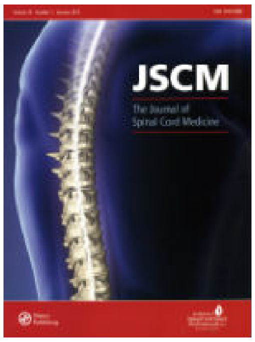

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Design recommendations for exoskeletons: Perspectives of individuals with spinal cord injury

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Research Article

Design recommendations for exoskeletons: Perspectives of individuals with spinal cord injury

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Objective: This study investigated the expectations of individuals with spinal cord injury (SCI) regarding exoskeletons.
Design: The survey consisted out of questions regarding multiple aspects of exoskeleton technology.
Setting: An online survey was distributed via the monthly newsletter of the Dutch Patient Association for Spinal Cord Injury (SCI).
Participants: Individuals with SCI who are members of the Dutch Patient Association for SCI.
Outcome Measures: General impression of exoskeleton technology, expectations regarding capabilities and user-friendliness, training expectations and experiences, future perspectives and points of improvement.
Results: The survey was filled out by 95 individuals with SCI, exoskeletons were considered positive and desirable by 74.7%. About 11 percent (10.5%) thought one could ambulate faster, or just as fast, while wearing an exoskeleton as able-bodied people. Furthermore, 18.9% expected not to use a wheelchair or walking aids while ambulating with the exoskeleton. Twenty-five percent believed that exoskeletons could replace wheelchairs. Some main points of improvement included being able to wear the exoskeleton in a wheelchair and while driving a car, not needing crutches while ambulating, and being able to put the exoskeleton on by oneself.
Conclusion: Individuals with SCI considered exoskeletons as a positive and desirable innovation. But based on the findings from the surveys, major points of improvement are necessary for exoskeletons to replace wheelchairs in the future. For future exoskeleton development, we recommend involvement of individuals with SCI to meet user expectations and improve in functionality, usability and quality of exoskeletons.

Keywords: Spinal cord injury, Exoskeletons, Ambulation, Patient's perspective

Introduction

One of the impairments patients with a spinal cord injury (SCI) often have to face is loss of (some degree of) walking function. Long-term consequences indicate increased risk of cardiovascular and metabolic diseases, osteoporosis and bowel constipation. Moreover, individuals with SCI, their relatives and their health care providers frequently classify the recovery of the ability to walk as a high priority.[1] Rehabilitation therapy is needed in order to regain (some) ambulatory function.

Technological advances in robotics have led to the development of lower extremity robotic exoskeletons for rehabilitation therapy. Exoskeletons are wearable robotic suits with electromotors at the hip and knee joints, rechargeable batteries, and a computer-based

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control system.[2] Robotic exoskeletons are suitable for taking over strenuous and repetitive tasks from therapists, and could thus be used to relieve some of the burden required by rehabilitation therapists to aid in ambulation. Moreover, these exoskeletons may potentially increase the efficiency of the therapy, since they could provide more intensive training, better quantitative feedback and improved functional outcomes compared to manual therapy.[3] In this way, therapists could focus more on other tasks, such as interacting with patients, assessing the outcome of the therapy and intervening during the training session if necessary.[3] Optimal robotic training programs could be designed and adjusted according to the patient's condition.[4,5] Multiple studies have already reported the safety of mobilizing with an robotic exoskeleton, as well as their feasibility and efficiency.[3,6–11] Moreover, exoskeleton training has already been shown to be beneficial for more than just walking function.[12,13] Examples include a potential 38% reduction in spasticity and 61% improvement in bowel function.[12]

