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RESEARCH ARTICLE

A user-inspired mobility experience of the future: a qualitative investigation

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ABSTRACT

Wheelchair users (WCUs) face additional challenges than non-WCU to multi-tasking (i.e. open doors, cook, use a cell-phone) while navigating their environments. While assistive devices have attempted to provide WCUs with mobility solutions that enable multi-tasking capabilities, current devices have been developed without the input of end-users and have proven to be non-usable. More balanced approaches that integrate the end-users' voices may improve current assistive technology usability trends. This study sought to empathically understand the lived experience of WCUs, their needs towards a mobility device, and their perceptions towards hands-free mobility. Full-time WCUs and care providers participated in semi-structured interviews examining wheelchair use and perceptions towards current and future mobility devices. Thematic analysis was used to analyze interview data. 9 WCUs (aged 32.1 ± 7.0 years; wheelchair experience 17.9 ± 11.6 years) and five care providers (years caring for WCU 3.75 ± 0.96 years) participated in the study. The most common disability type was spinal cord injury (WCUs: $n = 3$; care providers: $n = 3$). Qualitative analysis revealed four key themes: (1) Current wheelchair usage, (2) WCU and care provider perspectives, (3) Future wheelchair, and (4) Hands-free wheelchair. Accordingly, participants desire bespoke, light-weight mobility devices that can through tight spaces, access uneven terrain, and free the hands during navigation. This study provides meaningful insight into the needs of WCUs and care providers that assistive technology innovators can use to develop more usable assistive technologies. Amongst study participants, the concept of a hands-free mobility device appears to be usable and desirable.

IMPLICATIONS FOR REHABILITATION

- Integrating end-users' voices into the development of assistive technology may improve current usability trends
- Wheelchair users desire access to their hands and the ability to multi-task while navigating their wheelchairs
- The development of a hands-free mobility device may profoundly improve the quality of life of wheelchair users.

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Introduction

Daily wheelchair use is increasing and yet the design of the chair is relatively similar to the patent for a "hand driven" chair from over 150 years ago [1]. In the US, over 3.6 million people use a wheelchair daily to navigate their environment [2], a number expected to increase as the population over the age of 65 continues to rise [3]. For an individual with a mobility impairment, a wheelchair may be critical to fully participating in society and living a high-quality life [4]. However, even though wheelchairs remove many barriers for accessing the environment and performing activities of daily living (ADLs), wheelchair users (WCUs) still report many limitations with using a wheelchair to participate in the community [5].

There are two commercially available wheelchairs to the general population: manual wheelchairs (MWCs) and powered wheelchairs (PWCs). MWC are typically light-weight and bespoke to the body [6, 7]. However, the stereotypical movement patterns of MWC propulsion are inefficient and may lead to upper extremity soft tissue injury over time [8]. During a single day, MWC users may accumulate over one mile of upper body propulsive-related movements to perform ADLs [9], which may contribute to chronic upper limb fatigue and chronic soft tissue pathology [10]. Currently, over 70% of manual WCUs experience upper extremity pain and injury [11–14]. Due to this risk for shoulder pain and injury, a manual WCU may switch to a PWC for daily mobility needs. However, PWCs are bulky and heavy, making them difficult to fit into tight spaces and transport independently [15].

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MWC and PWC also require the use of one's hands to navigate the environment (i.e. manual propulsion or joystick operation), which limits the ability to multitask while moving [16]. This inability to multitask while moving likely detracts from a WCU's quality of life, creating difficulty when opening doors, cooking, or holding a loved one's hand while moving. Research has begun exploring ways to create a hands-free mobility experience for WCUs where they can engage in tasks not associated with propulsion while moving [17]. Impressive work has emerged integrating voice command and eye and head movements into a hands-free navigation experience for WCUs [18, 19]; however, these devices in their current state appear conspicuous and detractive from a WCU's desire to blend in with their environment [20, 21]. Thus, these devices may struggle to gain long-term adoption amongst WCUs.

To maximize the quality of life of WCUs, it is time to explore novel technologies that enhance this population's mobility experience. Examining the literature on novel mobility experiences and assistive technology development suggests that current devices are too niche and not developed alongside users with disabilities, causing them to be non-usable following product uptake [17, 22]. WCUs report difficulties with accessing usable assistive technology and experience high rates of assistive technology abandonment following initial product uptake [22].

