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ORIGINAL RESEARCH

Appraisals of robotic locomotor exoskeletons for gait: focus group insights from potential users with spinal cord injuries

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ABSTRACT

Purpose: To describe appraisals of robotic exoskeletons for locomotion by potential users with spinal cord injuries, their perceptions of device benefits and limitations, and recommendations for manufacturers and therapists regarding device use.

Materials and methods: We conducted focus groups at three regional rehabilitation hospitals and used thematic analysis to define themes.

Results: Across four focus groups, 35 adults participated; they were predominantly middle-aged, male, and diverse in terms of race and ethnicity, well educated, and not working. Participants had been living with SCI an average of two decades. Most participants were aware of exoskeletons. Some were enthusiastic about the usability of the devices while others were more circumspect. They had many questions about device affordability and usability, and were discerning in their appraisal of benefits and suitability to their particular circumstances. They reflected on device cost, the need for caregiver assistance, use of hands, and environmental considerations. They weighed the functional benefits relative to the cost of preferred activities. Their recommendations focused on cost, battery life, and independent use.

Conclusions: Potential users' appraisals of mobility technology reflect a nuanced appreciation of device costs; functional, social, and psychological benefits; and limitations. Results provide guidance to therapists and manufacturers regarding device use.

➤ IMPLICATIONS FOR REHABILITATION

- Potential users of robotic locomotor exoskeletons with spinal cord injuries appreciate the functional, social, and psychological benefits that these devices may offer.
- Their appraisals reflect nuanced consideration of device cost and features, and the suitability of the assistive technology to their circumstances.
- They recommend that manufacturers focus on reducing cost, extending battery life, and features that allow independent use.

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Some individuals with spinal cord injury (SCI) ambulate using canes, walkers, crutches, and orthotic devices such as knee-ankle-foot orthoses and reciprocal gait orthoses, though users often abandon orthoses because they fail to meet users' needs [1]. For persons with SCI who are not ambulatory, preferred modes of mobility are manual and powered wheelchairs or scooters [2]. Gait training is thus a vital aspect of SCI mobility and rehabilitation therapy and supports the health benefits of standing and ambulating, such as increased cardiopulmonary functioning and reduced contractures [3].

Over-ground ambulation and recovery of motor function are often primary goals for persons with SCI during rehabilitation. Gait training can improve walking ability and general health [4]. Exercising larger muscles while upright promotes cardiovascular fitness, metabolic control, and psychological well-being [5]. People with SCI have several methods of gait training, including bodyweight supported treadmill training, over-ground harnessed, treadmill-based robots, and functional electrical stimulation [6]. Increasingly, therapists use robotic exoskeletons during gait therapy [1]. Robotic exoskeletons have the potential for community ambulation; however, health insurance rarely covers the purchase of exoskeletons for personal use.

Robotic exoskeletons can serve as a rehabilitation therapy tool and minimize the risk of secondary conditions such as contractures, spasticity, and cardiopulmonary deconditioning [7]. Exoskeletons used through the continuum of rehabilitation can provide walking practice and mobility, which can reduce the incidence of or delay secondary conditions and significantly reduce the cost of care [8]. A key advantage of exoskeletons is that they are not limited to a laboratory or clinic setting. Users can wear them in community and home settings, providing opportunities to practice walking outside of a clinical environment. However, injury risk from falls remains an unresolved issue.

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Supplemental data for this article can be accessed here.

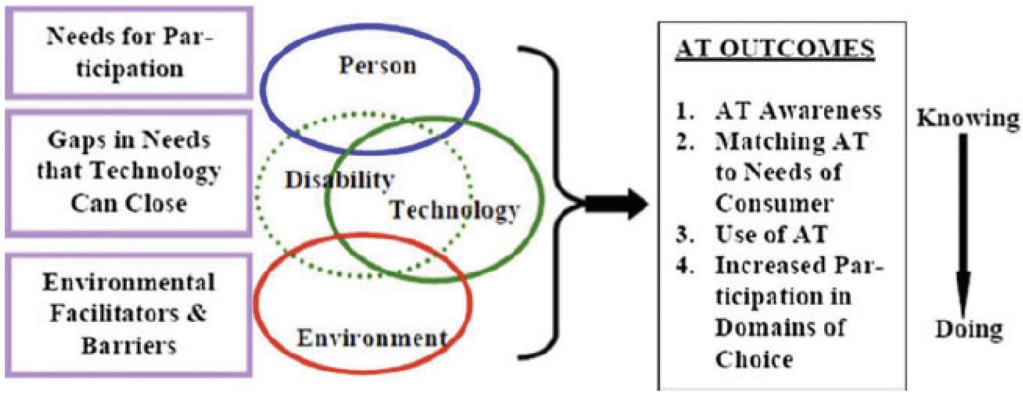

Figure 1. Assistive technology and knowledge translation model. Reprinted from Adya et al. [22].

