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My Body, My Exoskeleton: Co-Designing Intersectional Visions of Robotic Augmentations through Drawings

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Abstract

Robotic exoskeletons have the potential to improve people's mobility and physical capabilities significantly. However, current design choices often overlook the diversity of users, leading to exclusionary and ill-fitting robotic systems that fail to address intersectional differences, such as age, health conditions, and gender. This introduces disparities in how user needs and their related safety concerns are met. At the same time, accessible methods that involve diverse end-users are understudied. To address these gaps, we explored an online drawing study methodology as an inclusive and fruitful co-design approach to exoskeleton design. We evaluated the feasibility of the methodology and the insights it yielded on the mental models participants from diverse backgrounds shared through their illustrations of robot embodiments. Methodologically, we discovered the merits and demerits of asynchronous drawing methodologies with naive participants. At the same time, the drawings, annotations, and interviews also allowed us to identify participant concerns—and a lack thereof—related to diverse body types and needs in the context of exoskeleton design. Our research contributes a novel, promising method for the inclusive design of exoskeletons and to broader discussions on diversity and inclusion in emerging technologies.

Keywords Exoskeletons · Diversity and inclusion · Human-robot interaction · Drawing studies · Intersectionality · Drawing study

1 Introduction and Background

Personal care robots, including service robots and assistive robotic technologies, are being designed to improve the standard of living for a diversity of people. While "personal," these robots and robotic augmentations can be found in various contexts. These technologies offer physically *intimate* embodiments: typically worn on the body and tightly coupled to the user's movements and movement intentions [1, 2]. For example, Slade et al. [2] developed an ankle-based exoskeleton to assist walking in real-world environments, achieving a 9±4% gain over regular walking shoes by modifying the user's ankle angle and velocity. Industrial innovations and advances in brain-machine interfaces (BCI) are now paving the way for even more intimate forms of coupling between machine and user [1]. This merging of robot and human based on trust and bodily synchronicity raises several ethical issues from a user-centred perspective [3–5]. First, such robotic augmentations must cause no harm and prevent harm. Second, they must include a variety of user bodies and embodiments and prevent naive exclusion and discrimination, which is prohibited by law [6]. Furthermore, they must comply with—and perhaps propel—new standards and legal statutes [7].

Yet, ideals and practices often differ. Mismatches between the framing of the robot and *regulations* occur when technology-neutral and restricted to specific cases [8]. Also, the international *standard* on safety requirements for personal care robots (ISO 13482:2014 [9]) lacks safeguards

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for specific categories of users, such as children, pregnant women, and older adults [7]. However, recognizing each person's unique characteristics is essential to ensure optimal functioning, safety, and accessibility [6, 10, 11]. Design choices that do not account for *diversity* in user characteristics may lead to exoskeletons that do not fit their users [11]. We use *diversity factors* to refer to bodily and social characteristics, backgrounds, groups, and identities that are not dominant within a given society and often marginalized, like old age, various disabilities imposed on the mind and body, and a span of gender identities, including women but also "third" and other genders. Here, an *intersectional* lens is also crucial to account for compound experiences that arise where each of these diversity characteristics meet [12–14]. *Intersectionality* is a descriptive framework hailing from the context of American law that explains how power operates at the intersections of multiple social identities [12–14]. For example, discrimination against someone with a marginalized gender identity *and* disability is different and often worse than someone who only has the gender identity or the disability. Power differentials occur along axes of privilege related to each identity as well as their various combinations [13, 14]. We must also critique the assumptions embedded in the motives and eventual designs of such technologies: not only the "who" designed for but also the "why" [15]. Much assistive and interventionist technology relies on normative assumptions of ideal bodies and embodiments that privilege specific perspectives over others, notably deemed experts over end-users [16]. Similarly, a concerted focus is on *expert* perspectives [17]. While common in other areas of human-computer interaction (HCI), *user-centred* and *participatory design practices* are all but scarce from work on exoskeletons [18].

This state of affairs needs to be challenged and rectified. Robotic exoskeletons operate intimately with people's *bodies* [19] and their *embodiment*: the physical presence of the body but also how it interacts with and is implicated in the world and its social context and histories [20]. Ignoring this reality in robot design, test beds, policies, and technical standards may compromise user inclusion and safety because important distinctions exist among people [6]. Exclusion may also occur when facets of bodies and embodiments peripheral to the deemed aims of the exoskeleton are not considered. Exoskeletons may be designed to assist gait but not consider little people's bodies, for example, or integration with the dress of non-Western older adults [10, 21]. Even when different bodies have been considered elsewhere, such as general differences between male and female anatomy for the design of bicycles, these considerations still need to be implemented in exoskeleton design [6]. Indeed, Ármannsdóttir and colleagues [18] concluded that despite consensus among experts on the importance of user-centered approaches in exoskeleton development, standardized frameworks with regard to appropriate testing methods and design approaches are still lacking.

Engineers and designers have the opportunity—and hold power—to shape future user experiences with such technology if they can anticipate these insights and incorporate them into their R&D processes [22]. As yet, only a small number of studies have employed human-centered approaches in exoskeleton design [23, 24] and collected user requirements for specific user groups [25–28]. Indeed, the field of personal robotics, including robotic augmentations and exoskeletons, may draw from the lively history of human-centred computing in HCI [29–32]. Precedent exists, with systematic review work revealing the ability of actual and potential users to provide key design insights [5, 33]. Still, what user-centred work exists is expert-led, and when there is collaborative and co-design work, the collaborators are almost always experts [34]. Design-led efforts on exoskeletons that involve real and potential end-users, including design fictions [35] and design-test-redesign cycles [36], are still nascent.

One potential but underutilized method that can be employed to involve a diversity of users and stakeholders is *drawing study methodology* [37, 38]. Drawing as a methodology originated in the work of Machover [39], who in 1949 explored the potential of sketching to reveal personality factors. While disciplines like early childhood studies [40–43] and psychology have long employed drawing as a research tool [34, 38, 44], the human factors engineering world has been slower to catch on. Still, some work exists. In perhaps the earliest example, [45] demonstrated how drawings could usefully communicate user mental models of interactions. Gerling et al. [46] used drawings to elicit interaction ideas for game design from young people who rely on wheelchairs. Lee et al. [47] asked thirty-one smart speaker users to draw the "body" for the "voice" of the agent, discovering several novel expectations, including non-human embodiments. Similarly, Seaborn et al. [48] surfaced the merits of using drawing study methodology as a manipulation check for "sonic embodiments" by exploring impressions of a novel "older adult" voice assistant. This literature demonstrates the efficacy of drawing study for people of varying ages and abilities. Still, gathering participants—perhaps especially a diversity of participants and participants from specific user groups, who may be unable or unwilling to travel to the lab or reveal their identities—remains particularly understudied. Straka et al. [49] offers one of the only examples of an online drawing study, where they achieved a relatively large sample ($N = 174$). Still, the aim of this work was to develop *generalizable* guidelines for AI companions in a systematic way. In contrast, we aimed to surface the needs and concerns of *specific user* *groups* and *at-risk populations*. We also extended this work by employing supplementary qualitative methods—in a follow-up interview and annotation session—for confirmation of participant intentions and deeper insights that drawings alone cannot supply.

