Wearable Interactions for Users with Motor Impairments: Systematic Review, Inventory, and Research Implications

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ABSTRACT

We conduct a systematic literature review on wearable interactions for users with motor impairments and report results from a meta-analysis of 57 scientific articles identified in the ACM DL and IEEE Xplore databases. Our findings show limited research conducted on accessible wearable interactions (e.g., just four papers addressing smartwatch input), a disproportionate interest for hand gestures compared to other input modalities for wearable devices, and low numbers of participants with motor impairments involved in user studies about wearable interactions (a median of 6.0 and average of 8.2 participants per study). We compile an inventory of 92 finger, hand, head, shoulder, eye gaze, and foot gesture commands for smartwatches, smartglasses, headsets, earsets, fitness trackers, data gloves, and armband wearable devices extracted from the scientific literature that we surveyed. Based on our findings, we propose four directions for future research on accessible wearable interactions for users with motor impairments.

CCS CONCEPTS

• **Human-centered computing → Accessibility technologies**; **Ubiquitous and mobile devices**.

KEYWORDS

Motor impairments, wearables, review, survey, accessible input, smartwatches, smartglasses, headsets, rings, HMDs, fitness trackers.

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1 INTRODUCTION

Wearable devices are becoming mainstream as consumers increasingly adopt and integrate them in their lives [11, 65, 78, 141]. According to an IDC report [53], global shipments of wearable devices were of 345 million units in 2019 and forecast to reach 637 million units in 2024. Of these, smartwatches and wrist bands represented 91 and 67 million units, respectively. Other types of wearables, such as smartglasses and head-mounted displays (HMDs), are gaining momentum with the increased interest for Virtual and Augmented Reality (VR/AR) technology [114]. Also, the global market for Bluetooth and NFC smart rings is projected to reach US$12.6 million by 2027 according to a Global Industry Analysis report [42], enabling users with simple access authorization and contactless payments.

In this context, getting the right design for wearable interactions is paramount for mobile users to be able to operate effectively small screens [3, 41], tiny buttons [1, 56, 130], eyes-free UIs [87], and be efficient with gesture input involving precise movements of the fingers, hand, and head [66, 107, 135]. For example, touch interactions on the Samsung Galaxy Watch[1] include *taps* and variations of taps, *drag gestures*, where the finger touches an on-screen target and moves across the screen at a constant speed, and the *palm touch* gesture, where the display is covered with the palm to deactivate the screen. Fitbit Sense[2] features a small, 10mm-wide solid-state button that, when pressed for two seconds, gives quick access to applications. The Vuzix Blade AR glasses[3] are operated via taps and swipes on the touch pad embedded in their right temple. The Myo armband,[4] now a discontinued product yet employed in several of the systems identified in our literature review, enables several hand gestures, such as making a fist or spreading the fingers.

1.1 Context for Wearable Interactions and Users with Motor Impairments

Research on accessible wearable interactions for people with motor impairments has been scarce and mostly focused on rehabilitation systems, e.g., we found just four papers [57, 71–73] examining accessibility challenges for touch, gesture, and voice input on smartwatches, despite the large body of research available on smartwatch input in general [17, 65, 68] and the large worldwide adoption of these devices [53]. To put this finding into perspective, the focus on users with motor impairments has been overall disproportionate in the accessibility research community compared to addressing the needs of other user groups. For example, in their survey of 506 accessibility papers published at CHI and ASSETS between 2010 and 2019, Mack *et al.* [69] found that almost half of the papers addressed blind people or people with visual impairments, while

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[1] https://developer.samsung.com/galaxy-watch-design/interaction/touch.html
[2] https://help.fitbit.com/articles/en_US/Help_article/2086.htm
[3] https://www.vuzix.com/products/blade-smart-glasses-upgraded
[4] https://developerblog.myo.com/new-in-myo-connect-gesture-overlay-pointer-color-and-more/

motor or physical disabilities were discussed in just 72 of the papers they analyzed. In this context, it is no surprise that research on the niche topic of accessible wearable interactions has been scarce.

1.2 Contributions

We make the following contributions in this paper:

(1) We report results from the first Systematic Literature Review (SLR) conducted on wearable interactions for users with motor impairments. Our findings show that only a small number of scientific papers has been published on this topic, e.g., only four papers about smartwatch input [57, 71–73], five papers about input on smartglasses [2, 71, 74, 75, 79], and only one paper on possible applications of smart rings [37] for users with motor impairments, while most of the wearable prototypes from the literature were developed and discussed in the context of medical rehabilitation.
(2) We compile an inventory of 92 interactions for wearables consisting of gestures performed with the fingers, hands, head, shoulders, and feet, which we extracted from a number of 57 papers addressing smartwatches, smartglasses, HMDs, fitness trackers, earsets, headsets, data gloves, and armbands.
(3) We draw implications for future research on accessible wearable interactions and users with motor impairments. We identify four directions and propose the WISE framework (Wearable prototypes, Interaction techniques, Studies with users with motor impairments, and Expansion to other devices and smart environments) to structure future scientific investigations and practical developments in this area.

2 SCOPE AND METHOD

We present the method employed in our SLR study to address two research questions (RQs) specifying our scope of investigation for accessible wearable interactions and users with motor impairments:

RQ1: What categories of wearable devices have been considered in the scientific literature for users with motor impairments?
RQ2: What types of wearable interactions have been proposed (designed, developed, evaluated, discussed, etc.) for users with motor impairments?

The answer to RQ_1 structures the landscape of contributions from the scientific literature from the perspective of their focus on specific types of wearables (e.g., smartwatches, smartglasses, etc.), while the answer to RQ_2 is useful to understand the interactions that were proposed for these devices to inform future work.

