Towards a Hierarchical User Requirement Structure for Upper Limb Assistive Robotics

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This article presents the results of an interdisciplinary study encompassing data collected from 108 in-depth interviews and 15 participatory workshops aimed at exploring the requirements of a diverse range of stakeholders in relation to assistive augmentative technologies. The study involved 39 post-stroke patients with hand paresis, 39 individuals with spinal cord injuries affecting upper limb function, 38 relatives and 65 healthcare professionals. Through qualitative analysis of the accumulated data, this research identified the multifaceted needs, preferences and aspirations of the study participants. We propose a structured hierarchy for user requirements, inspired by Maslow's hierarchy of needs. At the foundation of this pyramid are the essential functional requirements, forming the bedrock for the subsequent layers. Moving hierarchically, we identified reliability and security requirements, followed by usability and user experience considerations, recognition requirements and, finally, personal growth and self-fulfilment criteria. The foundational functional requirements must be fulfilled before other aspects can take precedence, creating a systematic approach to address the diverse needs of individuals with upper limb disabilities. The pyramid of requirements identified may significantly contribute to the scholarly community and lay the foundation for the development of assistive robotics that align with the desires of individuals with upper limb disabilities.

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1 Introduction

Upper limb disabilities (ULD) are the result of a range of factors, including inherited, developmental or acquired conditions affecting the brain, spinal cord or peripheral nervous or muscular-skeletal systems. Among these factors, stroke stands out as a significant contributor to upper limb movement disorders. Notably, the annual incidence of strokes in the European Union is anticipated to increase by 34% from 2015 to 2035, resulting in a projected 25% increase in the number of post-stroke patients during this period, primarily attributable to improved acute care and treatment [1]. Despite advancements in treatment methods and the introduction of innovative rehabilitation approaches, upper limb motor impairments often endure throughout a stroke patient's lifetime. In the case of **spinal cord injuries (SCIs)**, they represent a prevalent cause of disability among young adults [2]. These injuries can result in partial or complete loss of sensory and motor control in the arms, legs or body, depending on the level of the spinal lesion: the specific level of injury, particularly at the cervical level, typically correlates with the degree of motor impairment, often leading to both sensory and motor deficits (beyond problems of sphincters' control) and bilateral disability in the upper extremities [3].

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Individuals with ULD often suffer from a loss of independence as they become dependent on others for daily activities such as dressing, grooming and eating [4–6]. As a result of their disability, their quality of life is negatively affected both physically, emotionally and psychologically [7]. Often, they have to retire from the jobs they have been doing, and there are limited future employment opportunities. All of the above factors may lead to social isolation, which further has a negative impact on their quality of life. It is not only the individuals with upper-limb disabilities who suffer but also their families and friends who have to become informal caregivers [8–12]. Indeed, the lack of support, the degree of patient's dependence, the complexity of care activities, the worsening of health status and the uncertainty of the future can, in many cases, lead the caregiver to social isolation, reduction or extinction of leisure activities, loss of job and lack of time for self-care [13] Furthermore, upper-limb disabilities also present challenges for society as a whole, as they involve healthcare costs and a loss of productivity [12].

Wearable sensorimotor interfaces and supernumerary robotic limbs for humans with upper-limb disabilities offer a potential solution to mitigate (if not overcome) some of the above-mentioned challenges. Assistive augmentative technologies may meet the needs of people with ULD, especially stroke and SCI patients, to support them in regaining independence in their daily lives. This may not only involve eating, dressing, personal hygiene and moving but also work, recreation and social aspects, where holding a book, using a computer and communicating through a mobile phone are common activities [14–16]. Adopting a **human-centred approach (HCD)**, where the solutions are iteratively developed for and with end users, is central to improving the chances of users accepting and requiring novel assistive technologies [17–19]. It is also crucial to collect input not only from potential end users but also from various stakeholders, including relatives and healthcare professionals.

The safety, usability, comfort, portability and functionality of assistive robotic technologies are stressed as crucial user requirements [20–23]. For example, a scoping review of the design requirements for home-based upper limb rehabilitation robotic assistive systems and devices for stroke survivors highlighted that robotic assistive systems and devices need to be safe, comply with all safety standards, easy to use, quick to set up, maintainable, transportable, simple to don and doff, reliable, cost-effective, and capable of promoting individualised, repetitive and intensive exercise [22]. A mixed-method study, which included focus groups, questionnaires and interviews, revealed that the success of assistive technology depends on its ability to enhance functionality, the users' positive attitude towards technology, their awareness of available technologies and the technologies' high usability and practical application [23]. A systematic review of upper limb soft robotic wearable devices revealed the need to avoid over constraining joints, support mobility and flexibility, be comfortable to wear, easy to don and doff and be lightweight and portable [20]. Despite a more than 50% increase in the development of wearable devices from 2015 to 2020, a review of rehabilitative and assistive wearable mechatronic upper-limb devices concluded that there is still a lack of guidelines for designers and developers [21]. This gap underscores the need for further research to identify user requirements for developing assistive robotics technologies [24–27]. Moreover, although eliciting the needs and preferences of target users is a well-established practice in consumer product marketing, numerous studies indicate that the intended users of assistive robotics are seldom consulted about their needs and wants in the developmental processes of assistive robotics technology [28–32].

