wheelchair.”* Earbuds designs with ear hooks are easier to put on, including by a caregiver that can visually verify their correct placement, an important aspect mentioned by one participant that identified the risk of small injuries because of the lack of feedback for the caregiver when helping with in-ear earbuds. Unlike earbuds, smartwatches and rings are tightly attached to the wrist and finger. However, because of that, they are also not comfortable: P₁₅ said that it was very uncomfortable for him to wear anything on his wrist, and P₂₁ reported: *“My watch is uncomfortable. Sometimes the strap is too loose, other times too tight.”* Two participants said they could not wear rings because rings felt uncomfortable (P₁₂) and interfered with operating the wheelchair (P₁₃): *“I gave up wearing rings because I could get hurt when using the wheelchair (the ring often made contact with the wheels) or when getting off from the wheelchair and into my bed.”* For P₁₇, none of the wearables examined in our study were perceived accessible and he said he wouldn’t be able to don by himself any of those devices.

Other participants’ comments were about wearing devices in public, which may attract attention to their disability. For instance, P₉ said that *“if people could see me struggling to put on my earbuds, this will definitely draw attention to me,”* and P₁₇ considered that *“if I wore a ring and had to use gestures, I will definitely draw attention because my movements will be slow and awkward.”* Other devices, such as earbuds, were perceived useful by P₄, but less suited to be worn during social interactions: *“it is not polite to wear earbuds in the presence of other people, even if you use them just for notifications.”*

DISCUSSION

In this section, we distill the findings of our study into opportunities for research and development toward more accessible wearables for users with motor impairments. To this end, we focus on three aspects relevant for the adoption of wearables, little examined in prior work: (1)

wearables are always-available, but not always easy to don and doff, (2) wearables are not always comfortable to wear, and (3) opportunities exist for the conjoint use of wearables and other devices, *e.g.*, chairables for wheelchair users.

Design wearables that are easy to don and doff

A desirable characteristic of wearables is that they are always-available and do not require fetching, *e.g.*, from the bag or pocket, compared to smartphones and other mobile devices. However, in order to use an always-available wearable, that device must be donned. Most of our participants reported spasm, low strength, rapid fatigue, lack of sensation in body parts, while the participants with hemiplegia can use only one of their arms; see Table 1. These conditions and symptoms make donning and doffing wearables challenging, *e.g.*, people with a tetraplegic functional hand experience rapid fatigue even when grabbing lightweight objects, such as earbuds. Also, most of our participants reported difficulties gripping and holding objects and controlling the direction and distance of movement. Tiny wearables that need to be positioned at and affixed to various parts of the body will exacerbate such difficulties.

Future work is thus needed to explore more ergonomic form factors, straps, fasteners, and hooks to assist donning and doffing wearables to accommodate various motor abilities, but also to reduce the possibility of social stigma during those actions. Donning and doffing assistance could also be the result of an adaptable device, and interesting future work may be dynamic-form wearables that change shape [18] to accommodate different motor abilities. These directions connect to designing for long-term acceptability, for which Kim *et al.* [11] presented evidence for ring devices as viable means for upper-limb rehabilitation therapy and post-stroke patients. Design for acceptability can also improve users’ perception of wearables, foster better adoption, and prevent abandoning of self-monitoring technology because of device weight and lack of comfort.

Design wearables that are comfortable to wear

Besides being effective [6] and useful [11], devices must be comfortable to wear [14]. However, wearing devices can be uncomfortable and challenging for users with motor impairments.