2.1 Scope

We start by presenting our operational definition of *wearable interactions* to delimit precisely the scope of our SLR. This delineation is important since wearables come in many flavors to address a variety of needs and present a wide range of functionality, from devices designed to track fitness and health [15, 76, 77] to notification implementers [40, 108], navigation tools [31, 36], gaming devices and controllers [125], personal mobile computers [35, 85], and fashion accessories [54, 106]. In this context, examining wearables as devices that were simply designed to be worn [4, 51] or

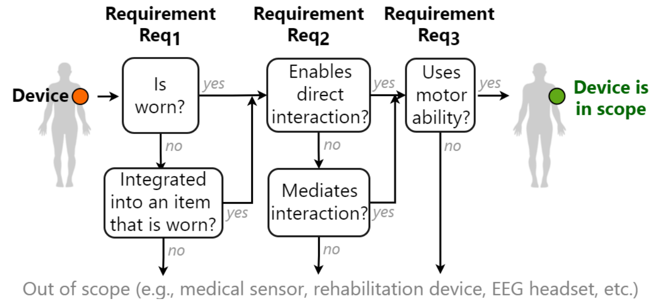


Figure 1: Flow diagram specifying the scope of our investigation on wearable interactions and users with motor impairments; see requirements Req_1, Req_2, and Req_3 described in the text.

incorporated into items of clothing and accessories [109] represents a definition too broad for our scope as it does not capture the *interaction* part—in fact, such a broad definition encompasses all devices, sensors, and electronics that, admittedly wearable, may not necessarily require interaction, e.g., medical sensors [5, 140]. Instead, a definition approach based on identifying relevant categories of wearables [105], their characteristics such as always-on operation and interactivity [51, 131], and design requirements for interactions, such as comfort, safety, usability, and satisfaction [32], is better suited to our scope. We are thus interested in all devices that can be worn, either directly or integrated into items that are worn, and that enable *direct interaction* on the device itself, such as tap input to read a smartwatch notification [24], or using the wearable for *indirect interaction* to control something else, such as performing a gesture with the finger wearing a smart ring to turn on the lights [38]. From this perspective, our operational definition for *interactive wearables* is specified by the following three requirements (see also Figure 1):

Req1: The device is worn or integrated into an item that is worn. Examples include smartwatches [72], rings [37], fitness trackers [15], smartglasses [79], data gloves [33], HMDs for VR [82], but also sensors embedded into clothes, such as IMUs sewed onto a hat [8] or touch pads placed on the body [75].
Req2: The device enables direct interaction to operate the device itself or mediates interaction, e.g., to control a computer [49], a robot [18], a virtual world [30], or the electric-powered wheelchair [52]. A wearable may also be used to control another wearable [43, 75]. Wearable devices that do not require interaction, such as heart rate sensors [45], are excluded.
Req3: Our scope addresses people with motor impairments, i.e., with any impairment in the ability to move all or parts of the body. Thus, our third requirement specifies physical movement of a part of the body to implement the interaction. For example, smartglasses that track head movement, gestures performed with smart rings [37], touch input on smartwatches [72] or on the body [75], earsets that require tilting and movement of the head [18], are relevant to our scope, whereas electroencephalography (EEG) neuroheadsets [62] are not, since they do not require physical movement. The

movement can be subtle, such as a small gesture of the finger wearing a ring [37], or more ample, such as rotating the wrist wearing a smartwatch to activate its screen. In general, the large muscle groups of a limb are expected to be involved in the interaction according to the design expectations of current wearable devices (see Section 1 for a few examples) and, consequently, this criterion excludes eye movements. *With this requirement, we delimit our scope to wearables that involve a part of the body to implement the interaction and, because of this design expectation, may present accessibility challenges for people with motor impairments.*

Requirements Req_1 to Req_3 specify our scope of investigation precisely, while they are broad enough to encompass a variety of wearables (Req_1) as long as the corresponding interactions (Req_2) require motor skills (Req_3); see Figure 1. For other categories of wearables and goals of wearable computing, we refer to Lara and Labrador's [60] survey of wearable sensors for activity recognition, Thalman and Artemiadis' [117] review of wearable assistive robots, Şiean *et al.* [111] for assistive technology involving mixed reality and ambient intelligence, Rose *et al.*'s [97] survey of VR for rehabilitation, Lazarou *et al.* [62] and Tiwari *et al.* [118] for brain-computer interfaces, and Pasqualotto *et al.* [88] for eye gaze input.

2.2 Study Design

There are many ways to conduct SLRs, which can be quantitative (like ours) or qualitative (e.g., narrative reviews) [10, 110]. In this work, we conduct a meta-analysis to structure numerically the landscape of research on accessible wearable interactions. We follow Siddaway *et al.*'s [110] Best Practice Guide and adopt PRISMA[5] [63] for reporting meta-analyses; see Figure 2 for an illustration of the *identification*, *screening*, *eligibility*, *snowballing*, and *inclusion* stages of our study. In the following, we describe each stage in detail.

2.2.1 Identification. The role of the identification stage is to locate work that addresses the research questions, a stage operationalized with search terms and queries in scientific databases. We chose the ACM DL[6] and IEEE Xplore[7] as two major databases for Computer Science research and DBLP[8] as a multi-publisher bibliography source to cover other publishers as well. After performing searches in these databases to familiarize ourselves with the literature, we concluded that by searching only through the titles of the articles, relevant references would be lost, while searching through the entire text would result in too many irrelevant results. Thus, we decided to search the abstracts as a compromise, and considered various categories of wearables to specify our keywords, such as "watch," "glasses," "bracelet," etc. alongside the generic keyword "wear." The ACM DL query was:

```
"query": {
   Abstract: ((motor) AND (impair* OR disab*) AND
   (wear* OR worn OR watch* OR (fitness AND band*) OR
   ring* OR bracelet* OR jewel* OR
   glass* OR HMD* OR ("head" AND "mount*")))
}
"filter": {NOT VirtualContent: true}
```

and returned 79 results. For IEEE Xplore, the advanced search form did not allow searching with all the wildcards * in one query, so we split the query in two parts (Q_1 and Q_2), as follows:

```
Q1: ("Abstract": motor) AND ("Abstract": impair* OR
    "Abstract": disab*) AND ("Abstract": wear* OR "Abstract":
    worn OR "Abstract": watch* OR "Abstract": glass* OR
    ("Abstract": fitness AND "Abstract": band*))

Q2: ("Abstract": motor) AND ("Abstract":impair* OR "Abstract":
    disab*) AND ("Abstract": ring* OR "Abstract": bracelet*
    OR "Abstract": jewel* OR "Abstract": HMD* OR
    ("Abstract": head AND "Abstract": mount*))
```

for which we obtained 192 and 37 results, respectively, but 12 were returned by both Q_1 and Q_2, so the total number of distinct results from IEEE Xplore was 217. The following form of the query:

```
motor impair|disab wear|worn|watch|glass|fitness|band|
ring|bracelet|jewel|HMD|head|mount
```

returned 17 results from DBLP. All the queries were ran on Oct. 28th, 2020. Overall, we identified a number of 313 articles; see Figure 2.

2.2.2 Screening. We discovered 22 duplicates that we eliminated from our list, resulting in a total number of 291 unique titles. We read the abstracts to determine whether the identified references were relevant according to our scope. We excluded 60 references that did not address people with motor impairments, but for which the keyword "motor" appeared in the abstracts in conjunction with "impairments" to denote, for example, electric motors used to deliver vibrotactile feedback to people with visual impairments [55]. We excluded another 4 references that did not focus on humans, but addressed wearables for dogs or monkeys [47, 80]. Also, a number of 40 references did not match our definition of interactive wearables: we excluded devices not designed to be worn, such as those integrated into wheelchairs, stretchers, robotic assistants, etc., and prototypes for which the operation was internal to the body, e.g., devices operated with the tongue [137] or designed to replace body parts, such as implants [112] and prosthetic limbs [119]. After the screening stage, we arrived at 187 references.