Limited studies support the safety and efficacy of these devices for individuals with SCI. Specifically, using the Indego exoskeleton, some individuals with paraplegia transition to limited community ambulation after five, 1.5 h gait training sessions [9]. The Indego requires less effort than knee-ankle-foot orthoses, and subjects perform strength and endurance tests 25 to 75% faster when using the Indego compared to traditional bracing [10]. Similarly, in a small, prospective study involving eight individuals with T1 level SCI and below, the Ekso could be used safely when monitored by a trained therapist [11]. Individuals with complete SCI achieved walking speeds and distances comparable to persons with motor incomplete injuries, although they achieved few changes in leg muscle activation or neuromuscular health [12]. Similar safety and efficacy study evidence exists for the ReWalk [13–15]. Currently, most studies on exoskeletons are limited to early-stage evaluation of safety and efficacy.

Users perspectives of robotic exoskeletons for gait

There has been much enthusiasm regarding robotic exoskeletons' potential; however, there are several limitations for its use as a rehabilitation therapy tool and as a personal mobility device [16]. Limitations relate to device safety, set-up requirements, slow speeds for community ambulation, level and completeness of injury, body composition and weight, range of motion required for use, and high cost [17]. Both potential users and therapists regard some limitations, such as walking speed, cost, and safety, as critical design issues [16]. However, potential benefits such as reduced spasticity and pain, improved bladder and bowel function, and enhanced quality of life motivate potential users [18]. In addition to physical health benefits, users report psychological benefits, such as enhanced social interaction and improved self-esteem [16].

We know little about the utility and benefits of robotic exoskeletons, both in terms of who might benefit and of potential user interest in them. The limited number of studies, small sample sizes, and variable methodological quality provide insufficient evidence to support the use of robotic therapy for persons with SCI [19–21]. It seems likely that persons with more severe impairments will make greater gains while receiving robot-assisted therapy than persons with less severe impairments; however, this speculation reflects the clinical experience that persons with more severe, incomplete SCI achieve a functional plateau earlier and receive little gait training. Meanwhile, individuals with complete SCI typically receive no gait training due to the nature of their injuries and use a wheelchair; as a result, they often experience health complications associated with seated mobility.

Adya and colleagues, provide a theoretical framework regarding assistive technology service delivery that informs the evaluation of robotic exoskeleton use in home, community, and clinic settings [22]. Their framework incorporates a multi-stakeholder perspective of disability that emphasizes participation as the goal of rehabilitation (Figure 1). They ground their model in the World Health Organization's International Classification of Functioning, Disability, and Health, [23] which allows investigators to evaluate the comparative effectiveness of different rehabilitation strategies, such as robotic exoskeletons. People may experience a variety of barriers to full societal participation. Assistive technology serves to mediate barriers people experience in their environments as they seek to participate in their communities. The right side of Figure 1 shows the favorable consequences people may experience when using assistive technology. These consequences form a continuum of favorable participation outcomes that result from a knowledge path that leads from awareness of assistive technology options (Knowing), to assistive technology acquisition and use, and then to improved participation in domains they value (Doing). Scherer asserts that effective assistive technology delivery models should focus on knowledge translation strategies to enhance the likelihood of the model's success [24,25]. Limited awareness of assistive technology options reduces potential users from selecting the most suitable option and increases the risk of abandoned technology.

Research needs

While robotic exoskeletons are novel rehabilitation devices for persons with SCI, potential users need information regarding the utility, affordability, reliability, and efficacy of these devices in clinical and community settings. The situation is not unlike the development of functional electrical stimulation for stance and gait 30 years ago when the promise of research benefits exceeded then-current technology [26,27]. Research focused on these issues would benefit manufacturers and therapists in device development, clinical practice guidelines, and application. This report addresses the following research questions:

1. What are potential users' awareness of, perceptions of, and questions regarding robotic exoskeletons?
2. How do potential users appraise the benefits and limitations of robotic exoskeletons?
3. How do individuals' roles, preferred activities, and environmental factors affect evaluations of robotic exoskeletons for mobility?

Table 1. Focus group participants' characteristics ($N = 35$).

Age (mean, standard deviation – years)	48 + 15
Time since injury (mean, standard deviation – years)	22 + 13
Sex (female)	17%
Race	
White	37%
Black	46%
Other	17%
Hispanic/Latinx* (yes)	14%
Education level	
9th–11th	3%
High School/GED	46%
Any post-secondary education	17%
Bachelors	17%
Masters	11%
Occupational status	
Employed full or part time	26%
Student	3%
Unemployed	46%
Retired	14%
Volunteer/Other/Decline	12%
Cause of injury	
Fall	23%
Vehicular crash	26%
Violence	29%
Sport	11%
Medical/Surgical Complication/Other	12%
Level of injury	
Cervical	46%
Thoracic	46%
Lumbar	9%
Injury completeness	
Complete	31%
Type of wheelchair used*	
Manual	74%
Power assist	6%
Power	23%
Scooter	11%
Do you walk, either on your own or in therapy/research? (yes)	40%
Assistive devices used for walking? (check all)	
None	0%
Cane	17%
Walker	17%
Crutches	11%
AFO or KAFO	26%
Veteran? (yes)	23%
If yes, injury occurred on active military duty or training	83%
Used exercise or fitness facility after inpatient	63%
Used Lokomat, Zero-G, KineAssist, other	23%
Currently receiving therapy of any type	21%
If yes, physical therapy	14%
If yes, other therapy	3%
Able to walk without assistance from another person	40%
Able to walk 30 feet without assistance from another person	40%
Able to stand without assistance	0%
Heard about robotic exoskeletons before this study	86%
Context of robotic exoskeleton exposure (check all)	
Media	60%
Social media	17%
Personal experience	34%
Research	31%
Healthcare professional	14%
Other	3%
Considered using a robotic exoskeleton	
No	83%
Yes	11%
Do not know	6%
Levels in home	
1	49%
More than 1	51%