The comprehensive study conducted in this work aims at addressing this gap and includes in-depth interviews with 108 participants and participatory workshops with 73 participants. These qualitative methods allow us to capture the intended user needs, wants and wishes for upper limb assistive robotics. The data analysis followed thematic analysis, as outlined by Braun and Clarke [33]. Our findings confirm previous research [20–23]. However, the novelty of our findings is twofold. First, the focus was on a relatively new class of robots, i.e., supernumerary limbs, which, as highlighted in a recent review [34], have mainly been studied from a technological point of view (structure, actuation, sensing) but still need to be fully evaluated in the context of assisting disabled people. Consequently, there is a shortage of studies addressing user requirements for supernumerary limbs [34]. Second, our study explores the many nuances of user needs for individuals with ULD and interprets the findings using a hierarchical structure (the pyramid of requirements), which can be used as an intuitive guide for technology developers. The hierarchy begins with essential functional requirements, forming the foundation, followed by reliability and security, usability and user experience, recognition and personal growth and self-fulfilment. The hierarchy of requirements emphasises that developers and designers should address user needs and preferences systematically, starting from the most fundamental requirements and progressing to higher-level ones. While users often focus on design and aesthetics, as these are the most visible aspects, this emphasis can overshadow more essential functionality requirements. Ensuring long-term use and adoption, according to our findings, depends on first meeting these foundational needs. If basic functionality is not adequately addressed, users may initially be attracted by the design but ultimately abandon the technology because it does not meet their needs in everyday practice [35, 36].

The article is structured as follows. We commence by exploring technology acceptance within the demographics of individuals affected by ULD and then delve into the cutting-edge advancements in sensorimotor interfaces and the ongoing development of supernumerary robotic limbs. Next, we present our HCD methodology, the employed data collection methods and the empirical findings. The article progressively builds towards an examination and discussion of the findings, establishing coherent connections and perspectives derived from our empirical study. In conclusion, the article culminates with a reflective assessment of the implications in practice for robotics developers and designers based on our findings.

2 Background and Related Work

This section provides background on technology acceptance among individuals with ULD and wearable sensorimotor interfaces and supernumerary robotic limbs.

2.1 Technology Acceptance among Individuals with ULD

The widespread acknowledgement of technology acceptance as a pivotal influence on the adoption of any technology is evident in the literature [37, 38]. The concept of technology acceptance encapsulates individuals' willingness and readiness to integrate a particular technology into their daily lives. The acceptance of a particular technology is posited to depend on the perceived usefulness and ease of use [37, 38]. Affordances, the perceived properties, of how a technology can be used plays a crucial role in shaping users' perceptions of a technology and its usability [39]. A systematic literature review of the needs of individuals with ULD indicated that the acceptance of home-based upper limb rehabilitation robots within the user group is contingent upon several factors [23]. These factors include the anticipated benefits of enhancing hand and arm performance. Upper limb rehabilitation robots should have a sense of familiarity or affinity with existing technologies. Users express a desire for upper limb rehabilitation robots for personal use in a home environment, adjustability to individual needs and prevent of incorrectly executed movements and overtraining.

Onofrio et al. [27] proposed that the acceptance of exoskeletons among individuals with ULD has both functional and emotional dimensions along from both individual and relational perspectives. In this context, the acceptance of exoskeletons among individuals with ULD is not solely driven by functional requirements; it also encompasses emotional considerations such as anxiety, stigma and mistrust. Moreover, the scope of exoskeleton acceptance extends beyond the perspective of individuals with ULDs to people such as family, friends and healthcare professionals. Onofrio et al. [27] highlight the relational aspect of exoskeleton acceptance, where the perspectives of various stakeholders collectively shape the overall acceptance of an exoskeleton. The relational aspect of assistive robotics acceptance among individuals with ULD has also been confirmed by others [23, 40]. Although the user requirements for assistive robotics among individuals with ULD are not fully understood [26, 41], there is recognition that the abandonment rate of assistive technology is high [42, 43]. The crucial role of device utilisation in explaining abandonment is tied back to its perceived usefulness [42].