2.2.3 Eligibility. We formulated the following eligibility criteria (EC) to further filter out work not relevant to our scope:

- EC1: *Availability of full text.* The full text of the work must be available and the work must be written in English.
- EC2: *Peer-reviewed work.* The work must be academic and peer reviewed, e.g., journal articles, conference papers, PhD dissertations. Magazine articles, brochures, etc., are excluded.
- EC3: *Focus on interactions.* The wearable must enable interactions either to operate it or to control another device or system. From this perspective, medical rehabilitation devices [98], systems for mobility assistance [116], and sensors employed for the assessment of motor skills [22] were excluded. We refer readers interested in such topics to Avutu *et al.* [5] and Zhou and Hu [140] for surveys on smart devices and human motion tracking for rehabilitation, Thalman and Artemiadis [117] for wearable assistive robots, and Rose *et al.* [97] for a review of VR for rehabilitation. This eligibility criterion connects to Req_2 specifying wearable interactions.

[5]The PRISMA acronym stands for Preferred Reporting Items for Systematic reviews and Meta-Analyses.
[6]https://dl.acm.org
[7]https://ieeexplore.ieee.org/Xplore
[8]https://dblp.org

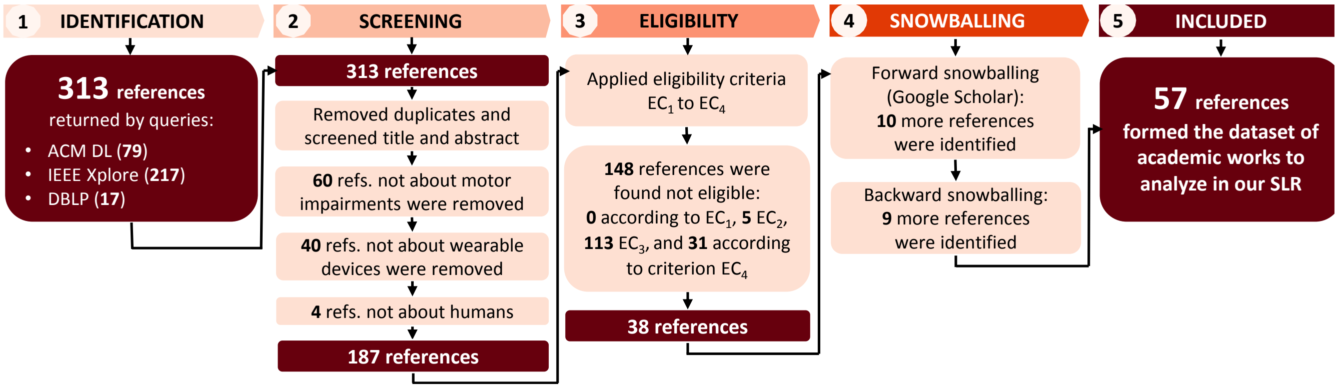


Figure 2: The PRISMA [63] diagram illustrating the results of the identification, screening, eligibility, snowballing, and inclusion stages of our SLR study on the topic of wearable interactions for users with motor impairments.

EC4: *Focus on motor abilities.* We excluded brain-computer interfaces (BCI) and mobile eye gaze tracking systems because, even though they represent devices designed to be worn, do not require motor abilities of the large muscle groups[9] and, thus, act as mere sensors affixed to the body. We refer the interested reader to the literature on BCI [7, 62, 118] and eye gaze input [27, 70, 88] for results in these areas. This criterion connects to our requirement Req_3 from Figure 1.

By applying these eligibility criteria, we eliminated 149 references, leaving a subset of 38 papers relevant for our scope; see Figure 2.

2.2.4 Snowballing. We used the 38 papers in two snowballing [134] procedures: *backward snowballing* (by looking at the lists of references of the selected papers) and *forward snowballing* (the citations are considered). Backward snowballing identified 9 more relevant papers. By scrutinizing the 583 citations (Google Scholar) identified with the forward snowballing, we selected 10 more papers relevant for our scope. Our final set consists of 57 peer-reviewed scientific papers published between 2005 and 2020; see Figure 2.

3 RESULTS

We present results from a meta-analysis of the 57 papers identified on the topic of wearable interactions and users with motor impairments. Figure 3 shows the distribution of these papers according to their publication year, starting with Moon *et al.*'s [52] work on wearable electromyography (EMG) control of electric-powered wheelchairs. A growing interest can be identified (R^2=.439) for wearable interactions but, overall, the number of papers is small.

3.1 Research Contributions

To catalogue the contributions made by the papers identified in our SLR, we employed the seven categories of Wobbrock and Kientz [132]: (1) empirical research, (2) artifact, (3) methodological, (4) theoretical, (5) data set, (6) survey, and (7) opinion. We found that

[9]Eye gaze input does represent physical movement, but it falls outside our scope, where we focus on motor abilities of larger muscle groups, such as finger touches on smartwatches, hand gestures for fitness trackers, or head movements for smartglasses and HMDs. Such types of movements are expected by the current designs of interactions available for smartwatches, smartglasses, smart rings, etc. and, thus, they are likely to lead to accessibility challenges for users with motor impairments.

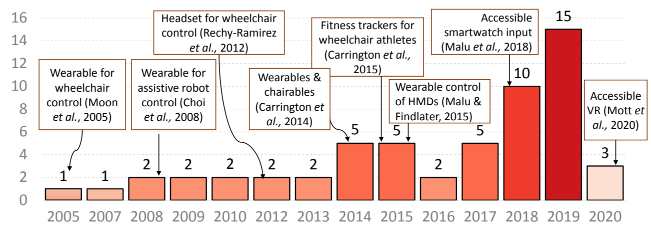


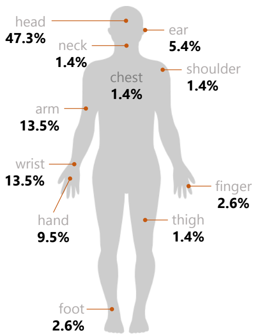
Figure 3: Number of papers from our SLR, shown per year. Several milestones are highlighted.