More balanced approaches that effectively integrate the end-users' voices may improve current assistive technology trends [23]. In clinical populations, the integration of end-user experiences and insights has led to the development of novel usable assistive technologies [23–25]. To improve the usability of future assistive technologies, this study examined the lived experiences of WCUs to understand their desires and needs for a novel mobility device. Researchers interviewed WCUs and care providers to evaluate their needs and perceptions toward mobility devices. Additionally, researchers assessed WCUs' perception of a hands-free mobility device to gain insight into its viability as a long-term mobility solution for this population. Insight from participants may be helpful for developing future hands-free mobility device.

Methods

This qualitative research study was conducted between January 2022 and December 2022. All procedures of the study were approved by the Institutional Review Board at the University of Illinois at Urbana-Champaign. Participants were recruited through the posting of social media posts on the internet and through word of mouth. If participants expressed interest, a research assistant screened them for inclusion. To participate in the study, participants needed to be (1) over 18 years of age, and (2) able to understand/read English. Additionally, if an individual used a mobility device, they needed to (1) use a MWC or PWC for at least 75% of their mobility needs and (2) have used a mobility device for at least one year. For an individual to participate as a care provider, the individual needed to provide care for a WCU for at least 320 h.

After obtaining written informed consent and agreeing to have the interview recorded, a face-to-face semi-structured interview was conducted online over Zoom (Zoom, USA) by a member of the research team (M.S) with each participant. First, M.S. asked participants questions related to their demographic information. Next, questions were asked regarding the participant's use of their wheelchair, perceptions towards their current wheelchair, and perceptions towards future wheelchairs. Questions were specifically asked about participants' perceptions towards a hands-free wheelchair. The interviewer explained to the participants that the hands-free wheelchair would utilize a torso-dynamics system and use intuitive upper body movements to navigate a wheelchair rather than the use of one's hands in current manual or powered wheelchair designs. These questions were similar for care providers but tailored to their experience and their perception of wheelchair use by the WCU that they cared for. Follow-up questions were asked to clarify various points and items of discussion. Audio and visual information from the interviews were recorded *via* Zoom and transcribed verbatim by a research assistant, K.H. During the interviews, notes were taken by M.S. to assist in the transcription recording when dialogue was inaudible to the transcriber. Table 1 provides a listing of all questions asked to participants. Each interview lasted approximately one hour. Participants were compensated $25.00 for their time.

Data analysis

When applicable, demographic information was characterized using SPSS version 28.0 (SPSS Inc, USA). Demographic characteristics such as age, years with disability, and wheelchair experience were reported as mean ± SD.

Thematic analysis was used to analyze interview data [26]. Co-authors, D.M. and J.P. were trained in qualitative data collection and trained all research assistants to ensure that best-practices in thematic analysis were conducted throughout qualitative data collection and analysis procedures. Interviews were transcribed verbatim by a research assistant, K.H. Once all interviews were transcribed, J.P. and a research assistant, M.C., individually coded the interviews to explore common themes [27]. To code interviews, J.P. and M.C. generated themes based on the transcription data with accompanying subthemes, code, and subcodes to further elaborate on the data. J.P. and M.C. met weekly to compare and discuss the key themes, subthemes, codes, and subcodes and reach a consensus for the development of a codebook. All final coded interviews were reviewed by D.M. for bias and discrepancies. Following, D.M.'s analysis, a codebook was developed regarding the qualitative data's key themes, subthemes, and codes and subcodes.

Results

Participants

A total of 14 participants participated in the study. Nine participants (4 females: 5 males) were full-time manual WCUs living with a variety of mobility impairments; five participants (2 females: 3 males) were full-time care providers for a WCU. Across the sample of WCUs mean age was 32.1 ± 7.0 years, years with disability was 22.9 ± 12.4 years, and wheelchair experience was 17.9 ± 11.6 years. Disability types varied across the sample of WCUs and included spinal cord injury ($n = 3$), spina bifida ($n = 1$), cerebral palsy ($n = 1$), and lower limb fractures ($n = 1$). Three participants did not feel comfortable providing disability-related information to researchers. Across the care providers, disability types of the WCUs cared for primarily consisted of people with spinal cord injuries ($n = 3$). Two care providers did not feel comfortable providing disability-related information about the WCU. Full details on demographics, wheelchair use, and functional status information can be found in Tables 2 and 3.

Thematic analysis results

Four key themes were identified from the interview data of the manual WCUs and care providers: (1) Current Wheelchair Usage, (2) Wheelchair user and care provider perspectives, (3) Future Wheelchair, and (4) Hands-free Wheelchair.

Table 1. Semi-structured interview questions for WCUs and care provider.