2.2 Wearable Sensorimotor Interfaces and Supernumerary Robotic Limbs for Individuals with ULD

Human sensorimotor augmentation re-defines the nature of physical human–robot interactions [34, 44]. The enabling technologies for augmentation are supernumerary robotic limbs and wearable sensorimotor interfaces. The central idea is that of integrating humans and supernumerary robotic limbs to perform complex manipulation tasks with both biological and artificial limbs under the direct control of humans. In this condition, the human cortical motor synergies, i.e., patterns of neuronal activation specific to goal-directed actions, must be redesigned to control robotic extra limbs, leading to new bio-artificial motor synergies as a consequence of an adaptation of the brain due to its plasticity [45]. In contrast to collaborative robotics, robotic extra limbs are not seen as collaborative external agents but rather as an augmentation of the human body [34, 44]. While the literature on supernumerary robotic limbs has mainly focused on *wearable augmentative* devices that enhance healthy users' abilities by adding extra degrees of freedom to the users' body [46, 47], this article considers supernumerary limbs that aim at compensating lost motor functions in patients with ULD. More in detail, this work encompasses the use of wearable fingers, that are typically rather light [48, 49] and of robotic arms and grippers that are fixed to static supports in proximity of the user, without adding weight to the patient's body [49]. Even though the envisaged robotic extra limbs are not necessarily worn on the user's body, we aim at achieving a human–robot integration in which the robotic devices are not seen as autonomous external agents, but rather as an augmentation of the human body [50], because they are partially controlled by the robot artificial intelligence and partially under the direct control of the human. In this context, user acceptance largely depends on finding the right tradeoff between user control and robot autonomy. The core technology of this interplay is the wearable sensorimotor interface, i.e., a mechatronic device that establishes a connection between the human sensorimotor system and the system of actuators and sensors of the robot. The interface embeds a sensing and an actuation part. The first detects human body motions (e.g., through tracking systems [51]) or muscle activations (e.g., through electromyography [52]) and maps them onto commands for the robotic limbs. The second delivers a combination of somatosensory stimuli to convey haptic sensations related to the task at hand, including vibrations [34, 53, 54], skin indentation [55] and temperature [56]. The tactile feedback is intended to further improve users' control accuracy and level of engagement. To avoid hindering users' movements, sensorimotor interfaces must be designed to be wearable and unobtrusive, and they should capture motions or muscle activations that are redundant with respect to the task that is being performed, so that human and artificial limbs can be controlled in a simultaneous and coordinated way. In [57] for example, a method to extract redundant human motions is presented. Further examples of supernumerary robotic limbs and sensorimotor interfaces are included in [34].

3 Methodology

As seen above, we already had predetermined technologically driven ideas, which in many ways constrain and shape the development of possible solutions [58]. However, in this context adopting a HCD approach ensures that these predetermined ideas are further explored and redefined with

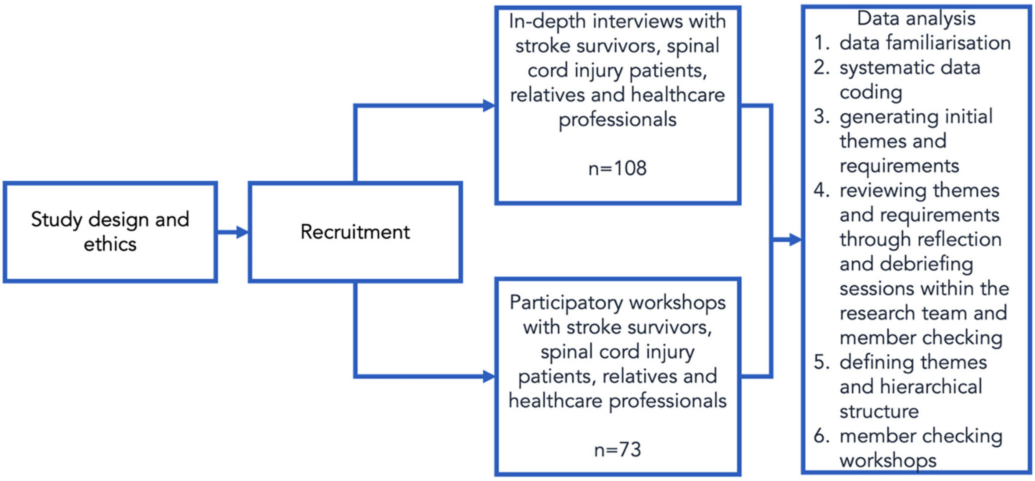

Fig. 1. Illustration of the study's data collection and data analysis.

the aim of finding the desired solutions to relevant problems for the target group. The ISO standard ISO 9241-210:2010 Ergonomics of human-system interaction—Part 210: Human-centered design for interactive systems (ISO 9241-210, 2010) describes HCD as a process that 'aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques'.