the most frequent contribution was *empirical research*, which we identified in 51 of the 57 papers (89.5%), followed by *artifact* (71.9%) with application categories including rehabilitation [12, 19, 23, 115], assistive robot control [8, 18, 46, 59], games [29, 127], text entry [34, 89, 92], and wheelchair navigation [2, 39]. The other types of contributions were less or little represented. For example, we found just two articles (3.5%) contributing opinions: Mott *et al.* [81], who discussed opportunities and challenges of accessible VR, and Gheran *et al.*'s [37] position paper about smart rings as assistive devices. Two articles (3.5%) made theoretical contributions: Carrington *et al.* [16] presented conceptual designs of devices integrating wheelchairs and Baldi *et al.* [8] described a method for tilt estimation using quaternions for their interface designed to control a robotic arm. We also identified three surveys (5.3%): Malu *et al.*'s [71] summarizing their prior work on accessible wearable interactions for people with motor impairments, Dobosz *et al.*'s [25] overview of head-based text entry methods, and Ghovanloo and Huo's [39] book chapter presenting an overview of wearable non-invasive assistive technology. To the best of our knowledge, no work has released datasets about wearable interactions and users with motor impairments.

3.2 Types of Wearables and Input Modalities

We examined the categories of wearables addressed by the papers identified in our SLR and extracted information about the body parts for which they were designed (see Table 1):

Table 1: Body parts for which wearables have been examined in the scientific literature for users with motor impairments, e.g., we found four devices designed for the ear [18, 100, 126, 127].



Worn on	Freq.†	%	References
head	35	47.3	[2],[6],[8],[12],[14],[19],[23],[25],[26],[30],[39],[44],[46],[49],[59],[71],[74],[75],[79],[81],[82],[91],[93],[94],[95],[96],[99],[100],[113],[115],[127],[128],[129],[129],[138]
wrist	10	13.5	[15],[28],[57],[71],[72],[73],[75],[76],[77],[113]
arm	10	13.5	[20],[29],[52],[64],[67],[75],[84],[90],[123],[128]
hand	7	9.5	[33],[34],[64],[75],[86],[91],[113]
ear	4	5.4	[18],[100],[127],[126]
finger	2	2.6	[37],[75]
foot	2	2.6	[89],[92]
thigh	1	1.4	[75]
chest	1	1.4	[75]
neck	1	1.4	[75]
shoulder	1	1.4	[52]
Total†	**74**	**100%**	

† Frequencies are reported cumulatively by considering all the devices reported in a paper, e.g., Wang *et al.* [129] described both a HMD for VR and a headset.

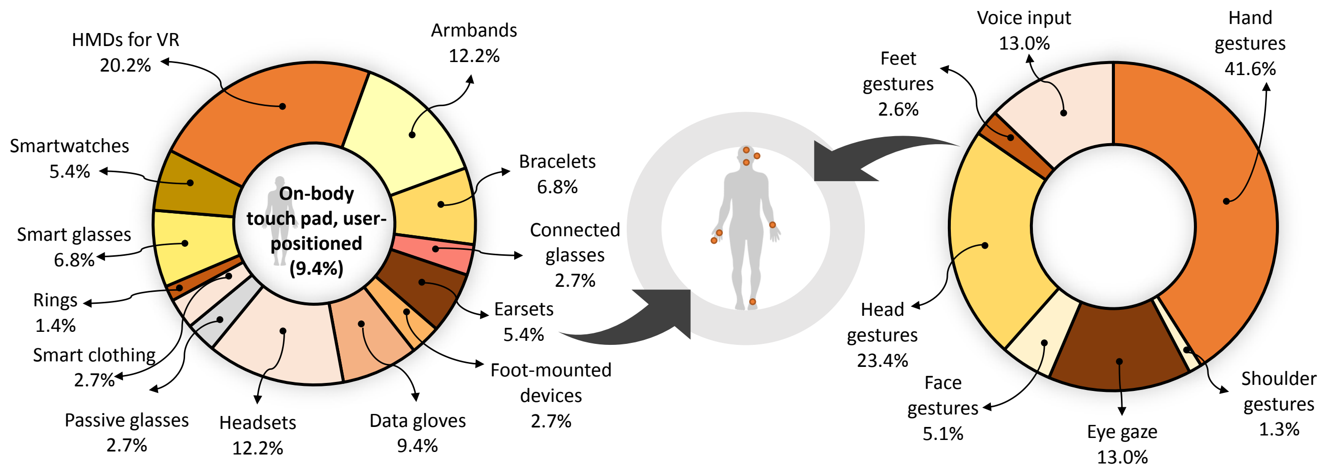


Figure 4: Categories of wearables (left) and input modalities (right) identified in our SLR. *Note:* percentages reported in the left figure are computed with respect to the total number of devices identified in the papers from our SLR (see Table 1).

(1) *HMDs for VR* represent the category with the largest frequency of occurrence (20.2%). For example, Hansen *et al.* [44] employed a FOVE HMD to enable remote control of a robot with head and eye gaze input with video from the robot displayed in the HMD. Ferracani *et al.* [30] used an Oculus Rift HMD to deliver immersive experiences to people with motor impairments for museum visits in VR. Bortone *et al.* [12] evaluated a wearable prototype for haptic feedback in VR games for neuromotor rehabilitation and children. Mott *et al.* [82] conducted interviews with people with limited mobility to document their experiences with VR, and identified barriers related to the accessibility of VR devices.

(2) *Headsets* were represented by 12.2% of the devices described in the papers from our SLR. Headsets can embed various sensors, such as IMUs [46, 94], electrodes for EEG [95], or magnetometers to track tongue movement [99], among others.

(3) *Glasses* devices accounted for 12.2% of the wearables that we examined, for which we identified three subcategories: *passive*, *connected*, and *smartglasses*. Passive glasses do not embed sensing, but are tracked by an external system, such as the glasses with infrared LEDs used by Honye and Thinyane [49] and Azmi *et al.* [6] tracked with the Wii Remote controller. Connected glasses embed sensors and can process or stream data to another device. Examples include the glasses used by Schäfer and Gebhard [100] with electrodes in the nose bridge and pads to measure the electrooculogram for controlling a robot, and the glasses frame of Rodrigues *et al.* [96] with a built-in gyroscope and accelerometer to enable remote control of a computer via head movements. Unlike passive and connected glasses, smartglasses integrate a display, such as the Google Glass used in Malu and Findlater's [74] and McNaney *et al.*'s [79] studies documenting accessibility challenges and the ORA-2 device used by Ajmi *et al.* [2] for AR navigation and wheelchair users.

