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Identification of needs for an assistive robotic arm in individuals with tetraplegia: a mixed-methods approach

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Abstract

Background A severe spinal cord injury (SCI) can profoundly affect an individual's physical abilities and social independence. For individuals living with tetraplegia, an assistive robotic arm offers the potential to restore some autonomy and reduce the need for constant assistance. However, current assistive technologies are often costly, impractical, and fail to meet the needs of those affected. This leads to high rates of abandonment and user frustration with the technology. The aim of this study was to identify the needs and expectations of both individuals with tetraplegia and their caregivers regarding an assistive robotic arm in performing everyday activities.

Methods A mixed-method approach was used, beginning with a focus group interview and followed by two online surveys; one aimed at individuals with tetraplegia and the other at caregivers. Qualitative analysis of the focus groups was performed using Focus Group Illustration Mapping. The online surveys were analyzed descriptively and qualitatively using structured content analysis.

Results A total of seven participants (individuals with tetraplegia, caregivers, physiotherapists, and an engineer) took part in the focus group interview. The online surveys were completed by 49 individuals with tetraplegia and nine caregivers. The results showed that the participants were open to using a robotic arm but none used one at the time of reporting. The participants reported that a robotic arm should assist in unilateral activities such as reaching, grasping, handling objects and body manipulation. The greatest need was reported for functions related to object manipulation and for contact with the person's body. The participants reported wanting control over the robotic arm via voice commands or with a joystick. Concerns were reported regarding costs, the weight and the space required for the robotic arm.

Conclusions In our study, individuals with tetraplegia reported that they would use assistive robotic arms for activities related to reaching, grasping, and object manipulation. Concerns regarding costs, weight and space requirements were reported. Our findings provide insights from a user perspective, informing future technical developments relevant to the tetraplegic population. However, generalizability might be reduced.

Keywords Activities of daily living, Assistive technology, Caregivers, Requirements, Needs, Robotic arm, Robotics, Spinal cord injury, Tetraplegia, User-centered

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Background

Activities of daily living (ADL), such as participation in sports, working, or grocery shopping pose significant challenges for individuals with physical impairments and patients with neuromuscular damage. With 0.9 million incidents and 20.6 million prevalent cases globally reported in 2014, spinal cord injuries (SCI) are a substantial contributor to physical disabilities [1]. SCI refers to traumatic or non-traumatic damage to the spinal cord [2], resulting in sensory, motor, and autonomic dysfunction below the level of lesion [3]. Damage to the cervical spinal cord leads to tetraplegia and can cause a partial or total loss of sensory and/or motor functions of the four limbs and the torso [4]. Restoring arm and hand function is reported to be the most important by individuals with tetraplegia, as even partial arm and hand function has a strong impact on independence [5]. Previous studies have demonstrated that increased independence contributes to improving the quality of life of individuals with tetraplegia [6, 7]. In a previous study, a total of 77% of the individuals with tetraplegia expected a substantial improvement in their quality of life with better hand function [8].

The loss of autonomy can lead to an increased level of psychological stress [9]. Caregivers are also susceptible to developing mental health disorders, as Keihanian et al. [10] reported that SCI-caregivers are at greater risk of developing physical or mental conditions or facing social challenges than caregivers of individuals with other chronic illnesses. This burden on caregivers significantly influences their quality of life [11].

Assistive technologies (AT), among other aids, can significantly enhance the lives of individuals with physical impairments, promoting their equal participation in society [12]. AT is defined as a semi-autonomous or fully autonomous unit that can take over human tasks [13]. AT promote participation, independence, self-esteem, and overall satisfaction after a SCI [14]. Individuals with tetraplegia who utilize AT in ADL appreciate the autonomy and spontaneity provided by these technologies, enabling them to engage in meaningful activities [15–17]. Rudioff et al. [18] categorized AT into five groups: neuroprostheses, orthotic devices, hybrid systems, robots, and arm supports. The choice of AT depends on a variety of factors, e.g., the degree of the condition and related impairments or environmental and personal factors such as age and fitness [19]. Robots are non-invasive AT devices that generate functional movements without the need for users to have any residual motor function [20]. Assistive robotic devices, such as robotic arms mounted on wheelchairs, have the potential to facilitate daily life and reduce the need for external assistance [21]. The development and use of an assistive robot in the daily

lives of individuals with tetraplegia are relatively new. [22] The implementation of assistive technologies in everyday life is challenging, as most existing devices are too expensive, impractical, and fail to meet the needs of individuals with tetraplegia and their families [23, 24]. In a recent study, it was found that controlling an assistive robot with six degrees of freedom (DoF) through a two-axis joystick and many different control modes appears to be a cognitive challenge, that requires a large amount of time to perform ADL [24]. This may be why the use of robotic arms for tetraplegia is mainly limited to rehabilitation and therapy purposes [18].

Literature shows that individuals with physical impairments can significantly contribute to the improvement of research quality [25]. Through user-centered design, we can develop assistive technologies for the upper extremity that truly meet the needs of individuals with tetraplegia by understanding their challenges, expectations, and preferences. A co-design approach would also allow a reduction in the rate of technology abandonment and user frustration [26–29].

There is limited available data assessing the needs of individuals with tetraplegia and of their caregivers in relation to robotic arms. Therefore, the aim of this study was to identify the needs and expectations of individuals with tetraplegia and their caregivers regarding an assistive robotic arm for performing ADLs, to support a user-centered development approach. We hypothesized that a robotic arm should primarily take over activities that occur several times throughout the day.

Methods

For the reporting of the results of the surveys, the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [30] for cross-sectional studies as well as the Checklist for Reporting Results of Internet E-Surveys (CHERRIES) checklist [31] were followed (Additional files 1 and 2).

Overall design

The study was approved by the ethics committee of Bern, Switzerland (KEK-No. Req-2022–01492) and was conducted in accordance with the declaration of Helsinki and the European Code of Conduct for Research Integrity.

This study used a mixed-method approach [32]. A semi-structured focus group interview was followed by two online surveys consisting of qualitative and quantitative questions (explanatory sequential design, open-ended questions, and questions with scales ranging from 1 to 10) [33, 34]. One survey was aimed at individuals with tetraplegia and the other at caregivers. Qualitative research was conducted first to explore unknown variables and gain deeper insights, ensuring that the

subsequent quantitative research was grounded in relevant findings.

Focus group interview

Procedure

The focus group interview was performed in a semi-structured manner. A set of initial questions (Additional file 3) based on Schulz et al. [35] were developed and the question-guide was divided into three thematic areas. The first thematic area, formulated based on literature research and discussions within the research team, aimed to capture participants' general experiences with AT. The second addressed the current research questions (i.e., expectations on AT). The third thematic area evaluated quality and suitability of pre-formulated questions for the online survey. The focus group interview was conducted online in Swiss German via Microsoft Teams (MS-Teams) on March 7, 2023, and video and audio were recorded. At the beginning of the interview, online ground rules and time plan were explained. Then, the different participants were asked to introduce themselves by name and role. The interview was conducted by a member of the research group, while another noted keywords in a cloud-based notebook to document the discussion. To ensure quality and objectivity, a summary was sent to the participants to check for completeness and accuracy.