1. How old are you?
2. What gender do you identify as?
3. What is your occupation?
4. Can you tell us about your disability?/Can you tell us about the disability of the individual that you care for?
5. How long have you used a wheelchair as your primary method of mobility?/How long has the WCU you care for been using a wheelchair?
6. What is your living situation right now?
7. What sort of impacts has your wheelchair had on your living space?/What sort of impacts has the WCU's wheelchair had their living space?
8. How many people do you know that use a wheelchair as their primary method of mobility?
9. If you could buy any wheelchair without monetary constraints, what would you get?
10. What are five words that describe your current experience using a wheelchair? What are five words that describe how you want your experience using a wheelchair to be?/What are five words to describe your current experience caring for a WCU? What are five words that describe how you their experience to be in the wheelchair?
11. Are there any experiences that you feel you miss out on because you use a wheelchair?/Are there any experiences that you feel you miss out on or the WCU misses out on because of the use of a wheelchair?
12. Are there any experiences using a wheelchair that you would never miss?
13. How many times a day do you typically transfer to an automobile?/How many times a day does the WCU typically transfer to an automobile?
14. What are three places that you most commonly use your wheelchair?/What are three places that the wheelchair user most commonly uses their wheelchair?
15. What are three places that you would like to use your wheelchair but are currently unable to?/What are three places that the WCU would like to use their wheelchair, but current cannot?
16. Can you recall a time you were frustrated with your (the) wheelchair?
17. Have you ever been surprised by the way people treat you when using your wheelchair?/Have you ever been surprised by the way people treat you or the WCU when in public together?
18. What are the best aspects of your current everyday wheelchair that we should consider in our design?
19. How did you choose the chair you currently use?/How did the WCU choose the chair they currently use?
20. Why don't you use your previous wheelchairs anymore?/Why doesn't the WCU use their previous wheelchair anymore?
21. What modifications or personalization, if any, have you (they) made to your (their) current wheelchair?
22. What, if any, are the benefits you see to using a manual chair rather than a fully powered or push-assisted system?
23. Would you use a PWC or electronic assist? Why or why not?/Would the MWC use a PWC or electronic assist?
24. What is more important to you in a manual wheelchair: safety or functionality?
25. For a daily wheelchair, would you prefer one that (1) weighed 40 pounds more but allowed easy access to grass, rocks, and snow or (2) weighed less than 10 pounds but could only navigate paved roads?
26. How do you feel about an everyday wheelchair with the following features?
    1. Hands-free movement
    2. Self-balancing
    3. Navigation over rough terrain
    4. Obstacle detection
    5. Self-navigation
    6. Motion controls
    7. Remote operation
27. How do you envision a hands-free wheelchair affecting everyday life?
28. What are the top three safety features that you would consider critical for a hands-free wheelchair?

Table 2. Wheelchair user demographic characteristics.

ID	Sex	Age (y)	Disability type	Years with disability	Wheelchair experience	Primary wheelchair type	Occupation
1	F	35	Cerebral palsy	35	30	Manual	Chef
2	F	30	NR – acquired disability	10	10	Manual	Caterer
3	M	33	NR – congenital disability	33	20	Manual	Seamstress
4	M	30	NR – acquired disability	26	10	Manual	Teacher
5	M	29	Lower limb fractures	7	7	Manual	Graphic designer
6	M	24	Spinal cord injury Level: NR AIS: NR	8	8	Manual	Marketing
7	M	49	Spinal cord injury Level: NR AIS: NR	40	39	Manual	Unemployed
8	F	28	Spina Bifida	28	NR	Manual	Disability specialist
9	F	31	Spinal cord injury Level: T5-T10 AIS: B	19	19	Manual	Marketing

M = male; F = female; y = years; WCU = wheelchair user; NR = not reported; AIS: Asia Impairment Scale.

Current wheelchair usage

This key theme was developed based on the responses to questions 5, 10, 11, 12, 13, 14, 15, 16, 21 from Table 1, which related to their current wheelchair usage. Participants were asked to discuss aspects related to this theme with follow-up questions to further clarify the participants' responses. From the participants' responses, five main subthemes emerged: (1) Fit, (2) Modifications, (3) Public Environment, (4) Future Environment, and (5) Difficulties. Table 4 presents the subthemes and codes that related to each participant's current wheelchair use.

Table 3. Care provider demographic characteristics.

ID	Sex	Age (y)	WCU's disability type	WCU's years with disability	Years caring for WCU	Occupation
10	F	28	Spinal Cord Injury	5	5	Cashier
11	M	20	Spinal Cord Injury	3	3	Student
12	M	35	Spinal Cord Injury	19	4	Laborer
13	F	21	NR	3	3	Unemployed
14	M	39	NR	NR	NR	Teacher

M = male; F = female; y = years; WCU = wheelchair user; NR = Not reported.