Here, we report on an *online drawing study* [37–39, 44–47, 49] with people of diverse bodies, identitites, and sociodemographic characteristics (e.g., gender, ethnicity), who may belong to overlooked or at-risk user groups. We were guided by recognition of the intimate relationship between exoskeletons and the body and the potential of drawing as a method of user-centred and participatory design visioning. Our goal was to establish the method's efficacy, especially in an online, reduced-risk format, and raise awareness about drawing as a tool for the inclusive design of exoskeletons. We also discovered new design patterns, mental models of embodiment, and insights from people with diverse bodies. We answer the call from the broader area of HCI [12, 50–53] as well as react to rising awareness within the sub-field of human-robot interaction (HRI) [21, 54–56] for exoskeletons. We asked two entwined questions: on the empirical front, ***how do people envision the embodiment of exoskeleton technologies when it comes to body diversity and inclusion? (RQ1)***, and, methodologically, ***are online drawing studies a feasible methodology for enabling this empirical work? (RQ2)*** Our work underscores the importance of individual differences for exoskeleton design. To the best of our knowledge, this study is the first to combine intersectional and co-design perspectives on exoskeletons.

Although initial, this work contributes to (i) raising the awareness of experts by expanding ideas about design approaches, user involvement, exoskeleton use, and diversity within and across user groups, i.e., intersectionality; (ii) generating representative design considerations for use in exoskeleton design practice based on diversity requirements; and (iii) providing evidence on the feasibility and efficacy of qualitative, multi-phased online drawing studies for this purpose. We hope this work will inspire a shift in exoskeleton design practice and research within HCI and HRI.

2 Methods

We conducted a mixed methods online drawing study [38, 45, 47] that included a questionnaire and interview components. The full questionnaire, containing all instruments and created with SurveyMonkey, is available on OSF.[1] Our protocol was approved by an ethics committee (ID #2023077) and preregistered on July 3rd, 2023 at OSF.[2]

2.1 Participants

Thirty people participated in our study. This sample size is in line with previous work within HCI, e.g., $N = 31$ in Lee et al. [47], $N = 42$ in Chan [41], and the $N = 32$ average derived from the thirty-two studies reviewed by Cheung et al. [37]. We recruited participants on Prolific (https://www.prolific.com), an academic participant pool with a rigorous sign-up procedure. We used broad criteria for the diversity factors under study, allowing participants to opt-in and tell us what aspects of their bodies and identities were relevant to exoskeletons. For example, we did not limit "disability" to physical impairments. This allowed us to avoid prescribing what was applicable to exoskeletons. As Table 1 indicates, this approach expanded our understanding of what diversity factors were relevant from a user-centred angle. Our Prolific screening criteria are available in Appendix A (Supplementary Materials). Participants were compensated in accordance with Prolific criteria at £9/hr.

Participants identified along an array of diversity factors (Table 1), with a mean of 2.8 intersections ($SD = 1.3, MD = 2.5, IQR = 2, highest = 6$), e.g., female at birth, non-binary, Black, and lesbian/gay (refer to Fig. 1 and Fig. 2). Participants also reported being drag queens, transmasculine, short, fat, and having "gypsy genes." 12 were aged 18–24, 15 were aged 25–34, two were aged 35–44, and one was aged 45–54. The mean age was 26 ($SD = 4.9, MD = 25$). Most participants had a bachelor's degree ($n = 10$) or some college but no degree ($n = 10$), with five having a graduate degree, four with an associate degree, and one with grade 12. Participants reported a range of occupations: marketing specialists, students, paralegals, developers, retail, medical technologists, social workers, anthropologists, self-employed workers, consultants, and interpreters. Five were managers and ten were unemployed.

Most participants were somewhat technically proficient, according to the affinity for technology interaction (ATI) scale [57] results ($M = 4.0, SD = 0.8, MD = 3.9, IQR = 0.9, range = 1 - 6$), with the lowest being 2.1 and the highest 5.4 (Cronbach's $\alpha = 0.93$). Most ($n = 22$) had never used an exoskeleton. The eight that did use the Lizard, REWALK, a back brace, one for exercise, medical ones, power leg braces, an ankle brace, Harmonic bionics, skates, and a scooter. Activities included walking, experimental tasks, running, desk assistance, walking the dog, caring for animals, and picking up a ball.

[1] https://osf.io/n8492

[2] https://osf.io/3s5tf2

Table 1 Demographics ($N = 30$) with a focus on diversity factors

Factor	Identity	Count
Sex/Gender	woman	13
	non-binary (NB)	13
	man	5
	trans	4
	another: genderfluid, genderqueer	2
	intersex	1
Intersectional Sex/Gender		6
	NB, trans	3
	NB, woman	2
	NB, trans, inter	1
Race/Ethnicity	white	2
	black and/or African	6
	Latino/Hispanic	2
	mixed race	2
	African-American	1
	Chilean	1
	Chontal	1
	Arab	1
Disability	glasses/eye condition	2
	depression	2
	chronic pain/fatigue	2
	heart condition	1
	neurological issues	1
	intersex	1
	unknown	1
	autism	1
	OCD, ADHD, anxiety	1
Sexuality	straight	7
	lesbian	4
	queer	2
	bisexual	1
	vague (in the lgbtqia + community)	1
	pansexual	1
	biromantic and demisexual	1
	asexual	1

2.2 Procedure

There were two sessions. The first was an asynchronous session (about 40 minutes) involving (i) study information and digital consent, (ii) the demographics questionnaire on diversity factors, (iii) the drawing study (instructions are in Appendix C of the Supplementary Materials), and (iv) a post-task questionnaire. Participants were given an introductory video on the drawing process and asked to practice drawing simple flowers (the video is available on OSF[3] with accompanying subtitles[4]). They then completed two drawings: one for **Scenario 1**, where we tasked participants to draw an exoskeleton supporting daily activities (e.g., walking on uneven surfaces, moving furniture, or placing boxes on various heights) and then, based on random assignment, either **Scenario 2 or 3**, in which we prompted participants to sketch an exoskeleton used for rehabilitation purposes or leisure activities, respectively. These scenarios were based on known use of exoskeletons and near-future applications for everyday activities, leisure, and sports. For each scenario, participants were allowed to choose one prompt (refer to Appendix B in the Supplementary Materials for details). We crafted the scenarios (and the prompts, respectively) intending to trigger participants' imagination, reflections, and reactions on how these typical everyday activities and tasks should adapt to diversity and inclusion.

The second synchronous session (about 20 minutes) was a follow-up qualitative interview in which the first author (i) co-annotated the drawings with each participant and (ii) elicited reflections and reactions about the process and personal assistive technologies, specifically exoskeletons. The researcher faithfully captured the exact words of participants and double-checked the wording and content with them before closing the session. Participants were compensated after each session.