The recordings were transferred to a secure server of the research institute, which was only accessible by the members of the research team. MS Teams recordings were deleted after the data transfer.

Sampling and recruitment

To enable optimal dynamics of the focus group with different perspectives and to ensure sufficient heterogeneity, the following groups were invited to participate: [1] individuals with tetraplegia, [2] caregivers, [3] physiotherapists, [4] engineers. All participants were recruited through the professional network of the authors via word-of-mouth. The participants were invited based on their expertise and expected specialist knowledge or experience. Interested people were required to understand and speak German and be at least 18 years old to participate.

Written consent was obtained from all participants agreeing to the purpose and terms of the investigation as well as to the associated potential risks and benefits.

Qualitative Data Analysis

The interview recording was transcribed manually by a research team member. The concept of 'Focus Group Illustration Maps' (FIM) described by Pelz et al. [37] was used for the qualitative data analysis of the focus group interview. FIM is part of the content analytical methods

and describes the visual presentation of results from focus group interviews. For the visualization and presentation of the FIM, the software Inspiration® (version 10, TechEdology®, UK) was used to highlight individual aspects, core themes, and statements [37]. The recorded interview and the keywords documented in the cloud-based notebook were examined for this purpose. Firstly, categories were constructed. Afterwards, the transcribed interview sections were coded and assigned to the constructed categories. An inductive approach was used. Color codes were used for each participant, allowing to keep track of what was said by whom. In favor of clarity and readability, multiple FIMs can initially be created and later consolidated into one [37]. Due to satisfactory clarity (focused discussion themes, only minimal overlaps between different topics, and relatively small number of participants), only one FIM was generated following the interview analysis. All qualitative results (the results of the focus group interview and additionally the qualitative results of the surveys, described in 2.3) were analyzed following the process described by Kuckartz [38]. Initial categories were constructed based on the International Classification of Functioning, Disability, and Health (ICF) in a deductive, top-down approach. In the ICF model, the functioning of an individual was considered a result of an interaction between the individual's health condition and personal attributes as well as contextual/environmental factors [39]. The results were coded and analyzed individually by three members of the research team with expertise in health sciences to enhance inter-subjective comprehensibility. To identify necessary and useful functions for the robotic arm, new categories were constructed through inductive reasoning, and all codes were redistributed. The formation of these categories was a consensus-based decision-making process, performed by three members of the research team, two with expertise in health sciences and one engineer, and they did not participate in the focus group.

Surveys

Procedure

The survey data were collected and managed using LimeSurvey® (version 2.56.1). LimeSurvey® is open source and is operated on the research institution's server. No personally identifiable data or IP addresses were collected, and no cookies were used. Two online self-administered surveys were developed, one for individuals with tetraplegia and one for caregivers. Due to the lack of existing surveys on the needs of individuals with tetraplegia regarding a robotic arm, the surveys were constructed based on the results of the focus interviews and the Assessment of Life Habits (Life-H) 3.0 Questionnaire. The Life-H questionnaire evaluates

the quality of social participation among individuals with disabilities by assessing how an individual performs activities of daily living and fulfills social roles [40]. Since the Life-H questionnaire did not cover all areas relevant to the research question, it was supplemented through discussions within the research team. The core project team has expertise in physiotherapy, movement science, and engineering.

The online surveys were not password-protected—and included closed questions (Likert-type items with a scale from 1 to 10, single-choice, and multiple-choice) along with open questions for comments. Each item provided a non-response option. The surveys, designed for individuals with tetraplegia and caregivers, could only be submitted after answering the question regarding their level of injury or, for caregivers, the level of injury of the individual they care for. Adaptive questioning (branching logic) was used to reduce the number and complexity of the questions depending on the participant's answers. Thus, the number of questions varied among the respondents. The questionnaire for individuals with tetraplegia contained between 30 and 50 items, while the questionnaire for caregivers ranged from 26 to 43 items. Once submitted, the responses could not be modified. It was technically impossible to do a completeness check before submitting.

The first pretest of the survey for individuals with tetraplegia was performed by two individuals with tetraplegia and two experts in neurological physiotherapy, while the survey for caregivers was evaluated by three caregivers and one engineer, who were not involved in the focus group interview. Relevance of the questions' content and comprehensibility were evaluated using Likert-type items with a four-point scale (–, –, +, ++), with the option to provide comments. The questions were modified if rated as a – or a – on the scale for either relevance or for comprehensibility.

After the first revision, both surveys were subjected to a second pretest by two experts in human movement science, one individual with tetraplegia, and an engineer, who were not involved in the focus group. To include as many points of view as possible, the assessors varied between the first and the second pretest. The evaluation criteria remained consistent. All assessors independently filled out evaluation sheets, and all were in favor of the survey, indicating unanimous agreement that each item was relevant, and the wording was appropriate. Prior to fielding the questionnaire, the functionality of the online survey was tested by members of the research group.

The final survey started with an introductory section, where participants were informed about the aim of the study, what robotic arms are, the estimated time required for completion of the survey, the name of the

investigators, data usage, and their rights. Consent was obtained by participants clicking the corresponding button on the page. The introductory section was followed by three sections with questions to be answered: [1] inquiries pertaining to the individual such as personal data and physical abilities, [2] inquiries concerning the related wheelchair, and [3] inquiries related to the robotic arm (experiences, perspectives, benefits, and barriers). In addition to the quantitative aspects of the surveys, the areas, and activities in which individuals with tetraplegia experience limitations and barriers in their daily lives (without the use of AT), and the areas, and activities in which there is a need for a robotic arm were assessed with open questions.

For several categorial questions, multiple answers were possible and were marked with an asterisk (*) in Tables 2, 3 and 5. The surveys were accessible online from August 14 to November 30, 2023.

With the use of a translation software (DeepL, DEEPL SE, GERMANY) both surveys were translated from German to English for this publication. The original versions and both translations are provided (Additional files 4 and 5).

Sampling and recruitment

Individuals with tetraplegia who had complete or incomplete motor and/or sensory paralysis and actively use a wheelchair in daily life were eligible for one of the surveys. There were no restrictions for participation in terms of severity of the lesion. Individuals who care for wheelchair-dependent individuals with tetraplegia in their daily lives were eligible to complete the other survey. An understanding of the German language was another inclusion criterion. The chain-referral sampling technique was used for recruitment. This technique was chosen as it was the most appropriate for the recruitment of participants given the limited number of individuals meeting the inclusion criteria. The survey invitation, the inclusion criteria for individuals with tetraplegia and caregivers, and the survey-link were spread with flyers and online via email, social media, and on the website of the research institute. Flyers and emails were sent to various associations, groups, and organizations for individuals with a disability. In addition, the study information was sent to all major clinics and physiotherapy/medical practices in German-speaking regions that treat individuals with tetraplegia.