Table 4. Themes, subthemes, and codes related to WCUs and caregivers' perceptions regarding one's current wheelchair usage.

Current wheelchair usage		
Subtheme	Code	Subcode
Fit	Heavy	
	Light	
	Bespoke	
	Comfortable	
Modifications	Upholstery	
	Proper storage	
	Remove brakes	
Public environment	Grocery stores	
	Church	
	Outdoor recreation/ exercise	
Future environments	Outdoors	National monuments
		Beach/sand
		Yard/garden
		Snow
Difficulties	Propulsion	Dirty hands
		Body pain
	Activities of daily living	Preparing food
		Cleaning
		Occupation
		Carrying objects
	Walking dog	
	Scuffing environment	
	Falling	
	Chair maintenance	

Fit

Nearly all participants discussed the overall fit and weight of their current wheelchair. A greater proportion of participants perceived their wheelchair was heavy:

> "(It's) Extremely important [regarding the importance of a wheelchair's weight]. **We switched from a 35lb chair to a 55lb chair**, and **it made it a lot more difficult, particularly with inclines**. The more weight there is, the more **it tires her out throughout the day**" (Participant 12).

Nonetheless, most participants felt positively about their current fit, describing it as bespoke and/or comfortable. For individuals that expressed a poorly fitted design, they expressed issues of pain and discomfort because of using the poorly fitted chair.

Modifications

Four participants discussed modifications that were made to their manual wheelchair to better meet their needs. The most common modifications related to improving the wheelchair's overall storage capacity:

> "I put in a little (customization) under the seat storage area…they're like a little sling with a board under it to keep a sort of level bottom to it. I've had those on my chairs for like 15 or 20 years or so, they're just so useful that I won't go without them." (Participant 7)

Public environments

Outside of the home, participants discussed several environments where they use their wheelchairs such as the grocery store and church. Participants also discussed using their wheelchair for outdoor recreation like exercising and attending concerts.

> "[When asked about the most common places the individual uses their wheelchair] At home, at work, (and) for recreation like to go play basketball or go see a concert" (Participant 10)

Future environments

Participants desired access to more outdoor activities. In their wheelchair system, participants explained that they were unable to fully access national monuments and landmarks, beaches, backyards, and snow-related activities. Specifically, one participant discussed her desire to access her backyard:

> **"**We have this beautiful yard, we have an acre of land that we picked out specifically because it had space and room, and we get to use so little of it**. It drives me nuts that I can't push around the house to check for problems with foundation**." (Participant 8)

Difficulties

Participants discussed numerous difficulties to life as a WCU. Wheelchairs can be complex, human-engineered systems that require proper maintenance for an optimal user experience. Participants discussed difficulties in maintaining their chair to keep it rolling smoothly and to maximize mobility. Participants also discussed the fatigue associated with chronic wheelchair propulsion and incidences of falling out of the wheelchair. The most common propulsion-related issue related to the dirty hands associated with chronic manual wheelchair propulsion.

> "I cannot keep my hands clean for love or money when going for a walk…it looks like I've murdered a carburetor every time I come home from a walk…" (Participant 7)

Two participants discussed difficulties with walking their dogs. Notably, performing activities of daily living (ADLs) presented the most common difficulties for WCUs. In total, six participants discussed difficulties performing ADLs like bathing, cooking, and carrying objects.

Wheelchair user and care provider perspectives

This key theme was developed based on the responses to questions 7, 10, 11, 12, 15, 17, 19, 22, 23, 25 from Table 1, which related to the participants' perspectives towards wheelchairs, disability, and the environment. From these questions, several subthemes emerged: (1) perceptions towards wheelchairs, (2) benefits of manual wheelchairs, (3) benefits of power wheelchairs, and (4) inaccessible environments. See Table 5 for a full representation of emerging subthemes and codes regarding wheelchair user and care provider perspectives.