One reason for adopting HCD in the development of emerging technologies is to consider the whole socio-technical system around humans rather than only focusing on isolated interactions between humans and technology [59, 60]. This provides a more comprehensive view of people's attitudes and intentions towards accepting a new technology, where perceived usefulness in a real-life context and ease of use in operating the product, are central factors for acceptance [37, 38].

3.1 Data Collection

The data were gathered through audio-recorded in-depth interviews [61] and participatory workshops [62] (Figure 1).

The first author formulated the interview and workshop guides, subsequently refining them in collaboration with the research team. The interviews and participatory workshops took place in Sweden, Italy and Spain and all followed the same interview and workshop guides. The insights from the various methods complemented each other. As we conducted interviews and workshops in three different countries, the data collection continued until saturation was reached both within each country and across the countries.

3.1.1 Participant Recruitment. In Sweden, participant recruitment involved collaboration with paraplegic and stroke associations, utilising their networks to disseminate information about the study to potential participants. Additionally, outreach efforts were extended to various healthcare facilities specialising in SCIs and post-stroke patients. In Spain, participant recruitment targeted healthcare professionals, individuals with SCI and relatives through collaboration with Sescam-Gobierno de Castilla-La Mancha, a hospital and rehabilitation facility specialising in SCIs, which facilitated the identification and inclusion of relevant participants. In Italy, participant recruitment of post-stroke patients, healthcare professionals and relatives was carried out in part at the hospital Fondazione Santa Lucia (Rome, Italy), in part at the hospital Azienda ospedaliero-universitaria

Senese (Siena, Italy), and in part in collaboration with the rehabilitation clinics Auxilium Vitae Volterra SpA (Volterra, Pisa, Italy) and Istituto Privato Riabilitazione Madre Divina Provvidenza Dei Passionisti (Agazzi, Arezzo, Italy).

In all three countries, potential participants were contacted via e-mail or phone, depending on their communication preference. From this group, a purposive sample of participants were recruited by applying specific criteria. To be eligible for participation, individuals had to meet the following criteria: be 18 years or older, have experienced SCI as an adult or be a post-stroke patient with hand paresis. Eligibility extended to those who were either a relative of someone with SCI or a post-stroke patient or a healthcare professional working with these targeted populations. Fluency in either Swedish, Spanish or Italian was also a requirement. Additionally, participants with a history of post-stroke or SCI were required to receive substantial at-home care, which could be provided by a family member or a personal assistant.

3.1.2 In-Depth Interviews. We conducted in-depth interviews aimed at eliciting extensive and detailed information about individuals' experiences, perspectives, beliefs and attitudes [61]. The practice of in-depth interviews originates from qualitative research areas such as phenomenology, ethnography and grounded theory, all of which share an interest in understanding human experiences and viewpoints in real-life contexts. In-depth interviews facilitate direct engagement with research subjects for the purpose of data collection [63]. The in-depth interviews explored the thoughts, experiences, attitudes and behaviours related to upper limb impairments and factors influencing the use or non-use of assistive technology. Initially, we asked about the circumstances surrounding their injury, its impact on their lives, their range of abilities and the assistance and aids they needed. As the interviews progressed, we introduced the concept of wearable sensorimotor interfaces and supernumerary robotic limbs, seeking participants' perspectives on the use of such technology. We also explored the advantages and disadvantages they perceived (Table 1).

Similarly, interviews with relatives of individuals post-stroke and those with SCIs focused on the relatives' perceptions of their relatives' experiences, attitudes and behaviours related to upper limb impairments, as well as factors influencing assistive technology usage (Table 2). Questions at the beginning covered the circumstances surrounding the relative's injury, its impact on both the relative and their own lives, the relative's range of abilities and the assistance and aids they needed. Towards the end of the interview, we introduced the concept of wearable sensorimotor interfaces and supernumerary robotic limbs, exploring participants' perspectives on the technology's use and its perceived advantages and disadvantages concerning their relatives.

The in-depth interviews with healthcare professionals mirrored the structure of those with individuals' post-stroke and those with SCIs and their relatives (Table 3). However, the focus shifted to healthcare professionals' perceptions of the needs and preferences of individuals post-stroke and those with SCIs. Our interview questions were designed to explore their insights into the needs of end users from their professional standpoint. Notably, our inquiries did not delve into the requirements for healthcare professionals to acquire, use or prescribe robotic devices; instead, we concentrated on their perceptions of end users' needs.