Statistical analysis

As each survey question was analyzed individually, all responses were included in the analysis regardless of missing data. Missing data were present, partly due to the branched survey design, causing the number of responses

per item to vary. The data were descriptively analyzed using R software (version 2023.09.1).

The outcomes were expressed in terms of frequencies and percentages for categorical data. For ordinal data (10-point Likert-type items), the median and the interquartile range (IQR) were calculated to state central tendency and spread [41]. Furthermore, a frequency distribution was computed to display the number of observations in each category.

Questions using a Likert-type item were included in the final analysis and discussion if the responses' median was equal to or larger than 6. Qualitative data were analyzed as previously described in Sect. "Focus group interview". The limitation in ADLs of individuals with tetraplegia as well as their needs regarding a robotic arm were further analyzed in subgroups (C5 and below versus above C5) to gather more detailed information.

Results

Focus group interview

The focus group interview took 2 h and 30 min. A total of seven participants joined the focus group interview. The group consisted of two individuals with tetraplegia (T1 and T2), two caregivers (C1 and C2), two physiotherapists (PT1 and PT2) and one engineer (E1). There

were personal relationships between some of the participants as C1 was the brother of T1 and C2 was the daughter of T2. The self-reported sample characteristics can be found in Table 1.

Experiences with AT in general

Both participants with tetraplegia in the focus group interview reported using electric wheelchairs as AT in their daily lives. T1 reported that their chin controls their electric wheelchair, while T2 uses a hand joystick. To facilitate their daily activities in their home environment, they reported having technologies such as automatic door openers (T1 and T2), window openers (T1), and television control systems (T1 and T2), which are operated by voice commands or with the touchscreen on their mobile phones (T1 and T2). The lack of further AT usage was reported from two primary factors: first, T1 and T2 have not recognized the need for additional AT and second, this reluctance is influenced by the unclear descriptions and complexity of AT (C2). C2 said, "We are always looking for solutions to a problem... or have to solve problems...". If AT could solve these problems, they would consider AT as a solution (C2 and T2).

Table 1 Sample characteristics of the focus group participants

Individual	Characteristics
T1	<ul style="list-style-type: none"> • Male • 67 years old • SCI at the level of C3 (AIS B, complete motor and incomplete sensory paralysis) • Traumatic SCI 2018
T2	<ul style="list-style-type: none"> • Female • 62 years old • SCI at the level of C4 (AIS A, complete motor and sensory paralysis) • Traumatic SCI 2009
C1	<ul style="list-style-type: none"> • Male • 63 years old • Caring for an individual with a severe contusion at the level of C3/C4 and a blood clot at the level of C2 (AIS C, incomplete motor and sensory paralysis)
C2	<ul style="list-style-type: none"> • Female • 37 years old • Caring for an individual with an SCI at the level of C4/C5 (AIS A, complete motor and sensory paralysis)
PT1	<ul style="list-style-type: none"> • Female • 40 years old • Professional experience for 16 years in the field of neurology • No professional or personal experience with AT outside this research project
PT2	<ul style="list-style-type: none"> • Female • 29 years old • Professional experience for 5 years in the field of neurology • No professional or personal experience with AT outside this research project
E1	<ul style="list-style-type: none"> • Female • 26 years old • Educated in biomedical engineering • Professional experience for 1 year in the field of AT development (electrical engineer with a specialization in pressure sensing)

AIS = American Spinal Impairment Scale [36]; AT = assistive technologies; T = individual with tetraplegia; C = caregiver; PT = physiotherapist; E = engineer

Expectations on a robotic arm

Four participants reported that they expect the robotic arm to undertake tasks that occur repeatedly throughout the day, such as adjusting optical glasses, scratching their head, bringing coffee (T1, T2, C1, C2), combing hair, and retrieving an item or clothing from the wardrobe (T2, C2). Additionally, a robotic arm is expected to assist with tasks that T1 and T2 preferred not to request help for repeatedly, including turning newspaper pages, nose blowing (T1, C1), dressing (T2, C2), picking up objects from the floor, and turning devices on or off (T1, T2, C1, C2). Therefore, it was concluded that the robotic arm is expected to perform mostly unilateral tasks (PT1). Since T2 reported to spend several hours alone each day and is not able to independently empty the urine bag of the permanent catheter, this also would be a useful function for T2. T1 and T2 have encountered issues with the pre-existing AT (e.g., automatic door opening), finding that it did not work as expected due to a technology-related problem. Therefore, the participants in the interview expressed a desire for a robotic arm to also take over the tasks currently performed by other AT if they malfunction. To implement all the aforementioned functions, participants envisioned an autonomous robotic arm with a gripper, operable through speech (T1, T2), a joystick with chin control (T1), and/or a touchscreen (T2).

Functions with low relevance

The participants expressed that time-saving functions were not a high priority, whereas the quality of task execution was. T1 expressed, “time is not a concern” to which T2 reinforced with the statement, “we have practiced patience”. Due to fewer self-reported motor limitations, T2 reported being able to perform certain tasks independently (brushing teeth, eating) or with slight assistance (dressing). Therefore, T2, reported no need for the robotic arm to perform these functions. However, T1 also stated that the robotic arm should not take over complex and bimanual tasks (eating, personal hygiene, dressing). This view was shared between C1, C2 as well as PT1. Participants reported that planned tasks (personal hygiene, brushing teeth, eating) that occur at the same time every day should not be taken over by a robotic arm. The reasons included: C1 and C2 reported being happy to help, that these tasks were well-organized, and it was presumed that the quality of a robot is not comparable to that of a human (T1, T2, C1, C2). In this context, quality referred to the lack of fine motor skills and sensitivity in a robotic arm, as well as the absence of human interaction, which are crucial for tasks like feeding, where a human would naturally combine food components with care and consideration.

Summary

The focus group interview revealed that both, individuals with tetraplegia and their caregivers have needs in relation to a robotic arm for grasping and reaching as well as for handling objects. Manipulation of one’s own body was particularly desired during fine motor activities such as scratching the head, adjusting optical glasses, or nose blowing.

Survey of individuals with tetraplegia

A total of 74 individuals with tetraplegia accessed the online survey, and a total of 49 individuals with tetraplegia completed the survey. The completion rate, therefore, was 0.7. It was technically not possible to determine a unique site visitor.