2.3 Instruments

We describe the main components of the questionnaire outside of the drawing activity below. For details, refer to the PDF available on OSF.[5]

2.3.1 Demographics Questionnaire

We first asked what best described the participant's sex/gender (woman, man, non-binary, transgender, intersex, prefer not to say, another sex/gender). Participants were then told *"We are recruiting people who are minorities and/or experience social or legal discrimination based on the social identities and characteristics they have. Please review the following list. For each that applies to you, please briefly describe how."* The list included: Origin, Age, Sex/gender, Disability, Sexual orientation, and other characteristics. Participants were then asked about their age group, race/ethnicity, level of education achieved, and occupation. We purposefully included these items before the drawing activity, so as to prime participants into thinking about their identity characteristics while drawing [58].

3 https://osf.io/a2j4v

4 https://osf.io/mjy4x

5 https://osf.io/n8492

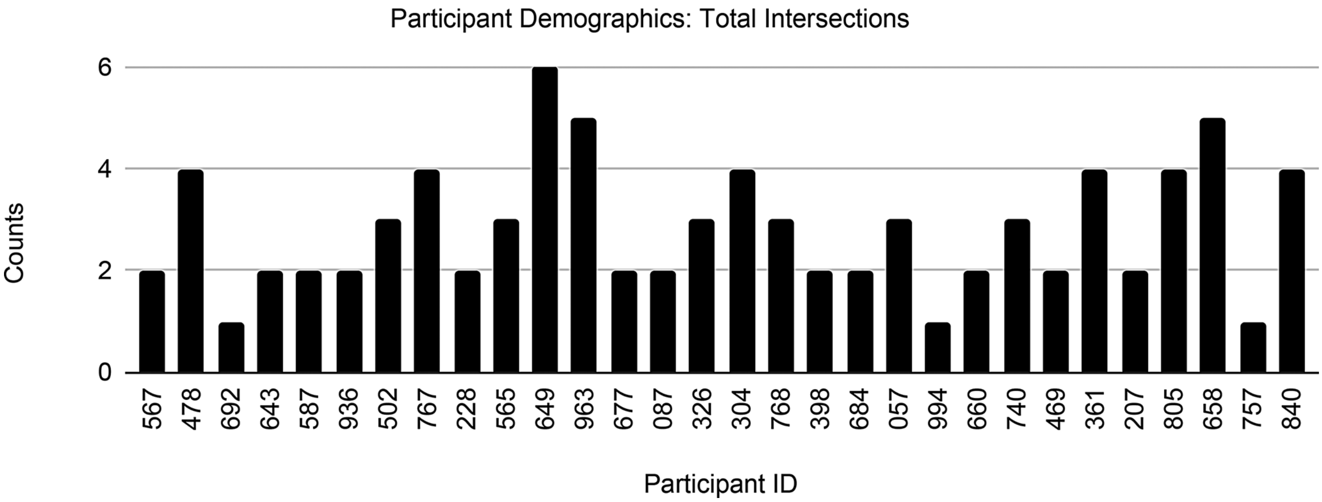


Fig. 1 Counts of intersections across diversity factors by participant ($N = 30$)

2.3.2 Post-Task Questionnaire

Questionnaires can provide individual and contextual insights in drawing studies [37]. Our post-task questionnaire aimed to capture attitudes and knowledge of exoskeletons and related technologies, which may play a role in how participants engaged in the study [57]. As such, we included a validated technology attitudes instrument called the affinity for technology interaction (ATI) scale [57]. Participants were also asked if they had used an exoskeleton before. If so, they were asked how often they used it, the types or names, and the tasks or activities. We placed these items in a post-questionnaire so as to avoid response biases, especially stereotype effects related to technology and certain social characteristics and identities [59].

2.3.3 Semi-Structured Interview

Drawing studies are often supplemented by an interview stage, with semi-structured interview methods recommended [37]. Predetermined questions included general views on assistive technologies and exoskeletons specifically, and experiences of positive and negative discrimination in assistive technology. Our objective was to better understand whether and how the drawings had been created with certain attitudes or experiences in mind, as well as elicit deeper insights that would help the researchers in understanding the drawings better. This is in line with drawing methodologies that are conducted in-person [37–39, 44–47].

2.4 Data Collection and Analysis

Questionnaire data and drawings were collected via SurveyMonkey. Interviews were conducted live on Zoom (with the camera off for anonymity). Descriptive statistics were generated for quantitative data; the ATI was scored according to the instructions. Two authors conducted a deductive thematic analysis [60] of the drawings using a diversity framework [61] contextualized for HRI [55] and participant demographics to identify what aspects of identity were included in the drawings. Given the small sample size, percentage agreement was used [62]. In the case of one disagreement, a third author was brought in. Another author carried out the inductive thematic analysis using affinity diagramming [63] on Miro. For this, the author deeply read the drawings and accompanying them annotations and derived recurrent themes related to the exoskeleton form factor (e.g., arm, full body, external to the body), exoskeleton abilities (e.g., balancing, back support), and the human factors (e.g., face, emotions expressed, ability, diversity factors).

3 Findings

All participants created two drawings each for a total of 60 drawings. All drawings are available on OSF[6], with examples shown in Fig. 3 and Fig. 4. For Scenario 1 (exoskeleton in everyday life), ten chose walking, 17 chose to carry, and three chose to reach and place boxes. 16 were randomly assigned to Scenario 2 (rehab purposes), for which two decided to do rehab, and 14 chose to grab an object. 14 were randomly assigned to Scenario 3 (leisure), split between outdoor activity and dancing.