The interviews were audio-recorded, transcribed verbatim and translated into English.

3.1.3 Participatory Workshops. In parallel with the in-depth interviews, we conducted participatory workshops [64]. While in-depth interviews allow for a deep exploration of individual needs, preferences and challenges that might not emerge in a group setting [61]. Participatory workshops, on the other hand, enable a collaborative environment where participants can interact, share ideas and build upon each other's experiences which allows the identification of common themes that might not surface through individual interviews alone. As such, we used both methods to capture

Table 1. Interview Guide for Patients

The interview guide contained information and suggestions on how the interviews should be conducted, considering different interviewers were involved. Interviewers were asked to address any questions that arise during the interviews related to assistive robotic technology or patients' needs and wishes. They were asked to use probes to delve deeply into these issues. For example, 'Can you elaborate on what you mean by xx?' 'Can you give examples of xx?' 'What do you feel when xx happens?' 'How often does xx happen?' 'You say xx, what do you mean?' to obtain in-depth and elaborated answers.

Interview questions for patients

(1) When did you have a SCI/or a stroke?
(2) Would you like to describe what impact the SCI/stroke has had on your everyday life?
    (a) In relation to others?
    (b) In relation to activities of daily living?
(3) How has the SCI/stroke affected your life?
(4) What kind of support do you benefit from?
(5) What kinds of movements or activities do you have trouble performing? What obstacles do you have in your everyday life?
(6) Are there aids that help you with the movements/activities mentioned?
(7) What support is available and works well?
(8) Which aids/assistive technology are available and work well?
(9) What support is missing?
(10) What aids/assistive technology are missing?
(11) What is your experience with the use of digital aids/assistive technologies?
(12) What kinds of aids/assistive technologies do you have experience using?
(13) Do you have experience with assistive robotic technology?
(14) Who is responsible for showing and teaching you how to use the aid/assistive technology?

(The interviewer describes what assistive robotic technology is (based on the technologies in the project) and what they can be used for—unless the interviewee has experience/knowledge of assistive robotic technology.)

(15) If you get to participate and influence, what would you like assistive robotic technology to be used for in your everyday life?
    (a) Any ideas on function/functionality?
    (b) Design?
    (c) What are your needs?
    (d) Wishes?
(16) What kind of benefits can you see with assistive robotic technology?
    (a) Disadvantages?
(17) How do you think assistive robotic technology can change your everyday life?
    (a) Benefits?
    (b) Disadvantages?
    Closure
(18) Is there anything else you can think of regarding assistive robotic technology that you think we haven't covered?

both the depth of individual experiences and the breadth of group dynamics. The data collection continued until saturation was reached.

The foundation of participatory workshops is rooted in the principles of participatory research, which underscore the importance of involving target users in every stage of the research process [65]. As such it is important that the facilitator take on a passive role, allowing participants to guide their own learning journey [66]. In our workshops, the initial phase focused on social concerns and the current state of assistive technology. Participants who had experienced a stroke or SCI, along with their relatives, were invited to explore meaningful opportunities and values in their

Table 2. Interview Questions for Relatives

(1) What is your role/relationship to X with SCI/or who had a stroke?
(2) How long has X had a SCI or when did X have a stroke?
(3) Would you like to describe what impact the SCI/stroke has had on your relationship?
(4) How has the SCI/stroke affected X's life?
(5) What kind of support do you benefit from?
  (a) You?
  (b) X?
(6) What support is available and works?
  (a) For you?
  (b) For X?
(7) What support is missing?
  (a) For you?
  (b) For X?
(8) What kinds of movements or activities does X have trouble performing?
(9) What obstacles does X have in their everyday life?
(10) Are there aids that help X in the mentioned movements/activities?
(11) What is your experience with X use of digital aids/assistive technology?
(12) What kinds of aids/assistive technology do you have experience using?
(13) Do you have experience with assistive robotic technology?
(14) Who is responsible for showing and teaching how to use the aid?

(The interviewer describes what assistive robotic technology is (based on the technologies in the project) and what they can be used for—unless the interviewee has experience/knowledge of assistive robotic technology.)