4. What recommendations do potential users have for manufacturers and therapists regarding robotic exoskeletons for mobility?

Methods

This study used focus groups of civilians and Veterans to address the study questions. Institutional review boards at collaborating sites provided ethical approval, as did the US Army Medical Research and Development Command Office of Research Protections, Human Research Protection Office. Focus group participants provided informed consent and received an honorarium for their participation.

Sample

We recruited participants at three regional rehabilitation hospitals and referrals from Veterans Affairs hospitals where therapists provide specialized SCI care: The Shirley Ryan AbilityLab (formally the Rehabilitation Institute of Chicago), the Kessler Foundation, Shepherd Center, and Jesse Brown, Edward Hines, Jr., James J. Peters, and Minneapolis VA Medical Centers. A moderator travelled to the facilities and facilitated a focus group. Inclusion criteria were SCI and age 18 years or older; exclusion criteria were clinical or research experience using robotic exoskeletons.

Procedures

We invited persons with SCI to complete an online Research Electronic Data Capture (REDCap) survey [28] to describe the extent of their experience with robotic exoskeletons and to report demographic and SCI characteristics between 6 September 2018 and 31 July 2019. REDCap is a secure, web-based software platform designed to support data capture for research studies. We selected survey participants to participate in focus groups based on their availability and ability to travel to one of the collaborating sites. We sought diversity in terms of age, sex, race and ethnicity, and Veteran status.

Research team members developed a focus group topic guide that the moderator used for all focus groups (see Supplementry Appendix). The moderator has 40 years of experience in designing and conducting qualitative research projects. The moderator led focus groups in person and a court reporter took verbatim notes and provided transcripts for content analysis. The research team masked personal identifying information to assure confidentiality before uploading the documents to a secure server and sharing them with the research team for coding.

We developed a short video to illustrate the use of robotic exoskeletons in clinical and community settings. We compiled video clips of research subjects and patients walking with the three FDA-approved devices and recorded narration that described the features and use of the devices. We played the video at the beginning of focus groups after participants introduced themselves. The video clip is available at https://www.sralab.org/node/87356.

Data analysis

We imported transcripts into QSR International's NVivo 12 Pro software, reviewed the text, and validated it before analysis. We used a thematic approach to summarize participants' responses [29,30]. For each transcript, this approach involved open coding and interpreting the interviews line-by-line; reading and annotating the data; describing, classifying, and interpreting the data into codes and themes; and then representing and visualizing the data by three research team members. We used an inductive analytic approach [31] to produce the codebook based on open coding of the first focus group interview. The research team reviewed the

Table 2. Representative quotes illustrating themes from focus group discussions.