6 https://osf.io/r6ykn

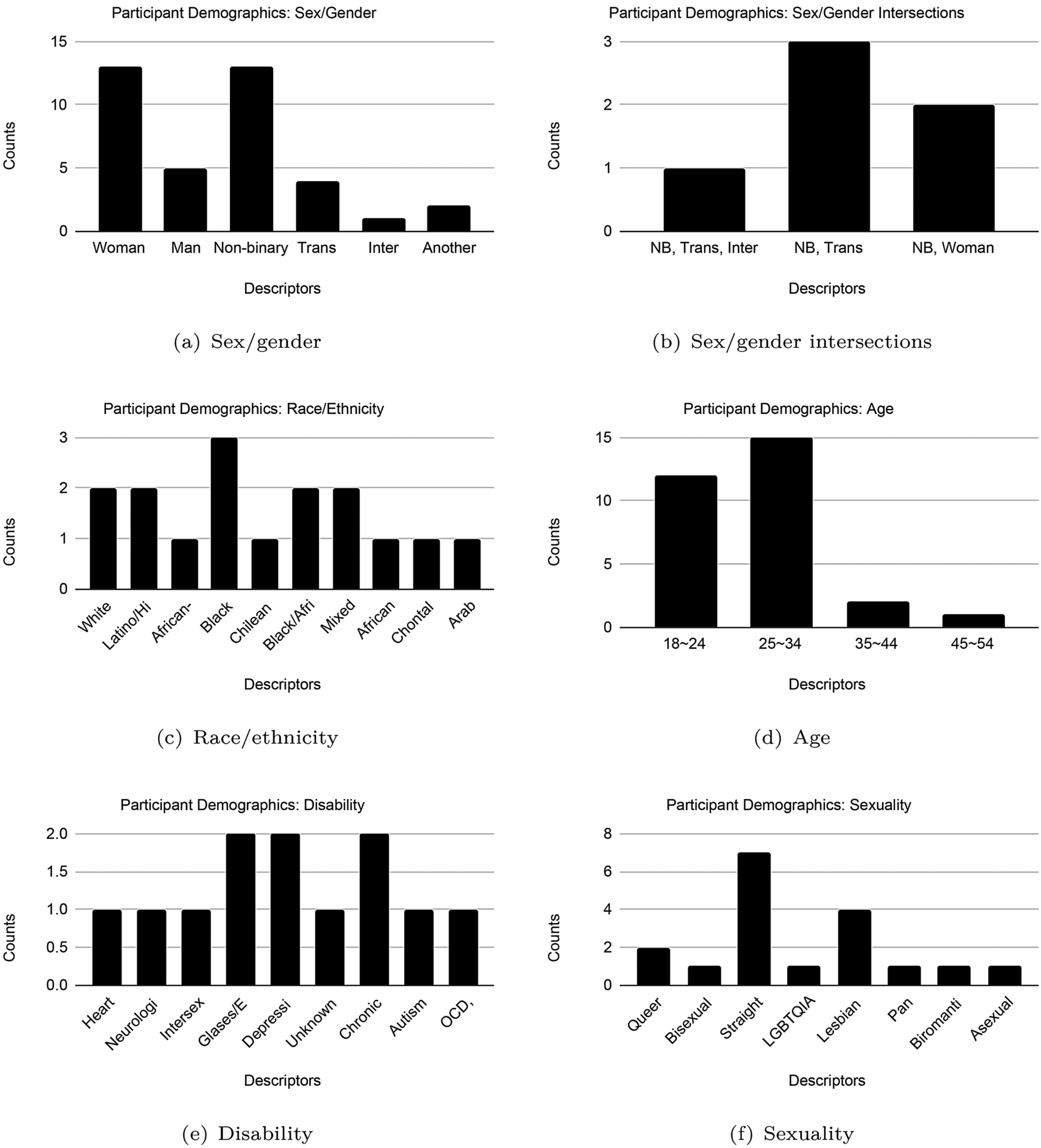


Fig. 2 Demographics ($N = 30$) by sex/gender, race/ethnicity, age, disability, and sexuality

3.1 Drawing in Diversity: Deductive Thematic Analysis

The degree to which diversity was drawn in varied by participant and characteristic (Table 2). Overall, 39 drawings (65%) featured a clear exoskeleton. Origin and sexual orientation were not detectable in any drawing. The most visible characteristic was sex/gender (38 or 63%), then age (20 or 33%), then race/ethnicity (9 or 15%). Disability was only visible in one case. Still, reading in such characteristics can be challenging, even with reported demographics as a guide. A further 18 (30%) for race/ethnicity, 9 (15%) for

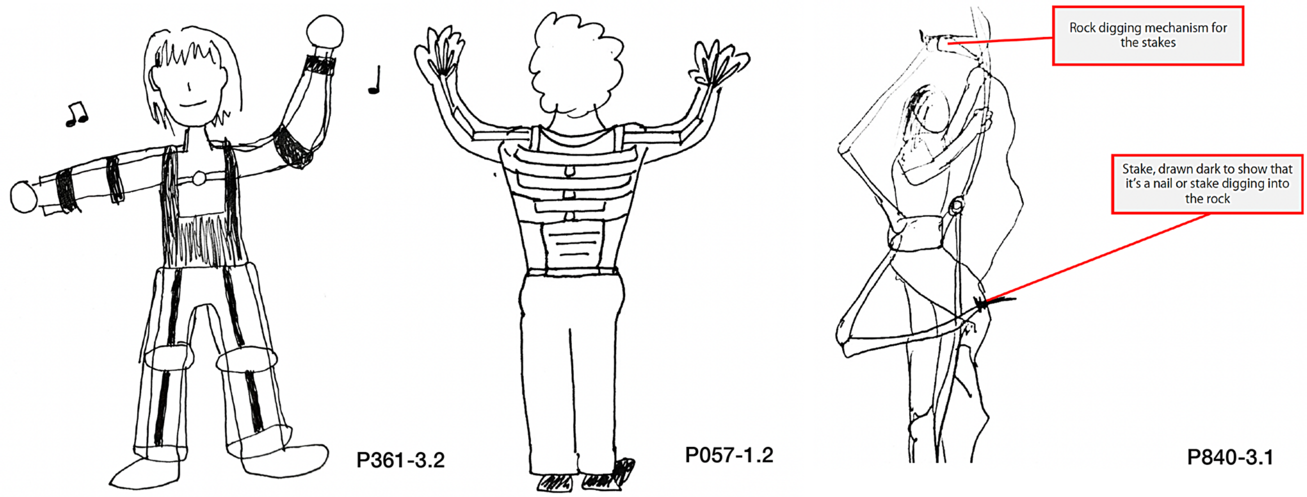


Fig. 3 Examples of exoskeletons and their embodiment drawn by participants. Left: An exoskeleton that aids dancing. Middle: An exoskeleton that provides back support. Right: An exoskeleton that enables climbing of sheer cliffs, notable for the combination of an arachnid structure with a typical pulley system. (Notation used: *ParticipantID-ScenarioID.PromptID)*

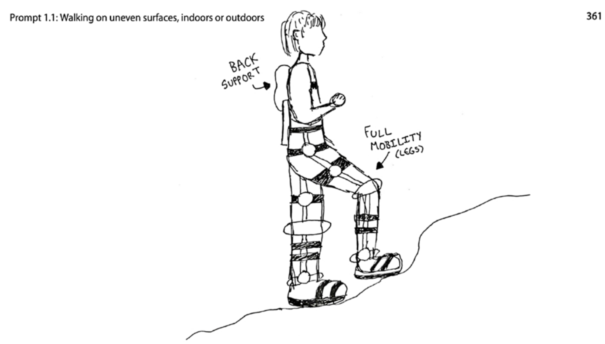
sex/gender, 4 (7%) for each of origin and disability, and 3 (5%) for age were unclear. Only sexual orientation appeared unrepresented or invisible, likely because the tasks did not lend themselves to matters of sexuality. Still, exoskeleton design could be geared (and queered) towards romantic and sexual engagement [64].

We also generated statistics by scenario (Table 3), in case the prompt elicited ideation about certain identity characteristics or intersections. Yet, as Table 3 indicates, scenario did not appear to affect how identity was represented by participants in their drawings. All scenarios show roughly equal ratios of identity characteristics, with over-representation of sex/gender, followed by age and then race/ethnicity. Rehabilitation did not appear to lead to clearer or more frequent representations of disability. Characteristics typically construed as "social identity" factors—sex/gender, race/ethnicity, age, and sexual orientation—had no apparent change in proportions within the leisure and social life scenario compared to the rest. We interpret this to mean that some identity characteristics are more salient than others, regardless of the scenario, activity, and task, including the implied social environment.