(15) If you get to be involved and influence, what would you like to assistive robotic technology could be used for when it comes to X and others who have a SCI/have had a stroke?
  (a) What do you think X needs?
  (b) Wishes?
(16) What kind of benefits can you see with assistive robotic technology?
  (a) Disadvantages?
(17) How do you think assistive robotic technology can change X everyday life?
(18) In what way do you think that assistive robotic technology will change your relationship?
  (a) Benefits?
  (b) Disadvantages?
Closure
(19) Is there anything else that you will think of that relates to assistive robotic technology that you think we haven't covered?

lives, discuss the assistive devices they currently use (including prescribed devices not in use) and, crucially, elucidate the reasons for non-usage. Additionally, they shared insights into challenging situations they encountered. The latter part of the workshops aimed to deepen our understanding of user requirements and identify potential opportunities. During this phase, we introduced wearable sensorimotor interfaces and supernumerary robotic limbs through videos and illustrations, fostering discussions among the participants (Table 4). Given the upper-limb disabilities of many participants, the workshops predominantly involved oral discussions. A whiteboard was utilised by the workshop facilitator to visually represent participants' ideas and thoughts.

While joint workshops were conducted with individuals' post-stroke and those with SCIs and their relatives, separate workshops were also held with healthcare professionals specialised in SCIs or post-stroke cases. These workshops unfolded in three stages: (1) discussions on perceived

Table 3. Interview Questions for Healthcare Professionals

(1) What is your role/occupation?
(2) How long have you worked as 'nurse/doctor/occupational therapist/other'?
(3) Would you like to describe your work to me?
(4) How many patients do you handle who have had a stroke/SCI during a work week?
(5) What kind of support do patients need?
(6) What support is available and works?
(7) What support is missing?
(8) What kinds of movements or activities do your patients have trouble performing?
(9) What obstacles do they (the patients) have in their everyday life?
(10) Are there aids that help them in said/above mentioned movements/activities?
(11) What is your experience of using digital aids in your care of patients who have had a stroke/have a SCI stroke?
(12) What kinds of aids do you have experience using?
(13) Do you have experience with assistive robotic technology?

(The interviewer describes what assistive robotic technology is (based on the technologies in the project) and what they can be used for—unless the interviewee has experience/knowledge of assistive robotic technology.)

(14) If you get to be involved and influence, what would you like assistive robotic technology could be used for when it comes to your patients?
(15) What do you think they need?
(16) Wishes for?
(17) What kind of benefits can you see with assistive robotic technology?
(18) What kind of disadvantages can you see with assistive robotic technology?
(19) How do you think that assistive robotic technology can change patients' everyday life?
(20) In what way do you think that assistive robotic technology will change your work?
(21) Benefits?
(22) Disadvantages?
Closure
(23) Is there anything additional that you will think of regarding assistive robotic technology that you think we haven't covered?

opportunities and challenges for post-stroke or SCI patients, exploring the support needed and how it is provided, (2) exploration on currently prescribed and used assistive technology by their patients, examining reasons for usage and non-usage; and (3) presentation of concepts through videos and illustrations on wearable sensorimotor interfaces and supernumerary robotic limbs, followed by a group discussion prompted by the visual aids (Table 4). In each stage, healthcare professionals first engaged in individual reflection, writing their thoughts and reflections on post-it notes. These notes were then posted on a whiteboard, facilitating group discussions.

During the workshops, one researcher acted as the facilitator and another researcher was responsible for comprehensive notetaking [62]. At the end of each workshop, all materials and participant notes were collected for analysis.

3.2 Data Analysis

The data collected from in-depth interviews and workshops were analysed using thematic analysis to identify patterns and themes [33]. The data analysis followed the sixth iterative phases described in [33] and in Figure 1. After becoming familiar with the data by reading and re-reading all the transcripts from interviews and the summaries from the workshops, initial ideas were noted. Then, all the accounts regarding the injury, its impact on their lives, their range of abilities, the assistance and aids they needed, as well as their wishes and wants for assistive robotic technology were