High-level theme	Mid-level theme	Sub-theme	Representative quotes	Frequency
Device characteristics				33
	Limitations		I don't see it as a practical solution. I mean, um, you're going to have somebody hook you up to the unit, that's the way it looks. And, um, that's not going to be a very independent type thing.	40
		Environmental	I would like to be able to use it to just simply take a walk through the woods. I would like to be able to walk on a beach. I would like to be able to walk through a vineyard.	7
		Physical	So as far as me having AHO [heterotopic ossification] it disqualifies me because it puts me at subject for uh, yeah fractures.	26
	Models			0
		ReWalk	They've got the VA reimbursement right now with ReWalk.	5
Environmental characteristics				4
	Access		Probably availability. Availability. You know, we got five in the building and got 55 people that want them, you know.	1
	Products & technology		I left Shepherd walking with AFOs, long-stem crutches, and a lot of determination. A year into being at home walking with AFOs, long-stem crutches, and determination, I came to the realization that I was missing out on a lot of things because I couldn't carry my backpack to school because it took me 20 minutes to get to class instead of five, you know.	10
		Lofstrand Crutches	I'm good for about 100 feet in forearm crutches and then my legs become tree trunks and just get so tight I have to sit up and then I can get up and do it again.	4
		Lokomat	After the initial operation I was on the stationary one for a while, and it corrected – but then corrected, and it was telling me what I was doing wrong with my gait. So it helped me to fix my gait.	4
		Orthotics	I feel like I'm getting stronger with different things I'm doing because I have braces at my house, I have the cufflinks.	2
		Walker	I kind of cheat with my rollator because I can fold it down if I am not doing super shopping. I can fold it down and drag it behind me onto an escalator or drag it up a set of stairs, if absolutely necessary.	1
		Wheelchair		24
	Setting			0
		Clinical	For – therapy it's for a short period of time, it's not meant to replace and become part of you for the rest of your life.	5
		Community	I guess my thing would be at that price point to walk across the street to the store, is it worth it?	27
		Home	Other than maybe getting something off the top shelf, I wouldn't really utilize it for anything. It would be cool to kind of – it would be cool to walk around, just haven't done it in a long time and that would be all right, but I don't see myself using it for anything other than just to have fun.	4
		Research	It's mainly a training device is what I've seen. It's not for normal living device, it's a training. You train with it, and then, um, you take it off, and you're done with it.	2
Patient benefits				7
	Emotional		Looking people in the eye again.	18
	Motivational		Once you get the hang of standing up and being up, you're gonna like that feeling.	8
	Occupational		I was a personal trainer … I would love to get back to doing exactly – and those lunges that I did with them, those squats and show and tell at the same time so, yeah, work's definitely a factor.	8
	Physical functioning			37
		Mobility	Reinforces the gait and the strengthening. Just standing up, walking again, you know, that way it used to be.	36
		Self-Care	… If you're at home by yourself, if you stay by yourself, you will get stronger. You don't have nobody to depend on.	1
	Physical			32
		Bladder Function	I feel like when I used to get on the treadmill that my bladder would, I would, as far as managing my bladder it would help with that. I wouldn't see it go from say six times a day to like four times a day I guess as far as bladder.	3
		Bowel Function	… You get like the quad gut … just feeling like everything is going down when you're standing up. And moving around.	4

(*continued*)

Table 2. Continued.

High-level theme	Mid-level theme	Sub-theme	Representative quotes	Frequency
		Cardiovascular		3
		Muscle Mass & Tone	Help with muscle memory. So if I can retrain certain muscles, if I can re-enforce training on certain muscles that will enable me to not only walk one day, be able to run again.	7
		Posture	I mean, you're upright …	16
		Spasticity		2
	Social			18
Patient experience				0
	Exposure (awareness)			53
		Impressions	I'm just realizing like 5 – like in 5 or 10 years how small and thinner they are going to be, like the ways (inaudible) they are sorting the sizes and shapes now. Yeah, it's going to be incredible.	40
		Knowledge		2
		Questions	How would one find out if they are qualified or could be a candidate for to use that? Do you think it will get to a point to where these things will be covered by insurance? I'd say easy on and easy off. Can you get into and get out of it quickly? Say if I'm up and say I take 20 steps and I'm walking headed to my car or something and all of a sudden I got to take a leak, well, how do you get out of this thing, you know? How would it work when I'm going out on a date, you know, I'm trying to dress up and be cute?	53
	Inside clinic			2
		Goals	Independence is something that we all would like to have again. That's something that's just, as far as me, yeah.	2
		Motivation	I'll use it in hopes to learn how to walk again and be able to use the – that would be my main use for it during rehab.	2
	Limitations			17
	Outside clinic		But as far as going out with it, I don't think so, I'm so used to this chair.	5
		Goals	If I was working full time or something, an eight-hour day would easily be something that I would require to get through the day. So something like that. Six would be like cutting it, you know, tight, but between six and eight hours. I am hoping [I] can walk to my friend's house.	5
		Motivation	I do a lot of shopping with my wife, grocery shopping. I do a lot of volunteer work out in the community, and it doesn't require me to walk.	4
	Patient interest in exoskeleton use		So I know for me, at this stage, it probably wouldn't be practical for like an exoskeleton user, but I'm hoping that within the future it may be something that may be an option.	13
		Yes	I can totally see the therapeutic side of it. Still I don't see the benefit of having it as something that you could use every day, but definitely the therapeutic side.	41
		No	So if the technology is evolved to the point where it would be practical for my needs then great, but it's just not there yet.	17
	Perceptions		Yeah people see you like damn I didn't know you were that tall.	8
	Realistic expectations		It's not that I'm less enthusiastic, it's just that I know from my experience the practicalities of it and the realistic expectations that the technology can and cannot do. So if the technology is evolved to the point where it would be practical for my needs then great, but it's just not there yet.	23
Patient risks of exoskeleton use				0
	Emotional		Because when I got disqualified I was a little bummed out because I was like trying to gear myself up for it. I was like oh you got AHO and I was like what. I had did all this other stuff so now to not do the exoskeleton is like oh man …	1
	Occupational			0
	Physical			5
	Safety		I mean for me, as a quad I would be kind of nervous not having somebody who knows what they're doing, or who's not a therapist. I don't know if I would just have like, let's say I was just able to get one and then just having like my dad or my mom or family member just	6

(*continued*)

Table 2. Continued.