The majority of the 49 individuals with tetraplegia were male with a mean age of 45.0 ± 15.7 years (mean \pm SD). Fourteen participants had an injury at C4 or higher. The most prevalent level of paralysis was at C5. Most participants did not require artificial ventilation (73.5%). Furthermore, 26 of the participants reported having a complete paralysis. The participants reported pain (38.8%), spasticity (42.9%), altered joint mobility (44.9%), altered sensibility (57.1%) or reduced strength (81.6%). They reported a mean remaining strength of 47.1% and of 46.7% in their left arm and their right arm, respectively. Table 2 illustrates the sample characteristics of individuals with tetraplegia who completed the survey.

Type and control mechanisms of wheelchairs

Most participants reported owning a manual wheelchair. A large proportion of participants who owned more than one type of wheelchair used their manual wheelchair most often. This choice was motivated by the desire to preserve personal strength and self-esteem. Practical considerations, such as its compact design and lightweight nature also influenced their decision. However, for longer distances and outdoor use, some of the participants employed power assist wheels to facilitate independent mobility. Power assist wheels provide a consistent level of assistance every time the individual with tetraplegia applies sufficient force [42]. Participants used electric wheelchairs for reasons including: emphasizing independence, mobility, and participation. Participants with electric wheelchairs, reported controlling them by hand with a joystick, by chin with a joystick, by sip and puff, or with the tongue. The descriptive analysis of questions regarding the type and control mechanisms of the wheelchairs of the participants with tetraplegia can be found in Table 3. Participants reported facing challenges with the width of their wheelchairs in everyday situations such as passing through a door, using an elevator, or shopping. More than half (52.2%) of the participants

Table 2 Sample characteristics of individuals with tetraplegia who completed the survey

Characteristic	Value	Occurrence n (%)
Gender (respondents = 49)	Male	29 (59.2%)
	Female	19 (38.8%)
	Diverse	1 (2.0%)
Age (years) (respondents = 49)	Mean	45.0
	SD	15.7
	Min	12
	Max	74
Level of injury (respondents = 49)	C1	2 (4.1%)
	C2	4 (8.2%)
	C3	4 (8.2%)
	C4	4 (8.2%)
	C5	14 (28.6%)
	C6	8 (16.3%)
	C7	3 (6.1%)
	C8	1 (2.0%)
	TH1	2 (4.1%)
	No answer/ unknown	7 (14.3%)
Completeness of the lesion (respondents = 49)	C1	50% complete, 50% incomplete
	C2	50% complete, 50% incomplete
	C3	75% complete, 25% incomplete
	C4	25% complete, 75% incomplete
	C5	75% complete, 25% incomplete
	C6	100% complete, 0% incomplete
	C7	100% complete, 0% incomplete
	C8	79% complete, 21% incomplete
	TH1	75% complete, 25% incomplete
	No answer/ unknown	67% complete, 33% incomplete
	In total:	100% complete, 0% incomplete
	Complete	100% complete, 0% incomplete, 1 unknown
	Incomplete	26 (53.1%)
Unknown	22 (44.9%)	
Symptoms in arm, hand and shoulder (respondents = 49)*	Pain	1 (2.0%)
	Spasticity	19 (38.8%)
	Altered joint mobility	21 (42.9%)
	Reduced strength	22 (44.9%)
	Altered sensibility	40 (81.6%)
	None	28 (57.1%)
Remaining strength (respondents = 49)	Left arm: mean (\pm SD)	2 (4.1%)
	Right arm: mean (\pm SD)	47.1% (\pm 34.7%)
	Left hand: mean (\pm SD)	46.7% (\pm 34.3%)
	Right hand: mean (\pm SD)	22.3% (\pm 31.4%)
		23.8% (\pm 30.7%)

*Indicates that multiple answers were possible

would not like their wheelchair to be widened by an AT more than 5 cm.

Use of a robotic arm

When asked about previous use of a robotic arm, 31 out of 33 participants, who answered this question, stated that they had never used one before. The main reason was that participants did not know that robotic arms existed or did not have enough information about their

capabilities. Other frequently mentioned reasons were impracticality, costs, and time expenditure. However, participants saw potential in using a robotic arm for their ADL (median 6, IQR 4.3). Regarding Life-H, participants considered the use of a robotic arm particularly meaningful for ensuring nutrition (median 7, IQR 8). Regarding nutrition, the desire for assistance from the robotic arm was found to be highest for going into a supermarket (median 7.5, IQR 4.3) and for drinking (median = 7.5,

Table 3 Descriptive analysis regarding the wheelchair of survey participants with tetraplegia

Characteristic	Value	Occurrence n (%)
Type of wheelchair owned (respondents = 46)*	Manual	26 (56.5%)
	Electric	17 (37.0%)
	Power assist wheels	16 (34.8%)
	Other:	
	• E-fix	2 (4.3%)
	• Swiss Trac	1 (2.2%)
	• Standing wheelchair	1 (2.2%)
Preference when owning several types of wheelchairs (respondents = 46)	• Push wheelchair with motor	1 (2.2%)
	Manual	21 (45.7%)
	Electric	15 (32.6%)
	Power assist wheels	10 (21.7%)
	Control of the electric wheelchair (respondents = 17) *	Hand with a joystick
Chin with a joystick		6 (35.3%)
Eye movements		0
Sip and puff		1 (5.9%)
Head movements		0
Tongue		1 (5.9%)
Brain-computer-interface		0
Voice		0
Touchscreen		0
Other:		
• No independent control		1 (5.9%)

*Indicates that multiple answers were possible

IQR 2.8). Preparing cold (median 7, IQR 3) and warm meals (median 7, IQR 4.5), eating (median 7, IQR 4.5) and preparing cold (median 7, IQR 3.5) and warm drinks (median 6.5, IQR 2.5) also seemed to be important.

The limitations/ barriers in the daily life of individuals with tetraplegia (without the use of AT) and their needs regarding a robotic arm were evaluated according to ICF and compared in Fig. 1. All respondents' answers were assigned to ICF Part 1 (functioning and disability). Very few mentioned needs relating to the robotic arm were assigned directly to the body function and structure ICF-component. These needs are not directly relevant to the potential development of a robotic arm because they do not provide sufficient detail on how such an arm could assist users or specify the necessary functions. Therefore, they were analyzed in summary form. For the activities and participation ICF-component, the answers were assigned to eight categories and were analyzed separately regarding limitations and needs. It was found that most limitations and barriers, as well as most needs, exist in the ICF-categories of mobility (i.e., changing/maintaining body position, carrying, moving, and handling objects, walking, and moving around) and taking care of oneself (i.e., washing yourself, caring for your body parts, using the toilet, dressing yourself, eating and drinking) (see Fig. 1).

Regarding the demands on the robotic arm, the ICF categories were not very useful because they do not describe the requirements of a robotic arm. Thus, the research group decided to build a new set of categories focusing more on the type of movement rather than the section of ADL. Four action categories were identified: reach and grasp, mobility/ locomotion, handling of objects, and manipulation of the own body. In this context, manipulation of the own body refers to any activity in which actions are performed on one's own body. The most frequently mentioned activities included scratching, personal care, brushing teeth, combing hair, and bladder and bowel emptying.