Table 4. Steps in the Workshops

Step 1. Introduction and Welcome		
—Introduction of the workshop facilitators and participants —Brief overview of the workshop objectives and agenda		
Step 2. Identifying Opportunities in Everyday Life		
	Execution	*Key questions for participants*
Discussion session: What are the valuable aspects of everyday life for the participants?	The participants were given a few minutes to individually brainstorm the opportunities and possibilities they had in their daily lives despite their upper limb injury. Once everyone had a chance to brainstorm, they shared their opportunities orally, one at a time, while the moderator wrote them down on a whiteboard. After all the opportunities were shared, the participants discussed the similarities and differences in their experiences.	What can you still do with your upper body, such as your arms and hands? Have you learned any new skills or techniques to compensate for your upper limb injury? What activities do you value in your daily life that involve the use of your arms and hands?
Step 3. Identifying Hindrances in Everyday Life		
	Execution	*Key questions for participants*
Discussion session: What hinders a good life according to the participants?	The participants were given a few minutes to individually brainstorm all the things they found difficult or limiting in their daily lives due to their upper limb injury, specifically with regard to their arms and hands. Once everyone had a chance to brainstorm, they shared their hindrances one at a time orally while the moderator wrote them down on a whiteboard. After all the hindrances were shared, the participants discussed the similarities and differences in their experiences.	What do you find difficult or limiting due to your upper limb injury? What activities that involve the use of your arms and hands are negatively affected by your upper limb injury?
Step 4. Familiarisation with Assistive Aids		
	Execution	*Key questions for participants*
Discussion session: What assistive aids do the participants currently use, and what are the reasons for their use or non-use?	The participants were given a few minutes to brainstorm aids they had at home and their motivations for use versus non-use. After brainstorming, they shared these aids and their uses one at a time, while the moderator wrote them down on a whiteboard and asked about the situations in which they used them. This was followed by a group discussion to explore usage, similarities and differences. Subsequently, participants shared the aids they had but did not use, discussing the reasons for non-use. The moderator recorded these insights, and another group discussion was held to further explore non-usage and compare experiences.	What aids do you have at home? What aids do you use? What do you use them for? In which situations? What aids do you have at home but do not use? Why do you not use them?

(Continued)

Table 4. Continued

Step 5. Envisioning and Evaluating Wearable Sensorimotor Interfaces and Supernumerary Robotic Limbs		
	Execution	*Key questions for participants*
Presentation: Introduction to wearable sensorimotor interfaces and supernumerary robotic limbs. Group activity: Participants brainstorm potential applications and benefits of these technologies in their daily lives. Group activity: Participants provide feedback and evaluate the envisioned solutions.	We showed different examples of wearable sensorimotor interfaces and supernumerary robotic limbs for humans with upper-limb disabilities through videos and illustrations. The participants were encouraged to share their impressions and insights, and questions were asked to clarify and explore their ideas for each example. In the first video, an exo-glove designed to assist a person to grip, hold and release objects by pulling an artificial tendon—like a puppeteer—was presented. We showed the following video: https://www.youtube.com/watch?v=KskES39OE6M In the second video, a robotic sixth finger, a wearable device designed to assist or augment human grasping capabilities, was presented. It can be tied to different parts of the body, such as the forearm, wrist or ankle and when not in use, it fit onto the body like a bracelet, anklet or belt. We showed the video: https://www.youtube.com/watch?v=MqGFQX1axBE We also used illustrations of a single robotic arm mounted on a table and on a wheelchair. The illustrations depicted different sensorimotor interfaces worn (1) on a finger (ring), (2) on an arm and (3) on a shoulder that could be used to interact with the robotic arm. The fourth example was a sketch illustrating a dual-arm robotic system with a fixed or mobile base, designed to perform bimanual tasks.	We identified common themes and issues about each example by asking: What are you thinking? What would make you use this product? In which situations?
Step 6. Wrap Up —Summary of findings from the workshop —Open floor for participants to comment, clarify and provide additional insights		

manually associated with initial codes which were then organised into themes through extensive discussions. At this stage, by analysing the relationships among the different themes, it became apparent that there was a hierarchy among user requirements, with some being prerequisites before others could take precedence. Sub-themes were created based on the needs, preferences, challenges and problems identified in the data. These were then translated into themes/requirements and ranked according to the dominance of narratives, accounts and detailed descriptions. Hierarchical level 1 represents the theme and insights that were mentioned by all participants, indicating its significance. In contrast, hierarchical level 5 represents the theme and insights that were mentioned by only a few participants, indicating that it is less dominant but still important (Table 5). Following the steps of thematic analysis, the themes were reviewed, further exploring how they fit together, and ultimately, they were named. A final consensus was reached after discussions among the research team and a hierarchical structure, akin to Maslow's hierarchy of needs [67], was developed.