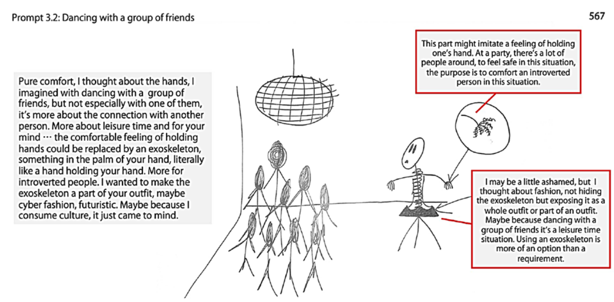
The annotations (26 drawings) indicated that diversity factors guided the drawing process, even when not directly represented. P567, for instance, explained that the hand exoskeleton in drawing 3.2 (refer to Subfigure 4(b)) simulates the experience of holding hands, meant for introverted people and potentially those with social anxiety. In their words: "it could be helpful to reduce anxiety levels. When I extended by views on exoskeletons beyond a workplace (…) then I think [there's] endless options for making one's life easier, on various levels. Mental health, everyday struggles"… At the same time, P565 raised the issue of prescription and generalization. "'Cause people's bodies are different," they explained, "people shouldn't have any say on a[nother] person's exoskeleton". This suggests that diversity is contextual and individual.

Intersectionality was also present, but in a limited way. P087, for instance, explained that her drawing represented being *"a woman of South African descent, meaning that I have a smaller waist and wider hips than most"*, later clarifying that who is meant by "most" is based on self-image and comparisons to general others: *"when I look at other people, that's how I see myself."* Some participants (P567, P502, P565, P684, P757, P840) noted how exoskeletons could level or disrupt social power relations and attitudes. P840 admitted to harbouring ableist thoughts that were corrected by exposure to fiction: "I changed my views from discriminating against this kind of technology (…) [to] how [exoskeletons] could advance humanity and (…) change the way that we perceive ourselves as able-bodied or not." P502 considered exoskeletons a way of avoiding dignity-crossing behaviour from others, sharing: "In family gatherings, when we're working, and everybody just starts doing things for me." Still, we must note that most participants did not explicitly annotate or discuss how multiple factors of diversity intersected in their drawings.

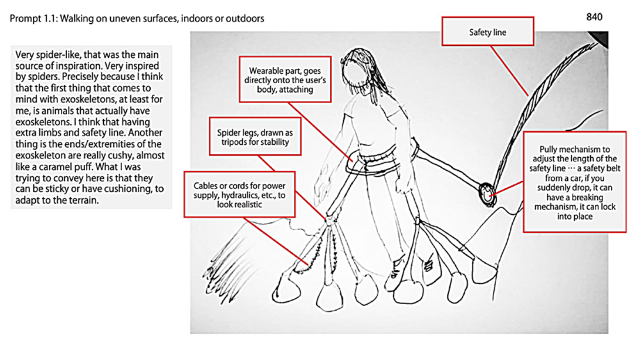
Participants also explored non-humanoid embodiments. While most exoskeletons on the market appear guided by the human form, this does not have to be the case—and may not be desired. P840, for instance, was inspired by arachnid embodiments, presenting an exoskeleton that not only added limbs but arranged them in a way reminiscent of spiders (refer to Subfigure 4(c)). In their second drawing, the embodiment changed to that of one common to spiders: scaling a sheer vertical surface with the aid of arachnid



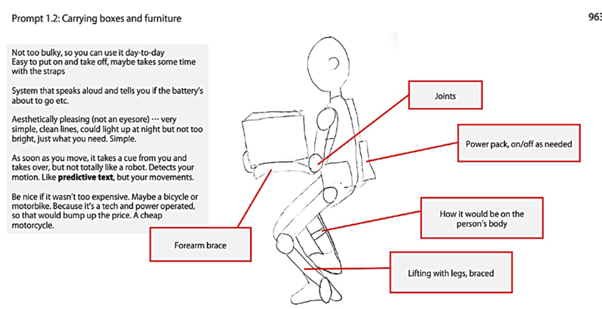
(a) Walking on uneven surfaces (P361-1.1)



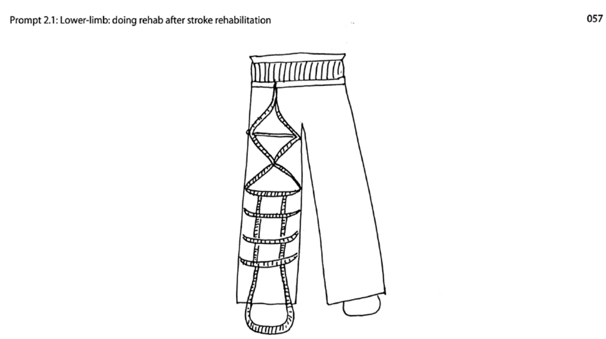
(b) Dancing with a group of friends (P567-3.2)



(c) Walking on uneven surfaces (P840-1.1)



(d) Carrying boxes and furniture (P963-1.2)



(e) Lower limb: Doing rehab after a stroke (P057-2.1)

(f) Reaching and placing boxes at different heights quickly (P478-1.3)

Fig. 4 Examples of the envisioned exoskeletons drawn by participants. (Notation used: *ParticipantID-ScenarioID.PromptID)*

limbs (refer to Fig. 3). At the same time, in that drawing, they described an automated "hammer and nail" system, alluding to non-zoomorphic mechanisms and demonstrating uncanny, perhaps zoomorphic androidism and interspecies harmony. P963 labeled their retractable hand a "claw", notably not a "hand" (refer to Fig. 5). We can take a cue from recent efforts to broaden the range of non-exoskeleton robots too zoomorphic forms and beyond [65, 66].

3.2 Affinities across Factors and Abilities: Inductive Thematic Analysis

The **daily life** drawings (**Scenario 1**) reflect a rich tapestry of perspectives, capturing not only *functionality* but also nuanced considerations on *safety, self-perceptions, and daily tasks*. Some participants reflected on how they perceived their bodies within the context of exoskeleton use. P469-1.2 expressed: *"I am small-built, I'm not tall, and if I wanted to reach something ... I've had cases, for example,*

Table 2 Diversity characteristic representation in drawings from the deductive thematic analysis. (Notation used: D = Drawing. • = Characteristic Absent. ○ = Characteristic Present. Δ = Presence of Characteristic Unclear. n/a = Characteristic Unreported)