Different filters and corresponding subdivisions (see Table 4) were established by the research team to analyze the requirements for a robotic arm from multiple perspectives. These filters helped to evaluate functions and performance criteria.

The largest differences between limitations (in the daily life of individuals with tetraplegia without the use of AT) and needs were assigned to the action categories mobility (limitation n=37, need n=6) and in the manipulation of the own body (limitation n=23, need n=12). Most limitations in ADLs were assigned to the handling of objects (n=54; cutting food, preparing food, dressing/undressing) and mobility (n=37; transfer, moving

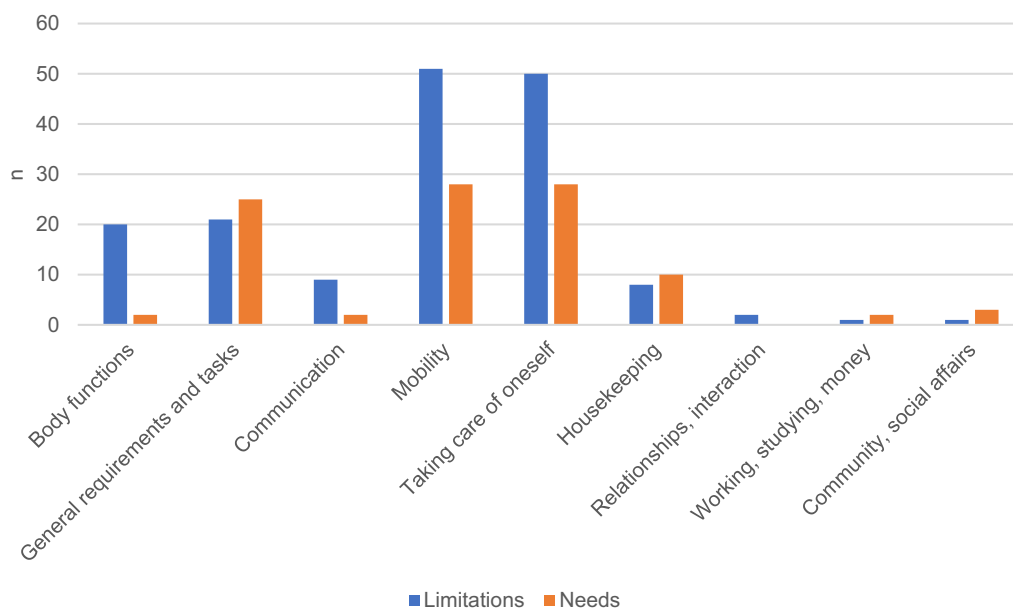


Fig. 1 Analysis of statements on ADL limitations and needs regarding a robotic arm framed within ICF

Table 4 Filters used for analysis

Filter	Subdivisions
Robotic Function	Pick and Place Transport Contact/Touch Manipulation
Number of hands needed	Bimanual movement Unilateral movement
Interaction	Improvement of autonomy Interpersonal activity
Task significance	Mandatory Beneficial Luxury
Motor Skill	Gross motor skill Fine motor skill
Task complexity	Easy Medium Complex

around, propelling a wheelchair). Most needs regarding a robotic arm existed in handling of objects (n=49; eating, drinking, opening the door) and reach and grasp (n=34; grasping, picking things up (from the floor), fixing/holding on to something). The limitations/barriers (without the use of AT) in ADL (n=140) and needs regarding a robotic arm (n=101) per action category are graphically shown in Fig. 2 and Fig. 3, respectively.

In a subgroup analysis, the results were analyzed separately for individuals with a self-reported level of injury above C5 and for a level of injury of C5 and below. This

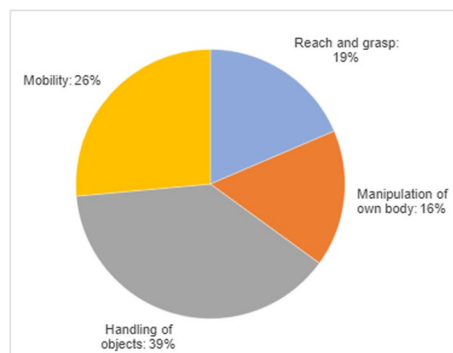


Fig. 2 Percentage of participants with tetraplegia reporting each specific limitation in their daily lives per action category

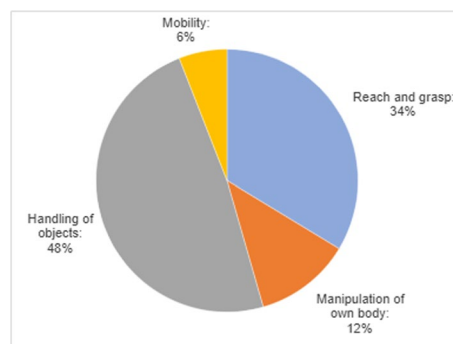


Fig. 3 Percentage of participants with tetraplegia reporting each need for a robotic arm

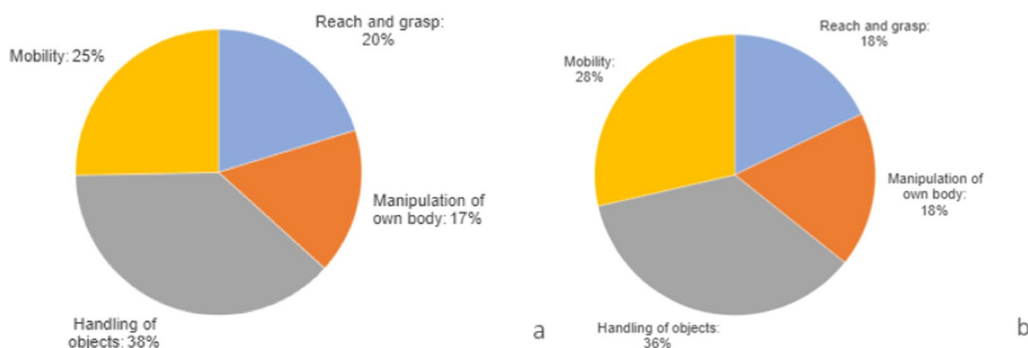


Fig. 4 Subgroup analysis of the limitations in ADLs of individuals with a level of injury of C5 and below (a) and of above C5 (b)