High-level theme	Mid-level theme	Sub-theme	Representative quotes	Frequency
			kind of supporting me, like I think a lot would go into it. Even as far as, autonomic dysreflexia or something like some type of medical situation, not really knowing what signs to look for, if you didn't have the trained person with you.	
	Social		I haven't been on the bus in my wheelchair since then. So I just can't imagine now with that bulky and practically going through the drama of getting on the bus, and dealing with the people, I – it's just illogical for me.	3
Recommendations				0
	To manufacturer		I would like to be able to hold my grandchild's hand and walk down the street.	48
			I want to get to a point where I won't need to use my upper extremities to manually help me along for balance. I would like to be able to carry a bag of groceries.	
			That kind of easy on, easy off and flexibility. So it's not that you just get into it and walk around your neighborhood and walk home. That's nice, but it's not what you really want to do to give you total independence.	
	To therapist			
	To patient		I'll try anything and everything. I got a one year of outpatient after my injury, and in that one year we tried a lot of different things and some of them seemed to hit a dead end. Okay, we tried something else. But at the end of that year I was able to stand up and take three steps in a walker. So it took a whole year to be able to do that tiny little thing, but she never gave up and I never gave up on it.	3
Service delivery				3
	Purchasing		I think if I could afford to get it, I don't – I don't think I would get it. I think I would – like a kid younger than me that couldn't afford to get it, I would rather get it for them, you know, so they can have the benefits of getting back up and walking. I am an older guy, you know, it's – it is what it is with me. So, you know, I'd rather for somebody that can use it, enjoy it and, you know, be able to some kind of way live – you know, live their life without having to be in a wheelchair.	58
		Appropriateness	From what I've always understood, without a grip I'm kind of out of the running for using it.	8
		Patient Characteristics	So the more physically fit individual the more you do some type of therapy or some type of consistent exercise throughout, then your better chances that you'll be …	1
		Referral	Well, I think with therapy, if a physical therapist would say, hey, you're ready, or, this would benefit you outside of our physical therapy, then that would be the professional that would advise you to okay, you're ready.	1
Training				0
	Caregiver		I just think it would be better if you definitely have someone that's a PA that will assist you. And I believe that will help me more – so become more independent, you know, with the exoskeleton, and not have to rely on like one of my relatives to help me. Although I know they want to help me, but to a degree at some point in time they might get a little tired, they want to do other things.	8
	Patient		I would turn back to you guys so you can train me. You have more knowledge about it.	2

first coded transcript to assess interpretations, reconciled discrepancies among the three primary coders, discussed the initial findings, and made modifications. Different teams of three researchers coded the remaining transcripts, including two primary coders who coded independently and then reconciled differences. The third coder read the transcript independently and reconciled the two primary coders' themes. When kappa coefficients, reflecting concordance of thematic coding, did not exceed 0.80, the team of three met to review the coded text and modify the codes to reach consensus. Finally, the team reviewed and harmonized codes across sites.

We used several strategies to assure methodological rigour. We enhanced interview reliability by using a standard, semi-structured moderator guide and having the same moderator conduct all focus groups. We developed the codebook early in the analysis process and refined it throughout the analysis. We assured investigator triangulation by having three investigators independently code transcripts before meeting to reconcile themes. A third

coder verified the first two coders' reconciliation independently. The three coders discussed discrepancies when kappa coefficients were less than 0.80. The entire research team met frequently to discuss the findings and analysis plans.

Results

Demographic characteristics of focus group participants

We conducted three focus groups in Chicago, Illinois, Atlanta, Georgia, and West Orange, New Jersey, and a fourth group comprised solely of Veterans in Chicago. Table 1 reports the demographic, injury, and other characteristics of the focus group participants. On average, they were middle-aged, predominantly male, and diverse in terms of race and ethnicity, well educated, and not working. The sample had been living with SCI for more than two decades on average; about half sustained cervical level injuries and about two-thirds sustained incomplete injuries. About three-quarters used manual wheelchairs for mobility, though almost half walked on occasion. About one-quarter had experience using powered mobility technology though by selection, none had used a robotic exoskeleton. Forty percent were able to walk without assistance, and 17% had considered using a robotic exoskeleton.

Thematic code development

Several thematic codes emerged from analysis of focus group transcripts. Table 2 lists representative quotes for each of the thematic codes and the frequency with which they occurred across sites. Figure 2 provides a word cloud of the codes with font size reflecting their relative frequencies.

Awareness, perceptions, and questions regarding robotic exoskeletons

Several participants had no previous knowledge of robotic exoskeletons, but several had seen one or more robotic exoskeletons in rehabilitation centers, on the internet, or in the news media. One participant had done extensive research about exoskeletons and had even invested in a robotics company (see Table 2). For example,

> I saw some research – or I started researching myself after [de-identified] had called me to look into it more, but while I was in the CRU unit, which was right next to research, I saw a couple of people using them as they were walking and we were doing rehab.

> I travel a lot doing public speaking and, like, support groups and stuff like that at different rehab centers, and I've seen them in a lot of rehab centers across the nation.