PID	Clear Exo.?		Origin		Age		Sex/Gen.		Race/Ethn.		Disability		Sex. Orien.	
	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2
567	○	○	•	•	•	•	○	○	•	•	n/a	n/a	•	•
478	○	○	•	•	•	•	○	○	•	•	•	•	•	•
692	•	•	•	•	○	○	○	○	Δ	Δ	n/a	n/a	•	•
643	•	•	•	•	○	○	○	○	Δ	Δ	n/a	n/a	•	•
587	○	○	•	•	•	•	○	○	Δ	Δ	n/a	n/a	•	•
936	○	○	•	•	n/a	n/a	•	•	•	•	n/a	n/a	n/a	U
502	•	○	•	•	•	•	•	Δ	•	•	n/a	n/a	•	•
767	○	○	•	•	•	•	Δ	Δ	•	•	n/a	n/a	•	•
228	○	○	•	•	•	•	•	•	•	•	n/a	n/a	•	•
565	•	•	•	•	•	•	○	○	•	•	n/a	n/a	•	•
649	○	○	•	•	n/a	n/a	Δ	Δ	•	•	Δ	Δ	•	•
963	○	○	•	•	•	•	○	○	•	•	•	•	•	•
677	○	○	•	•	•	•	•	•	•	•	n/a	n/a	•	•
087	•	•	Δ	Δ	•	•	○	○	○	○	n/a	n/a	•	•
326	•	•	•	•	○	○	Δ	Δ	Δ	•	n/a	n/a	•	•
304	•	○	n/a	n/a	n/a	n/a	○	○	Δ	Δ	•	•	•	•
768	○	○	n/a	n/a	•	•	○	○	n/a	n/a	•	•	n/a	U
398	•	•	Δ	Δ	○	○	•	Δ	Δ	Δ	n/a	n/a	•	•
684	•	•	•	•	○	○	○	○	Δ	•	n/a	n/a	•	•
057	○	○	n/a	n/a	n/a	n/a	○	○	n/a	n/a	Δ	•	•	•
994	•	•	•	•	Δ	•	○	Δ	Δ	•	n/a	n/a	•	•
660	○	○	•	•	•	•	•	•	Δ	•	n/a	n/a	•	•
740	○	○	•	•	•	•	•	•	•	•	n/a	n/a	•	•
469	•	•	•	•	○	○	○	○	○	○	n/a	n/a	•	•
361	○	○	•	•	○	○	○	○	Δ	○	○	Δ	•	•
207	○	○	n/a	n/a	Δ	Δ	○	○	○	○	n/a	n/a	•	•
805	○	•	•	•	○	○	•	○	•	Δ	n/a	n/a	•	•
658	○	○	•	•	n/a	n/a	○	○	•	•	n/a	n/a	•	•
757	○	○	•	•	○	○	○	○	○	○	n/a	n/a	•	•
840	○	○	•	•	○	○	○	○	Δ	Δ	n/a	n/a	•	•

Table 3 Diversity characteristic representation in drawings by scenario from the deductive thematic analysis Counts and percentages relative to the total number of drawings per scenario are presented. (Notation used: D = Drawing. • = Characteristic Absent. ◯ = Characteristic Present. Δ = Presence of Characteristic Unclear. n/a = Characteristic Unreported)

Factor	Scenario 1: Daily Life							
	◯	%	Δ	%	•	%	n/a	%
Origin	0	0%	2	7%	24	80%	4	13%
Age	10	33%	2	7%	13	43%	5	17%
Sex/Gender	19	63%	3	10%	8	27%	0	0%
Race/Ethnicity	4	13%	11	37%	13	43%	2	7%
Disability	1	3%	2	7%	4	13%	23	77%
Sexual Orientation	0	0%	0	0%	28	93%	2	7%
	Scenario 2: Rehabilitation							
	◯	%	Δ	%	•	%	n/a	%
Origin	0	0%	0	0%	13	81%	3	19%
Age	5	31%	1	6%	6	38%	4	25%
Sex/Gender	10	63%	3	19%	3	19%	0	0%
Race/Ethnicity	3	19%	3	19%	9	56%	1	6%
Disability	0	0%	0	0%	4	25%	12	75%
Sexual Orientation	0	0%	0	0%	15	94%	1	6%
	Scenario 3: Leisure & Social Life							
	◯	%	Δ	%	•	%	n/a	%
Origin	0	0%	2	14%	11	79%	1	7%
Age	5	36%	0	0%	8	57%	1	7%
Sex/Gender	9	64%	3	21%	2	14%	0	0%
Race/Ethnicity	2	14%	7	50%	4	29%	1	7%
Disability	0	0%	2	14%	1	7%	11	79%
Sexual Orientation	0	0%	0	0%	13	93%	1	7%

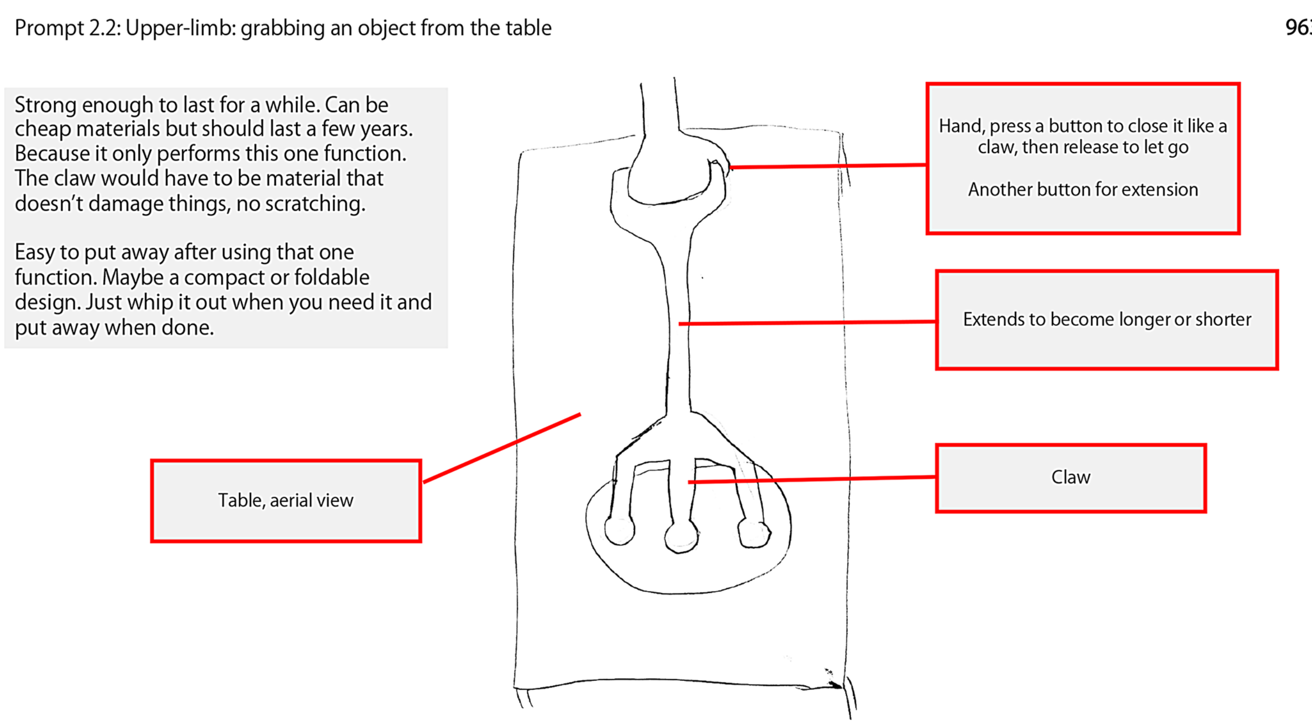


Fig. 5 Grabbing an object from the table (P963)