Perceptions towards wheelchairs

Participants discussed aspects related to accessibility, wheelchair-related costs, and stress. Three participants felt that having a wheelchair increased their access; however, the majority believed that wheelchairs limited their ability to engage with their

environment and peers. Ten participants found wheelchair use to be stressful with participants expressing feelings of negative stigma and being misunderstood by their peers:

> "People don't understand wheelchair users, or seeing a wheelchair user, they don't know how to walk around us, or they walk really slow, people walk slow." (Participant 10)

Benefits of manual wheelchair

Participants discussed the benefits of using MWCs. Two participants liked the lightweight components of MWCs; others felt MWCs were the cheapest option for mobility devices. Participants expressed that MWCs enabled them to function better within their environment. One participant noted:

> "But in the end, it's largely a practical thing. In terms of like a manual versus a full power chair, it's just simply weight and easy transport ability. We would have to get a van if I was using a power chair….my general philosophy with chair stuff is often that **the more complicated you make something, the easier it is to break, and the harder it is to maintain it**. (Participant 7)

Benefits of power wheelchair

Five participants discussed the benefits of a power wheelchair with most stating that they would use a power wheelchair if provided one. Participants believed that PWC increased function related to handling the wheelchair or gaining access to environments. One participant stated:

> "So, I have that power wheelchair, and **I can raise to about eye-level of typical people**. And so, using **that I learned that to get a little bit higher when you're trying to get a full bag of trash out is amazing**. I can take three bags for starters, and I am not worried about ripping it on the floor" (Participant 9)

Inaccessible environments

Participant discussed environments that were currently unavailable to them as a WCU. Regarding their environment, most participants discussed accessibility issues with the wheelchair-ground interface. Outdoor activities in nature or precipitation made wheelchair propulsion unfeasible. Issues with sidewalk surfaces or the resistance and friction from carpeted areas served as a barrier for participation, too.

> "I find that walking around town as much as I do…I'll find that I sort of end up drifting into fairly predictable patterns…I tend to do it (propulsion) along this street, as opposed to one of these others. And sometimes I'll realize I'm doing that, and think like, **why don't I try this other street?** Then I try it and I realize, oh, **it's because the curb cuts suck or they don't exist here** or **the sidewalk** is fine, but **it's slanted** in such a way that it's more of a chore to use that space." (Participant 7)

Participants also discussed being barred from environments that were above ground level if an elevator or ramp was not present in the building. Accessibility issues in restaurants also emerged as a recurring theme among participants.

Future wheelchair

This key theme was developed based on the responses to questions 15, 18, 21, 24, 25 from Table 1, which related to how participants would design a new wheelchair to best meet their needs and also address difficulties that emerged from theme "Current Wheelchair Use" (Questions 5, 10, 11, 12, 13, 14, 15, 16, 21). Several subthemes emerged regarding wheelchair: (1) Size, (2) Preference, and (3) Specification. Full description of subthemes and codes can be found in Table 6.

Size

Nearly all participants expressed the need for a minimal design. Participants desired a lightweight, low-profile wheelchair.

> "When the door is narrow, it's actually too small for the wheelchair to pass through, **if there's a wheelchair to be adjusted and reduced, just enough to pass through barriers**, it would help as well, **take care of that accessibility barrier**." (Participant 13)

Preference

Nearly all participants prioritized functionality and safety in the design in their future wheelchair. Participants stated concerns with developing skin injuries (i.e. pressure ulcers) and fall-related injuries. The wheelchair should be fitted properly to avoid skin injuries while also being low to the ground and equipped with anti-tip technology and speed governors to avoid injurious falls when propelling. Due to the long durations spent in the

Table 5. Themes, subthemes, and codes related to WCUs and caregivers' perceptions towards wheelchairs, disability, and the environment.

Wheelchair user/caregiver perceptions		
Subtheme	Code	Subcode
Wheelchair-related	Accessibility	Freedom/independence
	Limiting	
	Cost	Expensive
	Stressful	Mental health
	Negative stigma /misunderstood	
	Functionality	Reliability
	Weight	Handling
	Physical activity	Less complex
	Costs	
Benefits of PWC	Functional	Handling
	Lift	
	Would use a PWC	
Inaccessible environment	Wheelchair-surface	Carpeted areas
	Weather/nature	Sidewalks
	Interface	Lack of ramps
	Restaurants	
	No elevators/ramps	

Table 6. Themes, subthemes, and codes related to the future wheelchair.

Future wheelchair		
Subtheme	Code	Subcode
Size	Minimal	Low profile
		Lightweight
Preference	Functionality	Maneuverability
	Safety	Proper suspension
		Anti-tip
		Speed governor
		Low to ground
	Comfort	Skin health
Specification	Accessories	Cup/phone holder
		Seatbelt
		Cargo room
	Hydraulic lift	
	Hands-free	
	Outdoor terrain	
	Access stairs	

Table 7. Themes, subthemes, and codes related to a hands-free wheelchair.