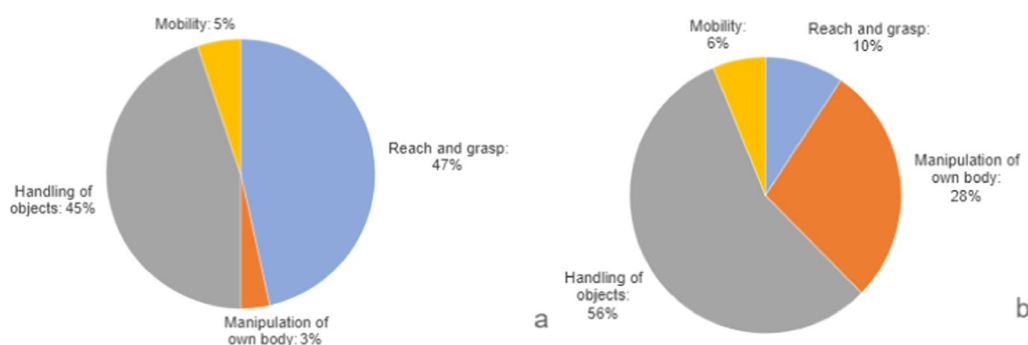


Fig. 5 Subgroup analysis of the needs regarding a robotic arm of individuals with a level of injury of C5 and below (a) and of above C5 (b)

analysis revealed that both subgroups experienced the most significant limitations in object handling and mobility, although their specific needs for a robotic arm differed. Individuals with a level of injury above C5 indicated the greatest needs for a robotic arm in activities related to handling of objects and for manipulation of the own body, while individuals with a level of injury of C5 and below identified the greatest needs for activities related to reach and grasp and for handling of objects. More detailed results of the subgroup analysis can be found in Figs. 4 and 5.

A further evaluation applying the described filters in Table 4 revealed that most of the limitations and needs pertain to unimanual and complex activities. In terms of robotic function, it was found that the greatest needs are related to the manipulation of objects. Furthermore, the robotic arm should be able to perform tasks that require body contact (Fig. 6).

The use of a robotic arm was expected to provide independence, ease of work, improved mobility, and enhanced quality of life. Concerns revolved around acquisition and maintenance costs, the weight and the space requirements. Furthermore, participants expressed a preference for controlling the robotic arm through voice commands (57.6%), followed by manual control with a

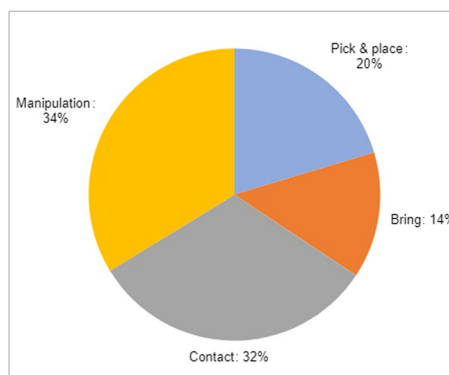


Fig. 6 Analysis of needs in context of important robotic functions

joystick (48.5%), a brain-computer interface (39.4%), and a touch screen (33.3%). Regarding power supply, 59.4% of the participants were willing to charge the robotic arm using the battery of their electric wheelchair even if this reduced the electric wheelchair’s battery quickly. On average, participants were willing to accept 21.5% (SD ± 7.1%) of the electric wheelchair’s battery capacity to be utilized for the actuation of the robotic arm. Participants reported that they wanted the attachment of the

robotic arm at the back (28.1%) or at the front (25.0%) of the wheelchair. For 93.8% of the participants, it was important that the robotic arm can be detached from the wheelchair. The descriptive analysis of questions regarding the robotic arm can be found in Table 5.

Survey of caregivers

A total of 29 caregivers initiated the survey. Nine caregivers completed part of the survey, but only four caregivers answered all questions. The completion rate, therefore, was 0.1. It was technically not possible to determine a unique site visitor.

The characteristics of the nine caregivers are presented in Table 6.

The caregivers reported that most of the individuals for whom they care, have a manual (66.7%) and/or an electric wheelchair (66.7%). The electric wheelchair was utilized more frequently, primarily due to the increased independence and mobility it provided. The electric wheelchairs are controlled with a joystick by hand or chin. For three out of six caregivers, the width of the wheelchair of the individual with tetraplegia posed a challenge, particularly in the context of narrow entrances and doors.

The four caregivers who completed the survey, they primarily provided support to individuals with tetraplegia with nutrition (median 10, IQR 0), housing (median 10, IQR 0.5), mobility (median 10, IQR 1.5), responsibilities (median 10, IQR 2.5), personal hygiene (median 8, IQR 5), mental and physical well-being (median = 8, IQR 2.5), leisure time activities (median 7.5, IQR 7), and communication (median 6.5, IQR 7). The same four caregivers also expressed a preference for assistance from the robotic arm in tasks related to nutrition (median 10, IQR 3), personal hygiene (median 10, IQR 5), mental/physical well-being (median 10, IQR 4.5), housing (median 10, IQR 0.5), mobility (median 10, IQR 1.5), responsibilities (median 10, IQR 2.5), leisure time activities (median 7.5; IQR 7), and communication (median 6.5, IQR 7). For tasks related to work and education, caregivers did not express a preference for assistance (median 1, IQR 4.5).

Caregivers reported seeing potential in the use of a robotic arm (median 9, IQR 3). They expressed their hope that, with assistance of a robotic arm, the individuals with tetraplegia can become more independent and mobile, that they will require less time for activities, and that their overall quality of life will improve.

Among caregivers, concerns revolved around acquisition costs (median 10, IQR 9), maintenance costs (median 10, IQR 0), the controlling mechanism of the robotic arm (median 10, IQR 9), and its dependence on power (median 6.5, IQR 5).

The caregivers saw the greatest potential for controlling a robotic arm by using a joystick with the chin (75.0%),

by eye movements (75.0%), or with voice commands (75.0%). In total, three caregivers were willing for the robotic arm to draw power from the wheelchair, estimating that 30.0% of the electric wheelchair's battery charge could be consumed by the robotic arm. Preferences for the attachment location were evenly divided, with 50.0% favoring the right side and 50.0% favoring the left.

Discussion

The aim of the study was to identify the needs and expectations of individuals with tetraplegia and their caregivers regarding a robotic arm for everyday activities. This was the first step of a user-centered development approach. Individuals with tetraplegia identified mobility and self-care as the primary limitations in their daily lives which aligns with their expressed expectations regarding robotic arms. Individuals with tetraplegia envisioned that the use of an assistive robotic arm would offer the highest benefit for activities related to reaching, grasping, and manipulation/ handling of objects. They also expressed some relevant concerns about costs, weight, and space requirements.

In the past, developers have been criticized for primarily designing for able-bodied users while insufficiently considering the actual needs of those with diverse capabilities [43]. The user-centered design process tries to address this issue by prioritizing the needs, wants, and desires of users throughout the design process, guiding the development of products, systems, or services [44]. This increases the relevance and acceptance and reduces the risks associated with the use of a product [45]. For the present study, a mixed-methods approach was pursued.