in a clothing shop where I struggle to reach certain clothing items hanging up because of my height, so maybe if [exoskeletons] were present they would assist in reaching those items for me." These introspections reveal a deeper layer of engagement, contemplations on the impact of one's self-image and physical experience. *Personalization* thus emerged as a key theme. *Safety considerations* were also prominent: back support, safety lines, and protective features (P840-1.1). Participants desired that exoskeletons shield them from external elements, such as protecting their feet while walking or minimizing exposure to loud noises (P684-1.1). This underscores a concern for personal safety and well-being. Some participants drew exoskeletons with wheels (P805-1.1; P658-1.1; P740-1.2). This highlights different perceptions of safety divergence in opinions on the *fun side* of exoskeletons and the *practicality* of walking versus using wheels. Designs featuring upper limbs (P478-1.3; P567-1.2; P936-1.2; P228-1.2; P057-1.2), lower limbs (P649-1.1), and/or full-body exoskeletons (P767-1.2; P963-1.2; P677-1.2; P768-1.2; P361-1.1) indicates diversity when *imagining the self or others* performing mundane daily tasks with an exoskeleton. *Comfort and ease of use* were recurrent themes: with not too bulky, easy to put on and take off, and capable of taking cues from user movements. P660 echoed this, despite concerns about the costs and maintenance of such devices: *"It's more easy to use because it can easily repeat tasks. On the negative side […] they require high power to operate, which is a problem because it's an expense."* The concept of a *predictive system* detecting and responding to user motions without fully taking over from P963-1.2 illustrates an expectation for a more intuitive UX with exoskeletons. At the same time, practical and real-life issues, such as costs, remain.

Scenario 2 centered on exoskeletons for **rehabilitation** purposes. Some participants depicted exoskeletons as *extension tools* rather than direct aids (P740-2.2; 658–2.2; 963–2.2): exoskeletons as accessories that complement rather than directly assist. However, drawings and follow-up interviews revealed that some participants *did not understand the concept of an exoskeleton* (P362-2.2; P469-2.2; 805–2.2). Notably, *rehabilitation settings were not drawn*, but this may relate to lack of experience or exposure. For instance, P469 reflected at the interview: *"I think that assistive technology has a positive impact on us as human beings, especially those not able-bodied, in the sense that they assist with jobs, getting things done, normal day-to-day things."* While participants acknowledged the benefits for rehabilitation, exoskeletons were generally perceived as useful for others, suggesting *a level of detachment* to their own experiences and/or needs.

Scenario 3 explored exoskeletons for **leisure and social life**. Some envisioned dancing with exoskeletons, suggesting an *optimistic view* of these devices as potential aids in social and recreational activities (P361-3.2; P587-3.2; P567-3.2). Others drew exoskeletons *facilitating activities* such as swimming and hiking. This imaginative range across participants renders exoskeletons as *versatile tools* capable of assisting in various situations. A notable commonality was the inclusion of users *smiling* (P994-3.1.; P768-3.1; P684-3.1; P398-3.2.; P587-3.2; P692-3.2). This suggests a general sense of joy and optimism associated with using exoskeletons in leisure and social contexts. Below explore each prompt in more detail.

Participants had *diverse and creative insights* into exoskeletons for **Prompt 3.1**: engaging in outdoor activities. For hiking, participants envisioned an exoskeleton with broad shoes featuring a gripping sole to prevent accidents (P840-3.1; P660-3.1). They incorporated *pertinent details*, like sharp fingernails or supporting mechanisms, e.g., climbing pitons (refer to P840-3.1 in Fig. 3) and broad hands to protect against injuries in case of a fall, offering a *comprehensive safety solution* for outdoor activities. P840 corroborated: *"Not everyone may be a world-class rock climber, for example, but these tools can give you the chance to do more outdoor […] physically demanding activities […] in a safe way."* Only one drawing depicted swimming (P684-3.1). The drawings for **Prompt 3.2** underscore the *significance of dancing in people's lives*. Beyond mere functionality, participants considered fashion, comfort, and personal expression, suggesting a profound connection between dancing and the potential role of exoskeletons. The *intricate details*, from cyber-futuristic aesthetics to the emphasis on joint flexibility for dynamic movements, reflect a desire for practical assistance and a keen awareness of the emotional and social aspects of dancing (refer to P361-3.2 in Fig. 3).

4 Discussion

Participants crafted a rich array of visions featuring "their body" augmented by exoskeletons. From these, we were able to glean insights into the importance of diverse embodiments and identities for exoskeleton design. At the same time, we encountered some barriers and limitations in the online drawing study methodology. Nevertheless, we achieved a baseline level of engagement that produced rich findings, which we discuss first. We also critically examined and later present options for correcting the key issues in methodology for future work.

4.1 Diverse User-Centred Insights on Exoskeletons and Embodiments (RQ1)

The drawings overwhelmingly support the notion that exoskeletons and their users are intimately connected [19]. Crucially, this also includes often overlooked features of embodiment: matters of the physical body embedded within a specific environment and activity, but also the user's social identity and social context [20, 67] (for instance, P469 and P587). Body and identity intersected within and across drawings in unexpected ways. Notably, the scenario, activity, task, and social environment offered by the drawing prompts or brought in from participants' imaginations did not appear to make certain identity characteristics salient over others. Sex/gender, race/ethnicity, and age were the most salient across all conditions and tended to intersect. As socially relevant identity markers [67], even for agentic machines and robotic embodiments [68], these factors had stable representation across individuals, regardless of scenario, imagined use, feelings about the technology, and awareness of having drawn-in such characteristics. Experts should take note: this may be a tacit pattern key to exoskeleton design, one that reveals the eminence of identity characteristics.

The visions crafted by our diverse cohort problematize common assumptions about exoskeleton use, as predicted [10, 15]. Our key takeaway echoes the first challenge posed by Davis et al. [23]: that without user involvement, designers and engineers will miss opportunities for enhancing the fit between exoskeleton and user, and possibly fail to achieve user acceptance [19]. At the same time, participants were not always able to express or articulate their needs and limitations with current exoskeleton technology. As P740 explained: "In my country, both assistive tech and exoskeletons are not quite advanced … I don't think I've ever seen any assistive technology or exoskeletons. Just [in] movies, not anywhere near me, not in my surroundings, no." This contextualizes our key takeaway with an important caveat: visionary experts are still a necessary ingredient. We can add online drawing methodologies to the expert's toolkit alongside game-based methods [24] and brainstorming [46].

Our goal for RQ1 was to show how people envision exoskeletons relative to themselves and their diverse characteristics. Still, from our analysis of the drawings, annotations and follow-up interviews, we can synthesize a high-level set of design opportunities grounded in the diversity requirements of our participants. While not generalizable, these can raise expert awareness and spark ideas on representative considerations for designers and developers of exoskeleton technology.