Hands-free wheelchair		
Subtheme	Relative code	Subcode
Overall perception	Positive	Multi-tasking
		Greater access
	Negative	Loss of physical activity
		Skepticism/fantasy/sci-fi
Perception self-balancing	Positive	Increased handling
		Anti-tip
	Inaccessible	Trunk function
Perception of accessing uneven terrain	Positive	Revolutionary
	Skepticism	Safety
Perception of sensor detection	Positive	Safety in low lighting
Perception of self-navigation	Fantasy/sci-fi/skepticism	
	Positive	
Additional specification	Remote control	

wheelchair, participants also prioritized the overall comfort in their future wheelchair design.

> "But I feel like comfort and functionality seem to be the issues we run into a lot more often. Whether because it's ill-fitting, or something like that…that leads to pressure sores and things (other negative consequences) you want to avoid." (Participant 12)

Specification

Participants discussed several unique specifications to be included in the design of a future wheelchair to enhance usability. Two participants desired a hydraulic lift to access hard to reach objects and social experiences. Similarly, participants desired a device that could access stairs for new social and life experiences. The most common specifications related to accessing outdoor terrain. According to one participant:

> "I know it's something that **she really wants** (accessing outdoor terrain), and **I would love to be able to get that for her**. **Going and visiting the various state parks is high up on our list of things we would love to do**." (Participant 12)

Participants also discussed ancillary accessories such as cargo/storage area, cup or phone holders, and seatbelts.

Hands-free wheelchair

This key theme was developed based on the responses to questions 26, 27, 28 from Table 1, which related to the participants' thoughts regarding the use of a hands-free wheelchair. Participants discussed their perceptions towards a self-balancing device, a device that could access uneven terrain and detect objects in the external environment, and a device that could self-navigate. Participants also discussed additional specifications they would like to integrate into the device and how a hands-free device could improve their quality of life. A full representation of subthemes and codes can be found in Table 7.

Overall perception

Overall, participants felt positive towards hands-free mobility as it would offer them an opportunity to multi-task while moving in their mobility device. However, this novel technology was viewed with skepticism as participants felt a hands-free device was fantastical and science fictional. Two participants expressed negative feelings towards this type of device because of the potential loss of physical activity from hand-free propulsion.

> "I think it would be really nice (multi-tasking capability). I guess the easiest parallel is my power wheelchair. It requires very little musculature and one hand, so it is really nice that **I can move around my house and use a cell phone at the same time**. I can have this other hand to do something and control it with this piece of my arm if I need to…**it is nice to get do activities with two hands**." (Participant 8)

Self-balancing

Five participants expressed positive feelings towards a self-balancing device. They were impressed with the thought of a device that would not tip over and believed this function would increase the handling capabilities of the mobility device. One participant expressed concerns about the use of the self-balancing device by an individual with limited trunk function.

> "I like it in theory. I guess I'm thinking…the **first thing I think is that it requires a lot of trunk control**. Even though you just specified everything else, that's what my brain stuck to, and wonders how well I could control that. **How much musculature would that require(?)**…" (Participant 8)

Accessing uneven terrain

Most participants were excited with the opportunity to access uneven terrains with a hands-free mobility device and believed this technology would improve their quality of life.

> "It's necessary**, it would be revolutionary**. I know the freewheel itself is life changing, a lot of people are like you need a free wheel if you want to go camping…**not having to do a tiny wheelie for miles would be amazing**." (Participant 10)

Two participants expressed concerns with uneven terrain due to safety reasons in the event of a technology malfunctions.

Sensor detection

A sensor detection function on the hands-free mobility device would ensure that objects and barriers are detected when navigating through the environment. Most participants felt positively about this function, especially in low-lit environments.

Self-navigation

Participants were asked to elaborate on their perceptions towards a self-navigation function that would navigate the individual to their desired destination. Five participants felt positive towards self-navigating functions. Three participants were skeptical of a self-navigating mobility device. One participant expressed the following:

> "…it's intriguing to consider…I **think I'm still skeptical of turning things completely over to those (self-navigating) kinds of technologies**. But I do, I can see them being useful, you know, as a starter bit of information for the user." (Participant 7)

Additional specification

Participants were asked to discuss additional specifications or capabilities they would like to have integrated into a hands-free mobility device. Several participants explained the benefits of a remote control or device for augmented navigation and the ability to bring the chair close to them when it is too far for a transfer.

> "Yes, it rolls away. **I'm just thinking of so many times my chair has rolled away while I was getting into my car**, then I had to drive my car over to my chair to get my chair…That'd (remote control) be great. (Participant 9)

Discussion

The purpose of this study was to examine the lived experiences of WCUs and their needs for a novel mobility device. 14 participants (9 full-time WCUs and 4 care providers) participated in semi-structured interviews to examine aspects related to life as a WCU and future assistive technology needs. Thematic analysis revealed four major themes: (1) current wheelchair usage, (2) WCU perspectives, (3) future wheelchair needs, and (4) the prospect of hands-free wheelchair. Researchers can use this information for future development of a novel mobility devices and assistive technologies for WCUs.