(4) *Armbands* were found in nine systems (12.2%) and were represented in the majority of the cases by Myo.[10] Applications ranged

[10] https://developerblog.myo.com

from interactions in smart homes [123], robot navigation and control [67, 84], games for children with motor impairments [29], and controllers for VR games [127]. Moon *et al.* [52] developed a system for recognizing shoulder elevation gestures using EMG measurements to control the electric-powered wheelchair, for which the processing unit was attached to the user's forearm as an armband.

(5) *Data gloves* (9.4%) were used to implement text-based communication [33, 34], remote monitoring of physical rehabilitation of stroke patients [91], and multi-sensor gesture recognition [86].

(6) *Earsets* (5.4%) included EEG dry electrode sensors placed on top of the ears to detect eye movements and facial expressions [127, 128], the ear-mounted laser pointer of Choi *et al.* [18] for the remote control of an assistive robot, and electrodes positioned on and around the ear for EMG on the posterior auricular muscle [100].

(7) Interactions with *smartwatches* were addressed by four papers representing just 5.4% of the wearables examined in our SLR. Malu *et al.* [72] assessed the accessibility of smartwatch gestures, such as taps, swipes, and drawing letters for text input, and conducted an end-user elicitation study [133] in which participants with motor impairments were asked to create their own gestures. In a follow-up study, Malu *et al.* [73] compared smartwatch touch and bezel input and found that touchscreen gestures were faster, but bezel input was more accurate. Kim *et al.* [57] described a smartwatch application designed to assist in accessing the functions offered by a smart campus, such as monitoring the temperature and illumination from a room, calling elevators, and unlocking doors.

(8) *Fitness trackers and bracelets* (6.8%) were used to understand accessible health and fitness tracking practices for people with mobility impairments [76] and to provide implications for sharing activity data [77]. Carrington *et al.* [15] examined the inaccessibility of fitness trackers for wheelchair athletes.

(9) Other types of wearables were found in just one or two papers, such as Gheran *et al.*'s [37] position paper about rings, Baldi *et al.*'s [8] and Kyrarini *et al.*'s [59] systems with motion sensors attached to a hat, and Rajanna's [92] and Pedrosa and Pimentel's [89] foot-mounted wearables. Malu and Findlater [75] documented the preferences of users with motor impairments for placing touch pads at various locations on their body—on the arm, wrist, hand, finger, thigh, chest, and neck—which we counted as seven types of location-dependent wearables (7/74=9.4%) enabling personalized on-body input; see Figure 4, left.

We also analyzed the input modalities described in the papers identified in our SLR to implement wearable interactions. These included hand gestures (41.6%), movements of the head (23.4%), eye gaze input (13.0%), and voice input (13.0%). Other modalities, such as feet input, face gestures, and movement of the shoulders, were less represented; see Figure 4, right for an overview.

3.3 User Studies

A number of nine articles (9/57=15.8%) did not report user studies, while a number of eighteen articles (31.6%) reported studies conducted solely with people without motor impairments. The rest of the works (54.4%) involved participants with motor impairments, for which the number varied from one [28, 46, 89, 100] and two participants [8, 57, 92, 93] to a maximum of twenty [127] and twenty-one[11] [72], respectively, with a mean of 8.2 (SD=6.2) and a median of 6.0 participants with motor impairments per study. Of these, a number of fourteen studies (24.6%) involved both participants with and without motor impairments. In some of these studies, participants without impairments acted as the control group [92, 115], while in others they were represented by therapists [15, 77] and clinicians [16]. For example, Carrington *et al.* [15] included therapists in their study about the inaccessibility of fitness trackers for wheelchair athletes *"to gain a perspective on the role and impact of wearable technology from professionals who work with many wheelchair users"* (p. 196), and Malu *et al.* [77] conducted *"interviews with therapists [that] focused on understanding the opportunities and value of automatically tracked health and fitness data to therapy, while the interviews with people with mobility impairments focused on participants' interest in sharing such data both with therapists and with peers who have similar impairments"* (p. 138).

Regarding the medical conditions of the participants with motor impairments involved in user studies, we found participants with cerebral palsy in 30.0% (9/30) of the studies [12, 72–76, 82, 93, 94], followed by people with spinal cord injury (6/30=20%) [14, 39, 74–77], muscular dystrophy [72, 73, 75, 76, 82], multiple sclerosis [18, 59, 72, 76], and spinal muscular atrophy [73, 82], respectively. Note that not all of the papers with user studies presented this kind of information.

The ratio between the participants with and without impairments varied between 0.07 (1:15) and 14.0 (14:1) with a mean of 1.66 (SD=3.62) showing that, on average, when both participants with and without motor impairments where involved in a study, the number of the former was larger. However, studies involving users with motor impairments and wearables are overall small-scale, a finding that we connect to Mack *et al.*'s [69] results from their survey of accessibility research published at CHI and ASSETS. In that study, Mack *et al.* reported a median sample size of 13 for disabled and older adult participant groups and of 10 (mean 15.3) for people with motor/physical impairments. By comparison, the studies on wearable interactions identified in our SLR have employed less participants. An explanation may be given by the nature of these studies: 30% were qualitative, 63.3% quantitative, and 6.7% reported both qualitative and quantitative results.

3.4 An Inventory of Wearable Interactions

We extracted a total number of 152 gesture commands from the 57 articles identified in our SLR, representing 92 distinct gestures. These include tap and touch input [28, 57], multitouch input [72], pressing physical buttons on the device [49, 127], stroke gestures [74, 75], free-hand and mid-air gestures [28, 67, 84], head movement [46, 59, 127, 129], shoulder [52], face [129], and feet gestures [89, 92].

In the following, we structure this information according to the body parts involved in the interaction and consider: (i) interactions performed with the hand (Figure 5) and (ii) interactions performed with other body parts, such as the head or feet (Figure 6). In the first category, we found 67 distinct gestures representing poses and

[11] Two studies are reported in [72] with 10 and 11 participants, respectively.