Continuous development and improvement of exoskeleton technology requires sophisticated engineering training in mechatronics, controls, dynamics and computer science. In order to design the most innovative and technologically advanced exoskeletons, exoskeleton researchers think in terms of control algorithms, feedback loops, actuator band-width and power density[14,15] rather than patient perspectives. This may be encouraged by media attention and competitions such as the Cybathlon Experience: Powered Exoskeleton Race, in which individuals with SCI pilot an exoskeleton in an obstacle race.[16] There are only limited data available on patient perspectives regarding the development of exoskeletons, despite rapid progress in robotic exoskeleton design and technology.[17,18] Previous research has shown that the main benefits in involving users in device development are an increased and easier access to user needs, experiences and ideas, resulting in an increase in functionality, usability and quality of the devices.[19] Furthermore, it has also been suggested that in order to achieve successful integration of new assistive technology into daily lives of patients, it is crucial to investigate their expectations and their purpose for the device.[18,20] A discrepancy between the expectations regarding device requirements from patients and those from manufacturers could lead to the discontinued use of the device.[18]

A study by Wolff *et al.*[17] have already investigated the perspectives of wheelchair users and healthcare professionals regarding exoskeleton technology. They described the importance of comfort, affordability, minimization of fall risks and functional activities. However, this included individuals with various kinds of pathology and focused on general use of exoskeletons. Therefore the aim of this study was to investigate the thoughts and expectations of individuals with SCI regarding exoskeletons used for rehabilitation training purposes as well as personal use at home.

Methods

Design

We have reported the design and findings of the survey according to the Checklist for Reporting Results of Internet E-Surveys (CHERRIES) guidelines.[21] The survey was based on the current literature and feasibility studies regarding exoskeleton.[9,10] There were both open-ended and multiple choice questions. Questions were divided into multiple categories regarding demographics, general impression of exoskeletons, expectations regarding capabilities and user friendliness, exoskeleton training experiences, future perspectives and points of improvements. The design of the questionnaire was that of an open survey, accessible to each visitor using the provided link to the website. An English version of the questionnaire can be found in the Supplement.

The survey was assessed on readability and simplicity by the Dutch patient association for SCI: Dwarslaesie Organisatie Nederland. It was deemed comprehensible, well written and legible.

Ethics

Answers from the survey were manually entered and processed anonymously in Microsoft Excel, 2010. Informed consent was achieved by the participants completing the questions and submitting the answers. Approval for this study was obtained from the local ethics committee from the Radboud University Medical Center in Nijmegen, The Netherlands.

Recruitment process

All individuals with SCI were eligible for this study, regardless of age or comorbidities. Participants were recruited via the Dutch patient association for SCI in 2018. Potential participants were invited to participate in this study via a short message in an online monthly newsletter from the SCI patient association. A link provided in the newsletter referred people who were interested in participating directly to the online, anonymous questionnaire, where the study and the aim was further explained.

Survey administration

The questionnaire was created on a website dedicated to building online surveys, called Survio. The questionnaire could only be accessed by the direct link provided in the newsletter from the SCI patient association.

No incentives or prizes were offered for completing the questionnaire. The link to the questionnaire was placed twice in the newsletter from the SCI patient association over the course of three months. Data regarding IP address, view rates and completion rates were not collected, only completed surveys were used in the analysis.

Adaptive questioning was not used in the survey from this study. The questions were distributed over six pages, with a maximum of nine questions per page. For every page, the website checked that mandatory items were completed before continuing to the next page. Participants were able to change their answers through a Back button.

Results

The survey was completed by 95 participants; five of them (5.3%) were not familiar with exoskeletons. Most subjects (57.9%) had learned about the exoskeleton via television, for example, documentaries or the national news. Also, 36.8% of the participants had read about exoskeletons on social media such as Facebook, Twitter or LinkedIn.

Demographics of the participants are described in Table 1. The majority were male and lived with their partner. Not reported in this table: 45 participants (47.4%) had a paid job, on average 28 h per week (SD 12.8). Fifty-six respondents (58.9%) were content with their current way of mobilizing.

Thoughts about exoskeletons were mainly positive; 74.7% of the subjects considered it a good and desirable innovation. The participants who felt negatively about exoskeletons called them unpractical since you need to use crutches, are or may be slow, and too robot-like.