> My father gave me a newspaper article, I want to say probably about 2 months ago, and it specifically talked about the exoskeleton. So I went online and did a little research, and just to kind of check it out to see how it was made or what have you. And it's kind of – it's similar to the braces that I have. I have some RGO braces. But the only difference is that I noticed the difference between the 2 on the back part of the upper part of the brace is like a backpack or something like that.

> I've seen promotional videos, like on YouTube for ReWalk and some of the other prototypes that are out there.

> It was not just the piece of metal [like leg braces] so it looked very interesting, but I didn't read a whole lot other than that. It looked like they had expanded and were – the cost was some astronomical. It was like $2,00,000 in that neighborhood, so what they were able to do more and more with, they were doing research. Instead of just attaching it and helping you walk, they were using it for many other things.

> I learned a lot from ReWalk. I made an investment in Re-Walk a couple of years ago when they went public. I read all the quarterly reports and listened to what they all had to say and watched as the stock went up and just collapsed totally in spite of some of the reimbursements they're starting to get with the VA. So, the economics of them are still very suspect, but the possibilities of them is very exciting.

Participants varied in their opinions of the current state of robotic exoskeleton technology. Many were enthusiastic about the usability of exoskeleton devices and believed they compared favorably to other technology that is in use in rehabilitation centers. These individuals particularly liked that an exoskeleton user could be upright and mobile. For example,

> If you think about it they got a $1,00,000 Lokomat which – which is a state-of-the-art device, right – you're on a treadmill … and you can get up and you can walk, right? Now instead of you being harnessed into something that's stationary, now they get you harnessed into something that's mobile. So it's not the end all yet, but it's progress.

> … the standing frame I had, it's like you just stand there and it's like, okay, this is pretty boring, you know, so I think this is giving us the ability, if we so choose to use it, to take it a step further.

> I'd definitely be interested in getting one for a therapy session just the fact of the weight bearing, to stretch my muscles, to get back into that standing position and the muscle memory.

Other participants were skeptical about the value of robotic exoskeletons given the current state of the technology. They used mobile telephone and automobile analogies when discussing the benefits and limitations of exoskeleton technology. These

Figure 2. Word cloud of focus group themes.

participants would like to see the technology progress significantly before they would consider purchasing a device. For example,

> It's not that I'm less enthusiastic, it's just that I know from my experience the practicalities of it and the realistic expectations that the technology can and cannot do. So if the technology is evolved to the point where it would be practical for my needs then great, but it's just not there yet.

> You buy an expensive car for the features it has. So, if this has the features that would allow me to walk in a real world like a regular person somewhat, I'd figure out how to buy one.

Participants had many questions about robotic exoskeletons regarding affordability and usability. Most questions reflected the personal circumstances of the participant. For example,

> Do you think it will get to a point to where these things will be covered by insurance?

> Say if I'm up and say I take 20 steps and I'm walking headed to my car or something and all of a sudden I got to take a leak, well, how do you get out of this thing, you know?

> How would it work when I'm going out on a date, you know, I'm trying to dress up and be cute?

> How would one find out if they are qualified or could be a candidate for to use that?

> I'd say easy on and easy off. Can you get into and get out of it quickly?

> Have you noticed the health benefits for individuals that are using it on a regular basis?

Appraisal of benefits and limitations of robotic exoskeletons for mobility

Participants were discerning in their appraisal of benefits and suitability to their particular circumstances. Participants mentioned the psychological benefit of being upright for work or parenting tasks. For example,

> Just on a psychological level it's nice, I think, to talk to somebody eye to eye versus looking up at somebody and them having – looking down or not – if they sit down, it's not going to kill my neck.

> So it would be nice … to be able to wear it and be out in a public setting and just be able to get up out of your chair and have that conversation eye to eye. If you want to sit back down, you can. You can have that option available.

Many other participants considered potential physical benefits, including posture correction, stretching, weight bearing, prevention of pressure wounds, reduction of spasticity, and improving bowel and bladder function. For example,

> Bedsores. I never had them, but you'll take less risk of getting bedsores, pressure sores.

> For myself it would not only correct posture and my gait, it would help me possibly re-align myself, because I find that, for instance, when I sit down I lean forward a lot.

> So we were talking about helping – being able to help with the spasms and stuff, I would like to try for that reason and just get more balance and stuff.

In considering device limitations, general considerations centered around cost, the need for caregiver assistance, the use of hands, and environmental considerations. The need for a caregiver was a major drawback, particularly for single participants. For example,

> My only concern would be, as far as bringing it home, so that I could use it by myself. I don't want to be able to use it with someone around.

> So you would probably feel maybe less independent – probably feel more independent in your wheelchair because you are able to do what you need to do when handling (inaudible) with the exoskeleton you have to have somebody there.

> I feel like it would be more restrictive than the wheelchair. I can do a lot of different things in the wheelchair, keeping up with people and being independent, and nobody has to be with me and guard me. I don't want to get to the point that I have to have my own little circus to help me live day to day.