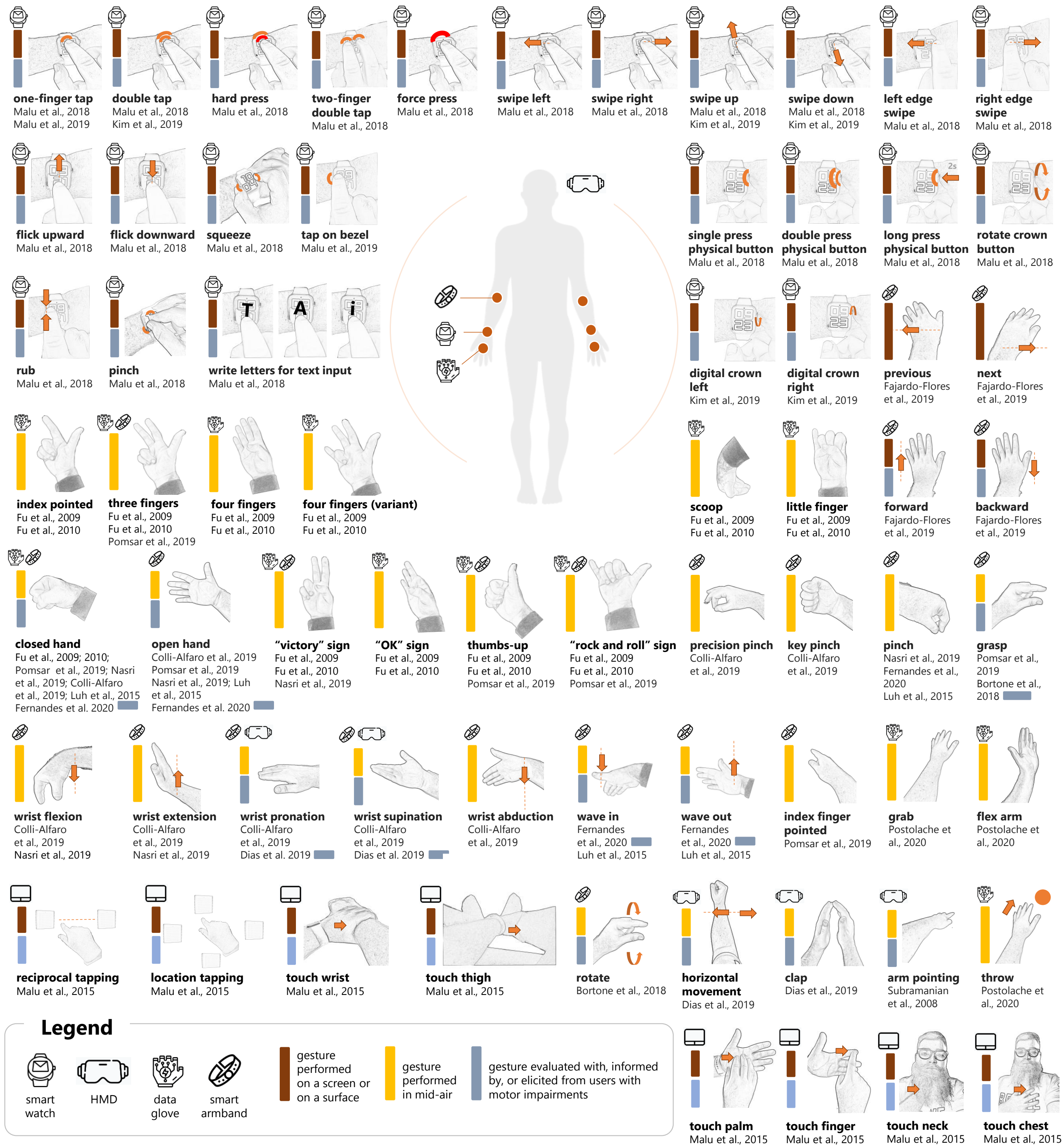


Figure 5: Interactions with wearables performed with the finger, hand, and wrist.

gestures of the hand in mid-air (such as the victory sign [33, 34, 84] or thumbs-up [90]), on the device (e.g., a double tap [57], a force press [72] on the touchscreen, or rotating the crown button [72] of the smartwatch), movements of the wrist [20, 23, 84], and on-body gestures detected by touch pads at various locations on the body [75]. In the second category, we found 25 distinct gestures representing nineteen movements of the head (e.g., move up and down [46, 59, 95]) and eye gaze input [127, 129], three gestures produced with the feet (i.e., rotations of the heel [89], press button with the foot [92]), and three movements of the shoulders [52].

Figures 5 and 6 illustrate these results. For each gesture, we indicate the reference where that gesture was addressed, e.g., the "grasp" gesture was employed in [90] and [12], but also the device for which it was intended, such as an horizontal movement detected by a glove [23], a one-finger tap on the touchscreen of a smartwatch [72], extension of the wrist sensed by an armband [20], or a tap on the touch pad placed on the body to interact with a smartglasses display [75].

Besides gesture input, our analysis revealed voice commands and eye gaze input as two other modalities to implement interactions with wearables with equal representativeness (13.0% of the papers); see Figure 4, right. However, unlike gesture commands that were explicitly documented by most of the papers implementing them, interactions using eye gaze and voice have been less detailed.

Eye gaze tracking was employed in the form of directional commands [128] to perform selections on a remote screen [92] and for mapping eye gaze movements to control another device, such as a robot [44]. For instance, Wang *et al.* [128] described a system to *"control any camera-mounted robot (e.g., endoscopic camera, drone) in the first-person's view to directly control the robot using eye movements. For instance, users can use: left, right, up and down, such eye movements to steer the robot (drone) in 2D direction"* (p. 370). Hansen *et al.* [44] described the eye gaze input modality as follows: *"He [the user] now uses his gaze to mark a waypoint for that room on a digital map, which launches the telerobot to drive to this room autonomously"* (p. 2). Figure 6 includes the eye gaze directional gestures extracted from these studies, even though eye movements were not part of our scope; see Section 2. We refer the interested reader to Majaranta and Räihä [70], Duchowski [27], and Pasqualotto *et al.* [88] for surveys on eye gaze input.

Regarding voice input, commands were not explicitly specified either, e.g., *"AR glasses allow users to have their hands free and to be able to interact with the system via voice command"* [2] (p. 4042). In some cases, more details were provided regarding specific commands or words that were implemented in the user interface. For example, in their preliminary exploration of Google Glass for persons with upper-body motor impairments, Malu and Findlater [74] reported insights about accessibility challenges of voice commands, e.g., for one participant the device only successfully recognized the word "Google." In a follow-up study [75], the authors provided more insights into users' preferences for voice commands, including the preference of one participant to use head movements instead of voice input for interactions in public places. Other papers presented in detail the voice commands employed in their systems, but those commands were very simple. For example, Honye and Thinyane [49] employed five voice commands to control mouse events (left click, right click, double click, mouse press, and mouse release), which were uttered by the users to *"control a two button mouse using spoken language as if they were transcribing to someone how to perform the same actions with the physical mouse"* (p. 192). In other cases, voice commands were even simpler, e.g., *"If the subject says voice command 'click,' for instance, then a mouse click is made"* [6] (p. 66). The most complex system and detailed description of a voice input recognition system is Ferracani *et al.*'s [30] that described a rule-based dynamic grammar employed to enable users to ask questions and express commands during virtual museum visits, e.g., *"When concepts are inferred, the grammar is updated and rules added so that the user may ask additional questions such as 'Which types of abstract art are present in the museum?' or 'Is Jackson Pollock an abstract painter?'"* [30] (p. 1234). Based on these findings, we were not able to complement our set of wearable interactions with voice commands, but we refer readers to McNaney *et al.* [79] and Malu and Findlater [74, 75] for details regarding accessibility challenges for voice input on smartglasses.