- **Explore practical methods for enhancing human bodies in activities of the daily living** People may perceive exoskeletons as an extension of their bodies to perform intended tasks, which comprise daily and leisure activities, including dancing, alone or in the company of others (*drawings* P361.3.2; P587.3.2; P567.3.2; P684.3.1; *interviews* P757, P502).
- **Consider the diverse forms and unconventional designs.** Exoskeletons may be visible, invisible, or take on new form factors that may not be solely mechanical, such as a "second skin" or clothing (*drawings* P840.3.1; P660.3.1, P478.1.3; P567.1.2; P936.1.2; P228.1.2; P057.1.2, P649.1.1; *interviews* P469; P840; P207).
- **Account for various cultural and gender expressions.** Exoskeletons should accommodate, if not integrate, social identity characteristics expressed through the body, such as wide hips and height differences or cues to culture and gender, which may not be verbally expressed (*drawings* P087.1.2; P304.1.3; *interviews* P840).
- **Aim for inclusive design.** Disability may inform the functional design while sex/gender, race/ethnicity, and age may inform appearance and/or aesthetics (*interviews* P469; P087).
- **Ensure contextual adaptations.** The context of use of the exoskeletons should be considered in detail. For instance, when climbing, designers could envision integrating supporting mechanisms or features such as the use of pitons or "fingernails" for traversing craggy rocks (*drawings* P361.3.2; P587.3.2; P567.3.2; P840.3.1; P660.3.1).
- **Communicate affect.** People may express emotions or meaning through the facial expressions of depicted exoskeleton users (e.g., most drawings depicted smiles on users, *see* P994.3.1.; P768.3.1; P684.3.1; P398.3.2.; P587.3.2; P692.3.2). Designers could explore the ways of expressing emotional needs of exoskeleton users.

4.2 Online Drawing Studies: Merits and Limitations (RQ2)

Online drawing studies as an inclusive method for engaging actual and potential end-users has not been done for exoskeletons. Here, we endeavored to digitize the drawing study methodology, a novel approach but risky. While all of our participants were able to produce drawings, several were not on task. The interviews suggested that some people did not understand what an exoskeleton was, conflating the concept with their own bodily skeleton. This may be a feature of this topic and terminology–"exoskeletons" is a special term—rather than digital drawing method itself.

We included online interviews as a complementary method to the drawing study approach. Our goal was to confirm our understanding of the drawings, as well as provide contextual annotations from the illustrators themselves. On this front, we encountered both great success and a bit of failure. Less than half of the illustrators participated in the interview. This meant that we had to rely solely on the illustrations. Participants were not professional illustrators, and drawing ability likely played a role in the degree to which they could accurately represent their ideas. Reflecting on the interviews conducted, we could have overlooked key insights and even potentially misunderstood aspects of the exoskeletons and embodiment. Moreover, we had no way to gain access to crucial elements *not* drawn, but which may have guided how people represented (or did not represent) their bodies and identities in the drawings. Perhaps most crucially, we are apprehensive of our understanding and interpretation of the *intersectional* qualities depicted, as well as latent intersections that only the participant could confirm. Reflexively, we acknowledge that we, as researchers who interpreted these drawings without the full participation of those who drew them (despite our best efforts) is an act of power [69] and subject to bias. (However, we have tried our best to resolve any ambiguity and come to an agreement during our data interpretation meetings within the team.) This is the main reason why we separated the drawings of those who were not interviewed from the rest.

On the positive side, we discovered that annotations were truly crucial for understanding the full set of drawings. While almost two-thirds of the drawings showed clear and interpretable exoskeletons, that still left nearly one-third in a state of ambiguity. We attribute this state of affairs in part to the complexity of the "exoskeleton" concept for laypeople. Researchers could choose a drawing method-only study with a large sample size (like Straka et al. [49]) and accept a certain level of ambiguity, given time or funding constraints, or in consideration of participant burden. Still, our prediction that an interview and annotation activity would be ideal was confirmed. We strongly recommend that future work take a combined drawing study and interview plus annotation approach, when possible. Doing this, as we have shown, can:

- Ensure understanding of what was represented in the drawings on our side
- Discover areas of importance in the drawings that may not be clear to us
- Add detail and make transparent any histories, values, assumptions, and tacit information that guided the drawing process
- Provide an opportunity for self-reflection and add-ons by the participant
- Allow the drawings to act as an anchor or prompt during the interview stage

We must also consider the online environment. When participants understood the instructions and engaged fully, i.e., joined the drawing study and interview phases, it was a success. We raise two points of concern, however. Some participants joined both phases but did not understand the instructions, especially, as mentioned, what an "exoskeleton" was. We recommend an attention or comprehension check prior to the drawing phase. This could take the form of a pre-survey or, if others use Prolific, a DM wherein the participant confirms their understanding of these key concepts. Other participants did not join the interview phase. One way around this is to make compensation contingent upon joining both phases. However, ethics boards may not support this approach, and participants may still drop out or be unable to participate in both phases for a variety of reasons, e.g., travel, illness, sudden regional conflicts, etc. Another option is to consider a hybrid approach. The drawing phase could be conducted synchronously, such as over video conferencing, e.g., Zoom, Skype, Jitsi, etc. If live engagement is difficult, the interview and annotation activities could be presented in a survey format and interactive board, e.g., Miro or Google Sheets. We point out that there is tremendous opportunity for the research and design communities to innovate here for the sake of accessibility and research quality.

Finally, we recommend that those seeking explicitly intersectional insights be direct in asking participants for this perspective. It was not enough to prime participants by asking about their demographics in advance of the drawing activity. We also did not directly address intersectionality in our interview or annotation methodology. Yet, some participants spoke to multiple facets of diversity in how they drew themselves and their exoskeletons; our deductive thematic analysis of the drawings also made plain that several aspects of diversity were present in each drawing, if not co-located in specific features of the body or exoskeleton. There is great opportunity here for future work to prompt participants with specific reference to whether and how these factors intersected in terms of access, comfort, and power.

4.2.1 Limitations

We acknowledge several limitations. Our sample size reflects that of many drawing studies [37] and was sufficient for answering our RQs. Still, work aiming at a generalizable set of systematically-derived criteria for exoskeleton design should follow Straka et al. [49] in running a larger-scale study. There was also a slight age bias in our sample, with the majority younger than 35 and none within the "older adult" age range of 65 and above. Future work will need to consider whether and how online methods and recruitment pools can be deployed to include a wider and older cohort.

We pilot-tested the procedure in-lab with people who have technical competence and basic awareness of exoskeletons. Terms like "body suit" may have been understandable to the pilot testers, but not necessarily the broader public. This may help explain some of the confusion we reported on. Future efforts should conduct rigorous pilot-testing of the procedure with laypeople.

Finally, we did not have a controlled comparison to show whether and to what degree drawings are ideal. Future work could empirically examine this point by comparing drawing-only and interview-only groups. Additionally, a participatory-style approach as in Gerling et al. [46] could be explored virtually, with participants directing illustrators in the design of their exoskeletons through a synchronous platform like Zoom, Skype, Jitsi, Microsoft Teams, or another video-enabled platform.

5 Conclusion

Online drawing studies can be a powerful tool for involving diverse end-users in the design of exoskeletons. Challenges remain, but we have shown baseline feasibility through a multi-phased approach involving interviews and annotations. Our findings raise the issue of diversity and intersectionality for experts in robotics and HRI. Our initial insights and considerations, while tailored to our relatively small and heterogeneous cohort, demonstrate the value and possibilities that a wealth of visualized mental models on exoskeletons from underrepresented populations can bring to bear, as well as opportunities for realizing these co-designed visions.

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Data Availability The drawings generated by participants are available on OSF at https://osf.io/r6ykn.

Declarations

Competing Interests The authors have no other financial or non-financial interests to declare.

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