Inability to grasp or carry objects while wearing the device was a frequently cited concern. For example,

> I would love to be able to utilize a skeleton, but I want to get to a point where I won't need to use my upper extremities to manually help me along for balance. I would like to be able to carry a bag of groceries.

> I mean, that's great that you can walk into the store, but like we're talking about, I mean, you have to eat the sandwich in the store at the counter or you have to carry the bag out in your mouth.

Participants viewed the amount of time required to don and doff the device negatively, as were the limited battery life of the exoskeleton and its inability to climb stairs. For example,

> I don't want to have to wait for someone to come and help me strap on this pack and get into these legs. The exoskeleton is going to have to be re-fined to the point where you can be truly independent with it.

> That's what a lot of people who have used it brought up, it's great for exercise or it's great for this, but it's hard when I have to go to the bathroom. I have to take at least part of it off.

> Ideally independence as we've been mentioning would be the end goal. To have a system where you can just put it on and just go and do your daily routine without second thought.

> If it had the ability to go up and down steps and a lower price point, then, you know, maybe we're, you know, more considerate of it, but, you know, just to walk across the street with somebody behind you for the life of – you know, the battery life of – you know, at that price point, then I don't see – I just don't see the benefit.

> If they had one of those attached to the wheelchair and then you could navigate one or two steps that would change my life tremendously.

Still other participants were disappointed that their physical characteristics would disqualify them from using robotic exoskeletons. For example,

> I tried to get one, but I got disqualified because I have HO [heterotopic ossification] in my left leg.

> Yeah that's what I've understood is that it's not really suitable for quads. It's more of a paraplegic application.

Influence of roles, activity preferences, environmental factors

A recurring consideration was whether the functional benefits would be worth the cost of an exoskeleton to facilitate specific roles or to allow participation in preferred activities or environments. For example,

> I guess if I was working I would use it around the office. I would walk around the office. I wouldn't move around place – places in the office to get up, um, because sitting in a chair all day and going from meeting to meeting is really boring. So if you can get up and stretch, get the oxygen flowing through your system, I would use it like that.

> I do as many things as I can do, but there's still a lot of things – I'd love to be able to, you know, mountain climb or go hiking or stuff like that that, you know, if this enabled me to do things like that, it might be worth it to me, but just to walk from here to there in six minutes with somebody going behind me wouldn't be worth it to me.

> I still can't walk my wife down the beach, nice sandy beaches or I can't go out and play, go out and hit baseballs and run the bases with my kids so I still can't do – it doesn't enable me to do enough things to make it worth my while.

> Man, if I could just leave my house, get into a car, go to the bar, go out to dinner, go like a normal person, that's priceless.

> My son rock climbs. To be able just going with him out on that terrain and not miss that part of his life that I don't want to miss.

> I'm only spending this exorbitant amount of money if it is providing the dream. I'm not spending a dime on the video I just saw.

> That would have to be something that we would have to be able to do, just like taking stairs; um, to get off and on buses; to get in and out of areas of stores.

> A lot less drama at the airport. TSA doesn't go crazy and you can walk on and off the airplane.

> Bad weather. It doesn't work great in the snow and the rain.

Recommendations to manufacturers and therapists regarding robotic exoskeletons

Participants made thoughtful recommendations to the manufacturers of the robotic exoskeletons. The primary considerations focused on cost, battery life, and independent use. For example,

> And for $1,50,000 you should be able to replace the parts when you need it, like some type of warranty, 5 or 10 years. Because the price is going to have to be expensive.

> The most constraining thing here is that battery. You call it 6 hours, but for somebody like me, 6 hours is fine for you, but 6 hours for me is just a very short period.

> But you need one more step in making it do it by itself without – so that way you can carry your groceries, you can comb your hair, you can do whatever, you can paint, you can do a million things with it. But by itself it's missing the part, which is with the balance.

Another recommendation focused on the perception that most treatment and technology research focuses on men with SCI. For example,

> I've noticed that there are a lot of treatments that are utilized, especially by the military, and they're usually tested on men. And so when they get a female patient it seems to throw everybody off. Nobody knows what to do. Nobody sure how to fit it. Nobody sure how it's going to react. Nobody knows anything about how it will relate to a female patient.

Participants also made recommendations relevant to clinicians regarding robotic exoskeletons. Some felt that being upright and walking would be motivating for persons with recent injuries. Several thought that clinic-owned devices would allow access for more individuals with SCI. Others thought that robotic exoskeletons would be useful as a therapy tool for individuals who have some ability to walk. For example,

> I think anybody new, like unfortunately anybody who's newly injured, it would give them a big boost, just hope and mentally, spiritually, psychologically. I think that just seeing something like that would give them the push and the drive to strengthen what they can train and hopefully build up to wanting to use a machine like that. Because that's the ultimate goal. At least in my mind. Anybody who's paralyzed, you want to be able to walk again. So just seeing that is like, 'I can get to that level,' or I can get to that hopefully it could be a goal for them. Whether it's realistic or not, it's realistic in your mind.