4 RESEARCH IMPLICATIONS FOR ACCESSIBLE WEARABLE INTERACTIONS

Our results show that research on accessible wearable interactions for users with motor impairments has been scarce, focused on just few categories of wearable devices, addressing mostly hand gesture input, while about half of the papers that we examined in our SLR either did not conduct user studies or did not involve users with motor impairments among their study participants. Based on these findings, we formulate several directions to foster more work on designing and evaluating interactions for users with motor impairments in relation to our two research questions RQ_1 and RQ_2 (Section 2) towards a diversity of wearables and input modalities adapted to users' motor abilities. We structure these directions with our WISE framework regarding (1) Wearable devices and prototypes (relation to RQ_1), (2) Input modalities and interaction techniques (RQ_2), (3) Studies and evaluations involving users with motor impairments (RQ_2), and (4) Extensions to other devices (RQ_1). For each category we identify several opportunities for future work.

4.1 Exploration of a Diversity of Wearables

Our examination of the literature on wearable interactions for users with motor impairments has indicated a large focus on devices designed to be worn on the head, such as HMDs for VR [81, 82], smartglasses for AR [74, 75, 79], and various prototypes of glasses with embedded sensors [6, 49, 96, 100], which we found to represent 44.6% of the devices examined in our SLR. Other categories of wearables, such as finger and foot augmentation devices, were found in just 4.1% of the cases; see Table 1. It is easy to observe a lack of proportion in the attention addressed to various types of wearables. Unfortunately, this state of things has prevented accumulation of practical knowledge for a large spectrum of wearable devices, such as knowledge regarding how people with motor impairments use smartwatches, rings, and armbands. For example, we found just four papers addressing smartwatch input for users with motor impairments [57, 71–73] despite the large adoption of these devices by the general public [53] and the large body of literature on input techniques for smartwatches [17, 65, 68]. Also, there has been an increasing interest in the HCI community for smart rings [38, 104, 107, 139], but we found just one position paper [37] pointing to the opportunities that smart rings may open for people with motor impairments. Thus, one important research direction in relation to our research question RQ_1 (Section 2) is to understand usage patterns, user behavior, and accessibility challenges for a variety of wearable devices. Complementary to this goal, prototyping new wearables is recommended to address practical needs. For example, the athletes in wheelchairs from Carrington *et al.*'s [15]

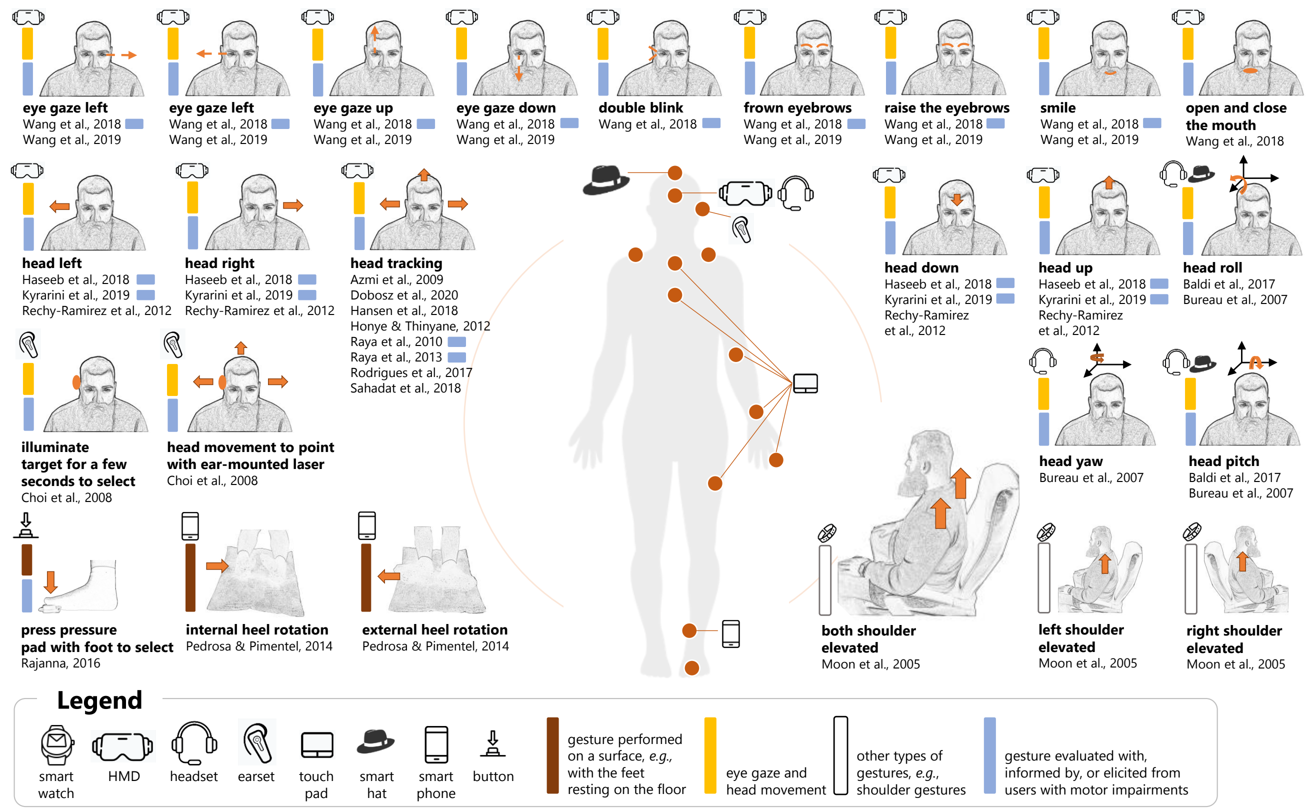


Figure 6: Interactions with wearables performed with eye gaze, movements of the head, feet, and shoulders.

study about the inaccessibility of fitness trackers expressed interest in tracking their physical activity, but the generic system functions of fitness trackers, such as step counting, need to be reconsidered, e.g., *"What happens to a step counter when the user does not take steps?"* [15] (p. 193). Moreover, multi-functional wearables that combine medical sensing for rehabilitation purposes (a category of wearables that fell out of scope for this work) and general-purpose wearables, such as smartwatches and glasses, may be interesting to explore in conjunction.