Needs and expectations regarding a robotic arm for everyday use

According to ICF, most of the identified needs regarding a robotic arm appeared to be at the activity and participation levels. Individuals with tetraplegia reported that a robotic arm holds the highest potential for supporting unilateral movements, including reach and grasp, handling of objects, and manipulation of the own body. In the focus group interview, it was mentioned that a robotic arm should assist with non-foreseeable activities that occur repeatedly during everyday life such as straightening glasses, scratching the head, making coffee, combing the hair, blowing the nose, turning newspaper pages, and picking up items. For tasks related to eating, washing, and brushing teeth, assistance by a robotic arm was not needed. This differs from the results of the surveys for the Individuals with tetraplegia and in the one for the caregivers, where assistance by a robotic arm in activities related to nutrition seemed to be very important. The caregivers also reported a desire for assistance

Table 5 Descriptive analysis regarding a robotic arm of survey participants with tetraplegia

Characteristic	Value	Occurrence n (%)			
Use of a robotic arm (respondents = 33)	Yes, at the moment	0			
	Yes, in the past	2 (6.1%) (Both less than 1 day)			
	Never	31 (93.9%)			
Reason for never using a robotic arm (respondents = 31) *	Costs	8 (25.8%)			
	Impracticality	9 (29.0%)			
	Ignorance of existence/ not enough information	14 (45.2%)			
	Poor functioning	2 (6.5%)			
	Hard to control	2 (6.5%)			
	Time consuming	7 (22.6%)			
	Does not fit on the wheelchair	4 (12.9%)			
	Other:				
	• No access	1 (3.2%)			
	• Managed without so far	3 (9.7%)			
	• Developed alternatives	1 (3.2%)			
	• They are not good enough	1 (3.2%)			
	• Not interesting	1 (3.2%)			
Expectations of the robotic arm (respondents = 33) *	Ease of work	18 (54.5%)			
	Independence	25 (75.8%)			
	Gain of time	7 (21.2%)			
	Less unloved work	10 (30.3%)			
	Mobility	17 (51.5%)			
	Participation	10 (30.3%)			
	Increased quality of life	23 (69.7%)			
	Nothing	4 (12.1%)			
	Other:				
	• Dating	1 (3.0%)			
	• Opening doors	1 (3.0%)			
Concerns regarding the robotic arm (respondents = 32) (Likert-Scale 1–10, 1 = not at all, 10 = extremely)	Acquisition costs	Median	Min	Max	IQR
	Maintenance costs	8	1	10	5
	Weight	6.5	1	10	5
	Security	8	1	10	3.3
	Control	5	1	9	3.3
	Space requirements	4.5	1	10	4
	Lack of operator training	8	1	10	3.25
	Aesthetics	2.5	1	9	4
	Performance	5	1	10	5
	Dependence on power	5.5	1	10	4.3
	Loss of physical/ mental capability	5	1	10	4.3
	Other:	1	1	10	2
	• Low added value, increase in weight	1 (3.1%)			
	• Hard to imagine how it should support	1 (3.1%)			
	• No need	1 (3.1%)			
	• Outdoor use is difficult	1 (3.1%)			
	• Emergency stop	1 (3.1%)			
	• Reduction in self-esteem	1 (3.1%)			
	• Don't have it with you when you need it	1 (3.1%)			
• Unreadable answer	1 (3.1%)				
• None	4 (12.5%)				
Control of robotic arm (respondents = 33) *	Hand with a joystick	16 (48.5%)			
	Chin with a joystick	6 (18.2%)			
	Eye movements	7 (21.2%)			
	Sip and puff	3 (9.1%)			
	Head movements	3 (9.1%)			
	Tongue	2 (6.1%)			
	Brain-computer-interface	13 (39.4%)			
	Voice	19 (57.6%)			
	Touchscreen	11 (33.3%)			

Table 5 (continued)

Legend: *Indicates that multiple answers were possible

Table 6 Sample characteristics of caregivers who completed the survey

Characteristic	Value	Occurrence n (%)
Gender (respondents = 9)	Male	1 (11.1%)
	Female	8 (88.9%)
Age (years) (respondents = 9)	Mean	55.4
	SD	13.7
	Min	23
	Max	71
Level of the injury of the individual they take care of (respondents = 9)	C2	1 (11.1%)
	C3	2 (22.2%)
	C4	3 (33.3%)
	C5	1 (11.1%)
	No answer/ unknown	2 (22.2%)
Relation to the individual they take care of (respondents = 9)	Home care nurse	1 (11.1%)
	Spouse	5 (55.6%)
	Parents	2 (22.2%)
	Friend	1 (11.1%)
Daily hours of caregiving (respondents = 9)	5-6 h	2 (22%)
	7-8 h	3 (33%)
	> 8 h	4 (44%)
Years since caregiving started (respondents = 9)	< 1 year	1 (11.1%)
	1-5 years	3 (33.3%)
	6-10 years	2 (22.2%)
	> 10 years	3 (33.3%)
Completeness of paralysis of the individual they take care of (respondents = 9)	Incomplete	5 (55.6%)
	Complete	4 (44.4%)

in personal hygiene. The data received from participants are mostly in line with existing literature that investigated the needs of individuals with physical disabilities regarding AT in general. Weber-Fiori et al. [13] found that an assistant robot should perform tasks such as picking up objects from the floor, transporting objects and switching appliances on and off. Jardón et al. [46] and Andreasen Struijk et al. [47] state that plannable tasks such as everyday hygiene, eating and drinking should be carried out by the AT.

In terms of control preferences, individuals with tetraplegia (in both the focus group interview and the survey) reported priority for controlling the robotic arm by using voice commands. In a recent study, Battacharjee et al. [48] evaluated participants' user interface preference during dining and found, that the preferred control modality depended on the context. The participants preferred voice interface for individual dining, while a web-interface for social dining scenarios was chosen. Of note, in our online survey, the ten presented input modalities were not explained, potentially leading to varied interpretations based on each participant's technical expertise, previous experience, and personal preferences. For example, a voice interface could issue low-level commands

such as "move forward" or "close gripper" or higher-level commands such as "I would like to drink a glass of orange juice", which would then have to be interpreted and executed accordingly by the AT. This spectrum of command complexity highlights the need to determine the optimal level of autonomy for such systems.

The desired level of autonomy was investigated in a recent study by Battacharjee et al. [48], where a Jaco[®] robot arm (Kinova[®], Canada), was mounted on a wheelchair to serve as a robot-assisted feeding system. They used a web-based interface to control the robotic arm. The study found that low autonomy of the robot requires more effort from the individuals with motor impairments compared to when the robot is fully autonomous. Partial autonomy did not reduce the effort, so participants did not favor a robot with partial autonomy over one with low autonomy. In low autonomy mode, the user selects the food item and decides all key actions, such as the method for skewering the food and the feeding strategy, while the robot merely executes these chosen actions. In contrast, the partial autonomy mode allows the robot to autonomously manage one of the three phases: bite acquisition, timing decision, or bite transfer, while the user retains control over the remaining non-automated

phases. However, complete manual control, where each individual movement of the robot arm is commanded by the individual with tetraplegia, is considered impractical [48]. A software architecture proposed by Styler et al. [24] enables continuous adaptation across the robot arm's autonomy levels and functions, ensuring that it aligns with the complexity of the task.