A total 57 respondents (60%) would like to have an exoskeleton at home for private use. Forty-eight (50.5%) would be willing to pay to have an exoskeleton at home. Furthermore, 47 respondents (49.5%) would be willing to pay for training sessions with an exoskeleton. The amount participants were willing to pay vary from 10 euros per training session to 250 euros. In addition to that, participants were willing to pay up to 5000 euros and some even up to 10.000 euros to have an exoskeleton at home.

Expectations of the exoskeleton

Expectations regarding walking speed while walking with an exoskeleton, as well as usage of wheelchair or walking aids are described in Table 2. The majority of participants expected to still walk much slower than able-bodied people while using an exoskeleton. Additionally, 50.5% expected to use walking aids while walking with an exoskeleton, and not use a wheelchair anymore.

Next were questions regarding expectations on user-friendliness: putting it on, mobility, required training to be able to walk in an exoskeleton, comfort while wearing it and weight. A total of 73 respondents (76.8%) expected it to be difficult to put on the exoskeleton. Regarding mobility, 59 respondents (62.1%) expected that to be difficult. Meanwhile, 72 respondents (75.8%) expected it requires a lot of training before being able to ambulate in an exoskeleton. Additionally, 37 respondents (38.9%) expected the exoskeleton to be uncomfortable to wear, and 61 respondents (64.2%) expected the exoskeleton to be heavy.

Of the respondents, 24 (25.3%) expected that in the future the exoskeleton can replace a wheelchair. Common reasons why people think this may not happen were that crutches are needed to ambulate in exoskeletons, making it difficult to carry something.

Table 1 Demographics of the participants.

Sex	
Male	62 (65.3%)
Female	33 (34.7%)
Mean age (SD) in years	53 (14.1)
Marital status	
Married or living together	59 (62.1%)
Never married	26 (27.4%)
Divorced, widowed or did not want to say	10 (10.5%)
Mode of mobilization	
(Electrical) wheelchair	74 (77.9%)
Wheelchair and walking aids	21 (22.1%)
Walking aids alone	0 (0%)

Table 2 Expectations regarding walking speed and use of wheelchair or walking aids while ambulating with an exoskeleton.

Walking speed in comparison to able-bodied people	
Much slower	52 (54.7%)
Slower	33 (34.7%)
Just as fast	8 (8.4%)
Faster	2 (2.1%)
Walking aids while using an exoskeleton	
Wheelchair only	29 (30.5%)
Walking aids only	48 (50.5%)
No wheelchair or walking aids	18 (18.9%)

Also, it is not possible to drive a car while wearing an exoskeleton, and supervision while using the exoskeleton is required in case of errors or falls. Due to all this, participants thought that they are more mobile and faster in their wheelchair than in an exoskeleton. Furthermore, the current exoskeletons are often not suitable for people with higher SCI, because of the missing core balance.

Future perspectives

The main points of future improvement are similar to the reasons listed as to why participants thought an exoskeleton cannot replace a wheelchair. Namely, exoskeletons should be adjusted so that they are suitable for people with higher SCI as well. Also, it should be possible to ambulate in an exoskeleton without the use of crutches, thus allowing for carrying things.

According to the respondents, other points of improvement are the possibility to walk independently in an exoskeleton, walking on irregular surfaces, lighter weight and an easier way to put on the exoskeleton. Finally, the respondents would like to see the exoskeleton fit in a wheelchair and in a car while wearing it, so that they can still drive a car while wearing the exoskeleton.

Training with an exoskeleton

Seven respondents (7.4%) have had the opportunity to train with an exoskeleton. Of the 88 respondents who had not yet trained with an exoskeleton, 73.9% are open for training opportunities. The main reasons for respondents not to be interested in training with exoskeletons were that it would be too time-consuming and that it would not add anything to their quality of life.