> I mean, everybody is thinking at a cost of $1,00,000, you know, it's just not worth it. That's why I said at the therapy facility it would be awesome to have it because you could try it, see if you like it, you know, but what if it was available for lease or for rent?

> Yeah, I would be interested just because it reinforces the gait and the strengthening. I have like a crazy walk, and that would train me to walk properly, rather than – I just got a weird walk

Discussion

We recruited a predominantly middle-aged and male sample that was diverse in terms of race and ethnicity. Participants were well educated, unemployed or retired, and living with SCI for more than two decades on average. About three-quarters used manual wheelchairs for mobility, 40% were able to walk without assistance, and most had not considered using a robotic exoskeleton though awareness of the technology was high. Walking remains a priority for persons with SCI, and with the progress in the development of robotic exoskeletons, it seems likely walking may be a feasible goal for a larger proportion of the SCI community than ever before. Among individuals with SCI who did not have experience with robotic exoskeletons, awareness and knowledge of these devices were variable. Some individuals actively sought out information, going as far as committing investment funds; others learned about the devices only when a friend or relative gave them information. Among those with interest in the devices, some recognized that their injury characteristics, such as having impaired hand function or bony defects, restricted their ability to use these devices.

Given the current state of technology in which robotic exoskeletons are used primarily in rehabilitation centers, and only to a limited extent employed for personal use, it is understandable that perceptions of exoskeleton usability are variable. The health and wellness applications were recognized by a number of participants, as were the possible benefits of the use of robotic exoskeletons over other rehabilitation devices for specific applications. Being able to walk upright in their community environments, rather than performing weight bearing and walking in a stationary standing frame or in a treadmill-based robotic device, were clearly identified advantages. Conversely, participants noted that the robotic exoskeletons have limitations that negatively influence independence, including the requirement for stand-by assistance from another person and for use of assistive devices for balance that precludes using hands for other tasks. Other limitations cited were related to a perceived decrease in functionality relative to a wheelchair, particularly slower speeds of exoskeletons, the time requirements for donning and doffing exoskeletons, the circumscribed environments and weather conditions in which the robotic exoskeletons can function, and the inability to wear the device while doing activities such as driving.

The participants suggested ideas for how robotic exoskeletons might be constructed and marketed in a way that would better facilitate their uptake. These ideas revolved around lowering cost, extending battery life, and improving usability through mechanisms that would allow hands-free functioning. Despite not having used robotic exoskeletons themselves, the motivational aspects of upright walking were apparent to participants, who noted that they might be particularly motivating for individuals with recent SCI.

From a clinical perspective, it is clear that those who have not had the opportunity to use a robotic exoskeleton recognize their potential value. Beyond the possibilities of early introduction to a form of assisted walking, the robotic exoskeletons offer opportunities for lower extremity loading, move the lower extremities through a functional range of movement, and reacquaint individuals with new injuries to upright activities. There is also some,

albeit limited evidence that upright activities may promote improved respiratory and bowel function [16].

In the context of research, there are important questions that are yet to be related to the value of robotic exoskeletons. Evidence related to their comparative efficacy and effectiveness as a neurorehabilitation tool for improving over-ground walking ability in specific SCI subpopulations is lacking. In addition, studies reviewing the long-term benefits of mobility at home and in community settings on expensive secondary complications such as pressure ulcers, osteoporosis, and cardiovascular disease are lacking. Finally, customizing of practice guidelines for different exoskeletal technology is needed to guide clinicians on how to use these technologies effectively. While there are many benefits of upright mobility, whether robotic exoskeletons provide a cost-effective approach to upright mobility compared to other approaches remains to be determined.

Regarding research and development, there are many opportunities that require exploration. Advancements that would allow these devices to be self-balancing would enable hands-free use, and perhaps even the ability to use the devices without the requirement of stand-by assistance from another person. Updated usability features such as ramps, curbs, stairs, increased degrees of freedom, modularity, and progressive therapy modes would be helpful. Finally, manufacturing approaches, perhaps like three-dimensional printed components, may facilitate lower cost manufacturing that could be passed on to consumers.

Readers should note several study limitations. We selected participants to maximize diversity in terms of sex, age, race and ethnicity, though their geographical distribution is limited. We designed the video clip to highlight the uses of exoskeletons, but the following question-and-answer discussion may not have addressed all concerns of the participants. The facilitator sought to establish a non-evaluative environment yet the focus group format may have limited participants' willingness to voice opinions that conflicted with the perspectives of others.

Conclusions

Focus group participants' appraisals of robotic locomotor exoskeleton technology reflect a nuanced appreciation of device costs; functional, social, and psychological benefits; and limitations. Individuals with a greater inclination to adopt technology early in its development expressed greater enthusiasm, while others were prepared to wait for future developments that would provide greater benefits at a lower cost. Results provide guidance to therapists and manufacturers regarding desired device features and applications.

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