Concerns about a robotic arm for everyday use

Acquisition and maintenance costs were reported as the most important barriers for use of a robotic arm by individuals who completed the survey. Indeed, research also reported cost as a potential barrier [49] or as the most important barrier to AT [50]. Furthermore, in a recent scoping review, barriers to AT use were found in three areas: accessibility, affordability, and acceptability [51]. In the present study, individuals with tetraplegia were additionally concerned about the weight and space requirement, while the caregivers worried about the control options of the robotic arm. Another reason for the non-use of AT/robotic arms was the fear that AT might be too slow as reported by Correal et al. [52]. However, this statement contradicts our findings from the focus group interview as well as the results from the studies by Gopinath et al. [53] and Matsiko [54], where it was concluded, that time-saving functions were not a high priority, whereas the quality of task execution was. In the present study, caregivers placed more emphases on time-saving potential of a robotic arm, whereas for individuals with tetraplegia, the ability to perform certain activities again was more important, regardless of how much time they needed.

Limitations of the study and future work

The mixed methods approach with an explanatory sequential design was a major strength of the study. According to Creswell and Plano Clark [33] this design is typically characterized by a quantitative data collection phase followed by a qualitative phase. However, due to the research question and the limited literature available on this topic, it was decided to conduct the qualitative study first. This approach allowed to gain a deeper understanding of the subject and formulating more appropriate questions for the online survey. However, a limitation was that the developed questionnaire was only partially validated. In future studies, it is recommended to use a fully validated questionnaire to improve the significance of the data.

The present study had some more limitations. While 49 individuals with tetraplegia were successfully recruited through the chain-referral sampling technique, only nine caregivers participated in the survey, which limits the meaningfulness of our conclusions.

This discrepancy could be explained by research showing that individuals are more likely to engage in a study when the research topic is personally relevant [43]. While we have succeeded in involving those directly impacted, it is important to include their caregivers to enable a comprehensive user-centered approach in the development of new technologies.

Another limitation is that the needs were not analyzed based on the exact level of lesion or the self-reported extent of impairments (complete versus incomplete SCI) and the corresponding functional consequences. Individuals with different lesion levels or with a different extend of paralysis may have different needs regarding a robotic arm. To have better understood the study results, information on the movement restriction of the survey participants could also have been collected. The questionnaire could have benefited from including more specific inquiries about functional abilities rather than solely asking about remaining strength in different body parts. Furthermore, the time since injury was not assessed which may be significant since priorities for assistive robotic arms change as more time passes post injury.

Only German speaking individuals were included in the study, which may have limited the inclusion of individuals from other countries and different needs, whether due to cultural reasons or differences in healthcare systems. Consequently, our finding should not be generalized. In the International Surveillance Study of Bourguignon et al. [55], the total mean age of individuals with SCI found was 47.2 years. Additionally, according to the National Spinal Cord Injury Statistical Center [56], 45.6% of the participants in the database had a cervical injury, with levels of C4 (15.7%), C5 (15.0%), C6 (10.0%), or C7 (4.9%). The participants of the surveys were recruited using a chain-referral sampling technique. Chain-referral samples can introduce a sampling bias and thus do not permit generalizations [57]. Furthermore, the recruitment method for the focus group could be biased as the individuals were recruited via word-of-mouth. This method may have introduced selection bias by drawing from similar networks. In future studies, these factors should be accounted for to better understand the specific needs of different tetraplegic subgroups.

The current study's data provide important information that can be incorporated into the further development process of ATs. Future studies could consider the level of lesion or extend of impairment in individuals with tetraplegia to better understand specific injury-related needs. Building on the needs and preferences of both individuals with tetraplegia and caregivers, the next step would be to develop detailed concepts and system requirements for a robotic arm.

Conclusion

In this paper, we presented the development and results of a comprehensive online survey, preceded by a focus group, that assessed the needs and expectations of individuals with tetraplegia and of caregivers regarding the use of a robotic arm for everyday activities. None of the participants used a robotic arm at the time of data collection. Individuals with tetraplegia, that joined the focus group interview as well as the survey participants reported, that they would use an assistive robotic arm for activities related to reaching and grasping (34% of the survey participants), and manipulation/ handling of objects (48% of the survey participants). It was reported that a robotic arm should assist with non-foreseeable activities that occur repeatedly during everyday life, such as straightening optical glasses, scratching the head, blowing the nose, and picking up items. Both individuals with tetraplegia that joined the focus group interview as well as 57.6% of the survey participants reported priority for using voice command to control the robotic arm. Concerns about costs, weight, and space requirements were expressed. Individuals with tetraplegia identified mobility and self-care as the primary limitations in their daily lives, aligning with their expectations that an assistive robotic arm would enhance autonomy and quality of life. Our findings provide user-driven insight into the requirements for assistive robotic arms, paving the way for future technical implementations that address the needs of the tetraplegic population and their caregivers.

Abbreviations

ADL	Activities of daily living
AT	Assistive technologies
DoF	Degrees of freedom
FIM	Focus Group Illustration Maps
IQR	Interquartile range
SCI	Spinal cord injury

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12984-025-01642-8>.

Additional file1 (DOC 109 KB)
 Additional file2 (DOCX 31 KB)
 Additional file3 (DOCX 29 KB)
 Additional file4 (DOCX 76 KB)
 Additional file5 (DOCX 73 KB)

Acknowledgements

Many thanks to the participants of the online survey, to all persons involved in the validation processes and to all institutions, organizations, and associations that gave support in the recruitment of participants.

Author contributions

Study conception and design: A.B, P.E, G.G, R.R, N.L, A.M.R; creation of the online survey: N.H, A.B, P.E, G.G, R.R, N.L, A.M.R; focus group interview: A.B, V.S; recruitment: N.H, A.B, P.E, G.G, N.L, A.M.R; analysis and interpretation of results: N.H,

A.M.R; draft manuscript preparation: N.H., V.S., R.R., A.M.R. All authors reviewed the results and approved the final version of the manuscript.

Funding

The project was financially supported by the Swiss Paraplegic Foundation (Foko_2022_05).

Availability of data and materials

The data generated is available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study had been approved by the competent ethics committee (KEK-No. Req-2022-01492). We certify that all applicable institutional and governmental regulations concerning the ethical use of data of human volunteers were followed during this research. Participation in the study was voluntary and no disadvantages arose from non-participation or withdrawal from the study. No incentives were offered for participation. The participants were guaranteed permanent anonymity.

Consent for publication

All authors have given consent for publication.

Competing interests

The authors declare no competing interests.

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Received: 16 July 2024 Accepted: 2 May 2025

Published online: 20 May 2025

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