Of the seven respondents with experience with exoskeleton training, four (57.1%) considered the exoskeleton a positive, new innovation. This is lower compared to the participants without experience with exoskeleton training, of whom 74.7% considered the exoskeleton as positive. The remaining three respondents thought of it as irrelevant, not adding to their quality of life, too difficult to operate and exhausting. Two of the seven participants (28.6%) who had trained with an exoskeleton before thought the exoskeleton could replace a wheelchair. The main reasons of those who did not think so were similar to respondents who hadn't trained in an exoskeleton–namely, it is too exhausting to ambulate long distances with an exoskeleton, it moves too slowly and one needs to use crutches and exoskeletons are not suitable for people with higher SCI. The main points for improvement of the exoskeleton were similar as well: being able to ambulate in it without crutches, weighing less, easier to put on independently and greater suitability to ambulate indoors.

Discussion

The results from this study showed that although individuals with SCI consider exoskeletons a positive and desirable innovation, there are still major points of improvement. The main issues regarding exoskeletons raised by the participants were user-friendliness, such as the ambulatory speed of exoskeletons, weight and ease of putting the exoskeleton on, and balance issues which result in the use of crutches while using the exoskeleton, which is similar to the results from the study by Wolff *et al.*[17]

More than 50% of the participants thought they would not need crutches while walking with an exoskeleton. However, most of the current exoskeletons are not designed to maintain balance, which is the reason that the patient needs crutches during ambulation. An exception to this is the REX exoskeleton by REX Bionics.[22] This is also the reason that exoskeletons are currently unsuitable for users with higher-level SCI, who have poor upper extremity strength. Moreover, the ambulatory speed of current exoskeletons is relatively low, on average 0.26 m/s.[11] Despite that, over 10% of the participants in this study expected that one can ambulate with an exoskeleton just as fast or even faster than able-bodied people. However, the average walking speed of able-bodied people is far higher, namely 1.3–1.4 m/s.[23]

Compared to participants without training experience, those who had experience with exoskeleton training were more negative regarding exoskeletons. This is consistent with the findings from a feasibility study by Benson *et al.*[2] who described more negative patient perspectives after exoskeleton training compared to the expectations before the training. This implies that the reality of the exoskeleton training and its capabilities does not match the expectations that patients may have. Such disillusionment can lead to dropping out of exoskeleton training and abandonment of the device and its technology, which is a well-documented phenomenon.[18] To prevent that from happening to exoskeletons, we believe that it is important to involve patients in the development of exoskeletons.

Clinical relevance

Taking into consideration the results of the survey, one could say that exoskeletons should be able to ambulate at higher speeds, and without the use of crutches to allow the user to carry things. It should be possible for patients to get in and out of the exoskeleton by themselves, without the help or supervision of others. Moreover, being able to wear the exoskeleton while driving a car or using a wheelchair for longer distances also seems to be important for patients. In short, it seems to be important that users are equally mobile and independent while wearing an exoskeleton in the community as they are now with their wheelchair. However, we realize that this study questioned only a small number of individuals with SCI, and so we recommend further studies in order to pursue patient-centered care in the development of exoskeletons for people with SCI.

Limitations

There are some limitations regarding the results from this study due to the nature of the survey. There were no questions regarding the level and severity of injury or timing since injury. There may have been a selection bias of the participants, resulting in spinal cord injured patients with interest in technical innovations like the exoskeleton to participate in this study. Moreover, people who are technophobic or illiterate are not likely to have participated in the online survey. Therefore generalizability of the results is uncertain.

Conclusion

Based on the results from this study, the functional capabilities of current exoskeletons seem to be below the expectations of individuals with SCI. The main points of improvement seem to be walking speed, user-friendliness and independency while using the exoskeleton, since the expectations of individuals with SCI are not met in these areas. In short, it seems to be important that patients are equally mobile and independent while wearing an exoskeleton in the community as they are now with their wheelchair. We recommend involvement of individuals with SCI in future developments of exoskeletons in order to meet the users expectations and improve functionality, usability and quality of the exoskeletons.

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Conflicts of interest Authors have no conflict of interests to declare.

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