Currently, several solutions exist that provide people with mobility limitations with an ability to independently navigate their environments. However, many of these devices are abandoned soon after product uptake because they are non-usable [22, 28]. Assistive technology abandonment may detract from quality of life while also producing an unnecessary waste of resources and money [22, 29]. By capturing the lived experiences and needs of WCUs of various disability types, we hope to guide the development of future assistive technologies and minimize potential abandonment.

We first examined the current use of wheelchairs. According to most participants, their current wheelchair is comfortable and bespoke to the body. However, many expressed concerns with the weight of their wheelchair. According to the Paralyzed Veterans of America guidelines for upper-extremity preservation in wheelchair users with spinal cord injury, it is imperative that manual WCUs use bespoke, lightweight wheelchairs of less than 30lbs because lighter wheelchairs are more durable and place lower loads on the shoulders during propulsion [30, 31]. The use of a lightweight device may also make loading the wheelchair into and out of a car easier and thereby enhance participation in personal vehicle transportation [32]. Research supports independent transportation is essential for community participation and quality of life [33].

Participants complained about the dirtiness of their hands when propelling their manual wheelchairs. While the invention of the push-rim has reduced the amount of dirt that contacts the hands during manual propulsion [34], WCUs still report dirty hands as a major issue with wheelchair use [35]. Various devices, like lever systems, have been developed to reduce dirty hands [36]; however, these assistive devices have not shown to be usable because they are too bulky and difficult to maneuver and modify [37].

Participants also expressed issues with completing activities of daily living (ADL), especially in the kitchen and bathroom. The need to use one's hands for propulsion while simultaneously engaging in activities such as preparing meals may make basic cooking, cleaning, and carrying activities difficult and potentially dangerous [38]. Additionally, navigating through narrow spaces in a home environment such as in bathrooms may be difficult because of the size of wheelchairs. According to participants, frequent scuffs and damages to their home environment occurred from accidental bumping of the bulky frame.

On nearly all manual wheelchairs, casters exist to improve maneuverability and provide a wider base of support for added stability [39]. Unfortunately, the dynamic movement of caster systems tend to cause issues and get stuck or caught on non-smooth surfaces, leading to falls [40]. The hardware of a caster also rapidly decays and becomes rusted and stiff when exposed to adverse weather conditions [41]. Participants expressed difficulties with weather and uneven terrains as barriers to community participation, which may be due to the ubiquitous use of casters on current manual wheelchairs. While assistive technology developers have successfully innovated mobility devices to minimize the interplay between casters and variable terrain surfaces like the FreeWheel attachment (Go Free Wheel, USA), Omeo (Omeo Technology, New Zealand), iBOT (Mobius Mobility, USA), and All Terrain Wheelchair (GRIT, USA), problems still exist with these devices' indoor and outdoor versatility, size, and maneuverability [42–44]. Designers and developers should continue exploring novel ways to reduce the need for casters in future mobility devices.

When asked about a futuristic wheelchair, participants desired a wheelchair that was lightweight, functional, safe, and comfortable. Specifically, participants desired a wheelchair that was low to the ground, easy to maneuver and difficult to tip over. To further prevent wheelchair-related falls and injuries, participants also stressed the need for speed governors. While going downhill, it is easy for wheelchairs to gain excessive speeds [45]. A large percentage of falls occur during downhill movements due to the fast speeds and quick transition associated with movement on differently graded surfaces [46]. It was encouraging that participants understood these dangers and prioritized the need to maintain safe speeds when navigating their environments.

Three participants desired a hands-free mobility option for multitasking while moving. Notably, this desire preceded interview questions related to a hands-free wheelchair device. The idea of a hands-free mobility experience has recently emerged as a way for people with mobility limitations to navigate their environments while still maintaining access to their hands [17].

When specifically asked about the prospect of having access to one's hands while moving, qualitative analysis supported the concept of a hands-free mobility device. Participants felt that the ability to multitask while moving would greatly enhance their quality of life. Four participants did voice skepticism regarding a hands-free mobility experience because they believed it was too fantastical.

Recently, our group demonstrated that manual WCUs could safely navigate a test course on smooth pavement while seated on a hands-free ball-based robot (ballbot) wheelchair [47]. This ballbot mobility device utilized intuitive torso movements for navigation [48], and provided participants with omnidirectional capabilities without the need for casters. This design ensured that participants could keep their hands clean during navigation while also maintaining a minimal footprint, countering issues experienced by other mobility devices aimed at reducing the hand-wheelchair interface [37].