Also, if wearables are not firmly affixed to the body, their position needs frequent adjustment, a challenging task under motor impairments. Making wearables easy to readjust during use in ways that are casual, subtle, and do not draw unwanted attention, is one interesting direction for investigation. Another direction is wearables that can automatically adjust their position on the user's body, *e.g.*, epidermal robots [19] with the capability to move on the skin. Such new device capabilities will reduce and possibly remove the need to manually adjust wearables on the body. For devices with tiny form factors, such as rings, integrating the actuators needed for self adjustment on the user's body may lead to new categories of wearables, *e.g.*, finger-augmentation devices with form factors different from that of a ring, but featuring self-adjustment. Moreover, a wearable that repositions from one finger to another or to the wrist to alleviate wearing fatigue may increase its long-term acceptability. Despite such interesting opportunities for research, these aspects have been overlooked in the accessible computing community, where the focus has been on studying interactions *after* the wearable has been donned, whereas our findings show that how easy a device is to put on and adjust on the body are equally important factors for consideration.

Conjoint use of wearables and other devices

Although touch was the most preferred input modality overall, some of the participants raised potential problems with it, such as for raising their arms to the glasses. The high ratings for the *direct touch* and *smartphone* conditions can be explained by the familiarity of our participants with smartphones and their reliance on smartphones for communication and access to information. In this context, a notable finding of our study suggests that input for wearables may be compatible with and also supported by other devices. For instance, the option to control a wearable via a *chairable* [7] received an average rating of 3.2 with little variation (2.9-3.3) across all of the examined devices. Overall, participants were moderately convinced that this option would be useful, but it is worthy to note that *chairables* were preferred to *eye gaze* (2.0), *head gestures* (1.8), and *BCIs* (1.2), and scored very closely to *speech input* (3.4). Also, the *phone app* condition

scored 3.9 out of 5, ranking second after *direct touch*. These results suggest opportunities for future work on cross-device input [20] for users with motor impairments. For instance, on-body and on-wheelchair touchpads, found effective for interacting with head-mounted displays [6], might also work for other types of wearables, but many other ways to combine input on multiple devices—mirrored, distributed, and migratory user interfaces [20]—are interesting to examine for accessible wearable interactions. These include smart textiles enabling touch input via conductive fibers as alternatives to *direct touch* on the device and the *smartphone app*, but also new designs of chairables [7] that could equally be considered in the context of mixed chairable-wearable input.

LIMITATIONS AND FUTURE WORK

There are a few limitations to our study. First, our sample of participants included fewer women than men and, although the age range was large (28 to 59 years), our sample did not include adults above 60 years old. It is likely that women or an older demographic may have different preferences for wearables, *e.g.*, regarding rings and other categories of smart jewelry for women, or different perceptions and uses of wearables for older people. Also, our findings came mostly from people with spinal cord injury, whereas other health conditions were less represented, *e.g.*, spina bifida, or not represented, *e.g.*, Parkinson's, in our sample. Examining preferences from people with other demographics is recommended, and we leave such specific investigations of gender, age, and health conditions for future work. Also, although not necessarily a limitation since our study was meant to be exploratory in its scope, debriefing people after they had evaluated a sample of selected devices over a period of time as in longitudinal studies, will provide further insights into their preferences and needs for such devices. For instance, such studies could be conducted with earbuds and rings especially, very little examined in prior work for users with motor impairments, for which our findings revealed several accessibility problems.

CONCLUSION

We presented results from a study with twenty-one people with motor impairments to

address three research questions regarding perceptions of wearables, preferences for accessible input modalities, and willingness to wear and use devices. We found high predilection for touch input, high willingness to use wearables, but also that how easy a device is to don, doff, and wear are important factors for wearables. Our findings complement existing knowledge in the community on the accessibility of interactions with wearable devices [16], and suggest research opportunities toward more accessible wearables.

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Ovidiu-Ciprian Ungurean is a Computer Science Researcher in the MintViz Lab at the University of Suceava, Romania. He is interested in assistive technology for people with motor impairments. Contact him at ungurean.ovidiu@gmail.com.

Radu-Daniel Vatavu is a Professor of Computer Science at the University of Suceava, where he directs the MintViz Lab. His interests include gesture input, ambient intelligence, and accessible computing. His work has received awards at CHI, TVX, IMX, EICS, ICMI. Contact him at radu.vatavu@usm.ro.