4.2 Input Modalities and Techniques for Accessible Wearable Interactions

Our analysis has unveiled a large number of interactions with wearables designed to be performed using hand gestures (Figure 4, right), of which 28 gestures were designed to be performed on a surface (e.g., a double tap on the touchscreen of the smartwatch [72]) and 31 in mid-air (e.g., the "victory" emblematic gesture [34] or waving the hand [67]); see Figure 5. Unfortunately, not all of these gestures have been evaluated with users with motor impairments and, consequently, their suitability to implement accessible wearable interactions is unknown. Instead, end-user elicitation studies [133], such as Malu *et al.*'s [72] study on smartwatch gestures, can give insights regarding interactions that are in accord with users' preferences and motor abilities. Thus, one direction for future work regarding our research question RQ_2 (Section 2) is designing interaction techniques that capitalize on such knowledge to maximize motor abilities for accessible, effective, and efficient wearable interactions. Another direction is represented by multi-modal interactions, where different modalities can be employed depending on the context, e.g., voice input where the social context allows it and gesture input otherwise [79]. Validating the inventory of wearable interactions in further studies with participants with motor impairments will result in a useful resource for practitioners interested in designing new prototypes of wearables, new applications, and new interfaces for users with motor impairments.

4.3 More User Studies and Evaluations

The previous two research directions touched on the importance of user studies to inform design of wearables and to validate accessible interactions for such devices. In the following, we stress the need for such studies since 45.6% of the papers that we surveyed in our SLR either did not conduct user studies or did not involve participants with motor impairments. For instance, Honye and Thinyane [49] introduced WiiMS, a system combining head tracking and speech recognition to enable users with motor impairments to control a laptop computer and performed an evaluation with ten participants. However, they noted: *"Although the system was designed to help people with motor-impairments, able-bodied people were used as participants in this study. This was so because of the unavailability of motor-impaired users."* (p. 193). Another example is Rodrigues *et al.* [96] that evaluated a low-cost head-tracking pointing device with ten participants without motor impairments, and concluded that *"The metrics [...] prove the efficiency of the low-cost IOM device evaluated. Obviously when the tests are done with the target audience, the motor disabled users, we must compare it to another tool that they have already had access to for the mouse movement."* (p. 161). Spicer *et al.* [113] evaluated their VR system designed for severe stroke upper limb motor recovery with twelve participants without motor impairments and noted that *"future research will examine the feasibility and preliminary effectiveness of using REINVENT with older adults after stroke"* (p. 386). Other studies mentioned having informed their wearable prototypes with insights gained from involving people with motor impairments, but performed the evaluation with participants without impairments; see, for instance, Pedrosa and Pimentel's [89] foot-based text entry system: *"Our design is informed by a man with a motor neuron disease and the Man-in-the-Barrel Syndrome. Unfortunately, he could not be introduced to the current version of the prototype [...]"* (p. 963). Other studies were not explicit about whether their participants had any motor impairments.

Not employing representative users in accessibility research is a well-known problem [103], and participant recruitment from the target user group can prove challenging [21, 61]. Nevertheless, the need to study representative users is an imperative for inclusive design technology to reach the desired impact [103]. Thus, one immediate implication of our findings in relation to research question RQ_2 (Section 2) is that more user studies are needed for accessible wearable interactions. Examples of relevant and informative user studies in this case are represented by interviews to understand accessibility problems [15, 76, 82, 120], questionnaires [29], end-user elicitation [133] to understand preferences for input with interactive technology [72], participatory design approaches [76], and evaluation of user performance [12, 39, 73, 115] for specific wearables. Also, open data will be helpful to the community to advance knowledge and conduct replications. (Especially since the number of replication studies in HCI is overall low, of about 3% according to an estimation from Hornbæk *et al.* [50].) We did not find any work to release data about wearable interactions, while such data are, unfortunately, rarely published [69].

4.4 Extending Wearable Interactions to Other Computing Devices and Environments

Conjoint utilization of multiple wearables may be beneficial for maximizing the use of motor abilities for effective wearable interactions. In their work about wearable IoT devices, Hiremath *et al.* [48] mentioned the utilization of multiple wearables toward *"the ability to develop innovative services utilizing the storage, processing, connectivity and sensing capabilities available through multiple wearables,"* where such devices formed a personal wearable network. We also position in this category research that combines wearables with other devices for cross-device input [13]. Examples include conjoint operation of the smartwatch and smartphone [58], smartwatch and smart ring [136], and smartglasses and the smartphone [24], respectively. Although such interaction techniques have been examined in the HCI community, they have not been considered for users with motor impairments, to the best of our knowledge. An exception is Malu *et al.* [75] that explored input on touch pads placed on a surface or on the body for controlling the display of smartglasses. Their results showed that, by taking advantage of personalized locations for touch pad input, e.g., on the arm, finger, neck, thigh, all the twelve participants with motor impairments from their study were successful in controlling the smartglasses display. Other examples of cross-device input could involve wearables and gesture input performed on smartphones and tablets [122, 124], wearables and large interactive displays [83], or wearables and remote controls [120]. Besides cross-device interactions, interesting work is combining wearable input with interactions in smart environments characterized by a heterogeneity of devices, platforms, and services [101]. For instance, the smartwatch could be used to turn on the TV set, while voice commands could also be picked up by the smart environment as an alternative input modality, giving users more choices for how to interact with various devices, applications, and services from the smart environment they would like to access [121]. Moreover, such interactions could leverage information about user proximity [9] or take place at the periphery of user attention [102].

5 LIMITATIONS

There are several limitations to our work. First, we conducted our SLR in the form of a meta-analysis of the scientific literature available on wearable interactions for users with motor impairments. Since ours represents the first survey on this topic, we considered useful to characterize numerically the landscape of the research contributions, devices, and interactions in order to provide a first overview on the state of the art in this area. A qualitative survey, however, such as a narrative review [10] to link studies conducted on different topics and support the interconnection of their findings, will reveal further insights from a complementary perspective. Second, we conducted our search in just three scientific databases, but searching in others, such as Scopus and SpringerLink, will likely reveal other papers on the topic of accessible wearable interactions. We recommend such opportunities as future work.

6 CONCLUSION

We presented findings from a systematic literature review on accessible wearable interactions for users with motor impairments. We examined the number and types of research contributions and the categories of wearables addressed by prior work, and compiled an inventory of 92 gesture-based commands for wearable interactions. Our findings revealed that more work is needed to understand accessibility challenges, usage patterns, interaction preferences, and user performance for a variety of wearable devices, for which we proposed four research directions with the WISE framework. We hope that our contributions will foster new studies and developments in these directions towards wearable user interfaces and interactions adapted to various motor abilities.

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