By using a torso-dynamics estimation system, the hands-free ballbot quantifies the user's trunk movements and provides tunable reference signals that are tracked by the device [48]. Torso-dynamics estimation systems allow for a high degree of sensitivity and responsiveness, making it capable of translating limited trunk movements into direction and speed [49]. Recent results by Song et al. revealed that the ballbot could be operated by WCUs with substantially reduced torso function in comparison to able-bodied controls. Song et al. also included a supplementary video in their study of an individual with a fully fused spinal cord injury and minimal trunk control effectively maneuvering the ballbot mobility system [49].

While preliminary research appears promising, future research should expand upon this work and begin exploring ways to integrate hands-free mobility devices into variable terrains and adverse weather conditions to ensure its long-term usability. Future work should also address the cost-related inaccessibility related to purchasing a ballbot mobility device. Early market translation exploration suggests that this device can be competitively priced with

comparable electronically powered mobility devices. However, the cost of such devices ranges from $8,000 to $30,000, which may be exorbitant for a WCU. Researchers should investigate strategies to ameliorate the cost burden that may confront WCU when seeking to purchase this device such as gaining FDA classification as a medical device for insurance approval or accessing philanthropic agencies to subsidize the purchase.

Finally, with participants voicing concerns about the complexities inherent to maintaining a MWC, designers and engineers should investigate ways to minimize these difficulties in a complex hands-free ballbot mobility system. Recent work by Worobey et al. showed that a bi-annual group wheelchair maintenance programs improved WCU's capacity to maintain MWC and PWC [50]. Researchers recommend a mandatory group workshop and maintenance training program for the ballbot mobility device before providing users with access to the mobility device for everyday use.

Insight from participant interviews makes it clear that future assistive technology designers and developers should strive to develop transportable, lightweight devices that maximize user multi-tasking capabilities and assimilate to the multi-terrains of one's community. Additionally, devices should be customized to the functional level of users for improved safety and maneuverability. Following the development of assistive devices, developers may benefit from offering education courses so users can seamlessly and safely operate their devices too. Finally, developers should find ways to minimize costs in the manufacturing phase of assistive devices or maximize ways WCUs can utilize Medicaid-related resources so WCUs—who typically contend with a multitude of health-related expenses—can afford and access the novel device.

Limitations

Our study revealed the needs and perceptions of WCUs towards their mobility devices. Nonetheless, several limitations exist within the current study. First, this study examined wheelchair-related experiences and perceptions of 9 manual WCUs with neurological or neuro-muscular impairments and 5 care providers of WCUs, limiting the generalizability to all users of mobility devices. However, the intent of this study was to gain an in-depth understanding of these WCUs' needs and perceptions towards their mobility devices so future assistive technology can be more usable. Additionally, the majority of participants did not elaborate on their disability type, making this project difficult to translate to specific types of disabilities like spinal cord injury. Due to the heterogeneity associated with disability and the scope of this project, participants were only required to be full-time WCUs to participate in the study. While the interviewer asked all participants to elaborate on their disability type, many participants did not want to elaborate. Researchers acknowledge this limitation within the study's methodology and believe that by obtaining more comprehensive disability demographics information, researchers may have gained additional insight into the usability of Xiao et al.'s torso-dynamics ballbot mobility system [47]. Future work should specifically examine the perceptions of individuals with limited torso function to further understand how populations of lower functional levels perceive the current ballbot design. Another limitation is the type of questions asked. Due to time constraints of interviews, many important questions related to mobility devices were not asked that may have shed greater insight into additional needs of WCUs. Further questions regarding our sample's disability types and functional characteristics may have uncovered important aspects of our population that currently was not considered during our analysis. Despite these limitations, this research is important for the development of evidence-based assistive technologies that enhance the quality of life of WCUs.

Conclusions

In conclusion, current manual wheelchairs appear to be well-fitted to users; however, several modifications can be made to the wheelchair to improve the user's quality of life. Future technologies may benefit from finding ways to remove the requirement of hands during propulsion so the hands can stay cleaner and users can engage in more multitask-oriented activities. Devices should also find ways to remove the need for casters and reduce the overall footprint of a wheelchair so users can better fit into narrow spaces in and outside of their homes. The concept of a hands-free mobility device appears to be usable and desirable amongst our sample.

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Data availability statement

Additional data can be accessed by reaching out to the corresponding author.

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