Table 5. Order of Themes

Hierarchical level	Theme	Sub-theme	Example quotations
1	Functional requirements	Difficulty with gripping Reduce strengths Problems with holding objects Difficulty moving fingers and opening hand Wants to be able to cook Wants to be able to dress Prefers to manage personal hygiene without assistance Wants to be able to use the hand affected by the stroke	'I struggle to grip objects, which makes everyday tasks really challenging'. 'Patients often struggle with gripping, which can severely limit their ability to perform daily tasks'. 'The loss of strength in my hands has been significant. I can't lift or hold things like I used to'. 'The loss of strength in their hands has been a major hurdle, affecting almost everything they do'. 'Even holding a cup or a pen is a problem for me now. It's frustrating and limiting'. 'Many of our patients have trouble holding objects, which can to frequent accidents and frustration'. 'They have a hard time moving their fingers and opening their hand'. 'My fingers don't move as easily, and opening my hand fully is almost impossible'. 'I miss being able to cook for myself. I want to regain the ability to prepare my own meals'. 'We hear from many patients that they wish to return to cooking as a way to regain a sense of normalcy'. 'Getting dressed on my own is a goal I'm working towards. I want to be independent in this aspect'. 'The desire to dress independently is a major goal for patients, as it represents a critical aspect of personal independence'. 'It's important to me to handle my personal hygiene without needing someone else's help'. 'I want to regain the use of my hand that was affected by the stroke. Being able to use it again would improve my quality of life immensely'.
2	Reliability and security requirements	Speed: not too fast but not too slow Accurate and safe Able to turn off immediately Does not want to have to charge it all the time Worries that it will collect personal data	'I need assistive devices that work at a pace that's just right—not too fast to be overwhelming, but not too slow to be inefficient'. 'It's crucial that any technology I use is both accurate and safe. I can't afford to have errors or risks when using it'. 'I want the ability to turn off the device immediately if something goes wrong'. 'Having to charge a device constantly is inconvenient. I prefer something with a long battery life so I don't have to worry about it running out of power'. 'I'm concerned about my privacy. I don't want the device to collect or share my personal data'.
3	Usability and user experience requirements	Wants to be able to set it up and use it without the help of others Simple and lightweight design Wants to be able to move it or for it to be movable Familiarity with voice commands	'It's important for patients to be able to set up and use the device independently, as this promotes their autonomy and confidence'. 'A simplistic and lightweight design would make it much easier for me to handle and use the device effectively'. 'A lightweight design is crucial. It reduces the physical strain on patients'. 'I need a device that I can move around easily or one that is designed to be movable without my effort'. 'It would be great if the device could respond to voice commands since I'm already familiar with using voice-activated technology'.

(Continued)

Table 5. Continued

Hierarchical level	Theme	Sub-theme	Example quotations
4	Recognition requirements	Motivation and Engagement—patients Support for Recovery and Cognitive Functions—relatives Data Integration and Monitoring—healthcare professionals	'I need regular feedback or some form of motivation to keep using the assistive devices. Seeing my progress helps me stay engaged'. 'I would the assistive robotic devices to aid in physical recovery and provide cognitive support. My husband needs rehabilitation'. 'I think that data collected from assistive robotic devices should be integrated with electronic health records. It would allow for access and sharing of results'. 'I think it would be valuable if we could remotely monitor patients and their use of assistive robotics to ensure continuous care and timely interventions'.
5	Growth and self-fulfilment	Customisable and individual style Wants others to want one too Missing doing fun things and hobbies	'I want my assistive device to reflect my personal style and preferences'. 'Providing patients with customisable assistive devices may enhance their satisfaction and willingness to use them'. 'It would be great if others found the device appealing and wanted one too'. 'I really miss being able to do fun activities and hobbies that I used to enjoy. It's a significant part of my life that I want to reclaim'. 'Seeing my wife miss out on her favourite activities and hobbies is tough. I hope she can get back to doing what she love'.

To further ensure the accuracy and validity of the data interpretation and analysis, workshops dedicated to member checking were organised. Member checking is a qualitative research practice designed to confirm the accuracy and credibility of collected data by actively involving participants in the research process [68–70]. During member checking workshops, the achieved research findings were presented to individuals with ULD, their relatives and healthcare professionals, actively seeking their feedback, comments and corrections. This iterative process allowed us to make minor adjustments to refine the hierarchical structure, aligning it more closely with participants' lived experiences of ULD. The final structural hierarchy illustrated the extensive analysis and how the different users' requirements fit together (Figure 2). These themes were identified across the entire dataset, which included data from Sweden, Spain and Italy. We did not find any cultural differences. Although the healthcare systems differed, the identified themes and their hierarchical order were prevalent across all three countries. However, the recognition requirements differed among the different stakeholders. The results are presented below.

3.3 Ethical Issues

Participation in the study was voluntary and written consent was obtained from all the interviewees and workshop participants. This research study received ethical approval from Sweden (Dnr 2022-03154-01), Italy (CE/2023_012 and CAREUS No. 71/2022) and Spain (No. CEIC-961) and was conducted according to the ethical principles' guideline set out in the Helsinki Declaration.

4 Results

We conducted a total of 108 in-depth interviews and 15 workshops with 73 participants across three countries: Sweden (including post-stroke and SCI patients, relatives and healthcare professionals), Italy (comprising post-stroke patients, relatives and healthcare professionals) and Spain (involving

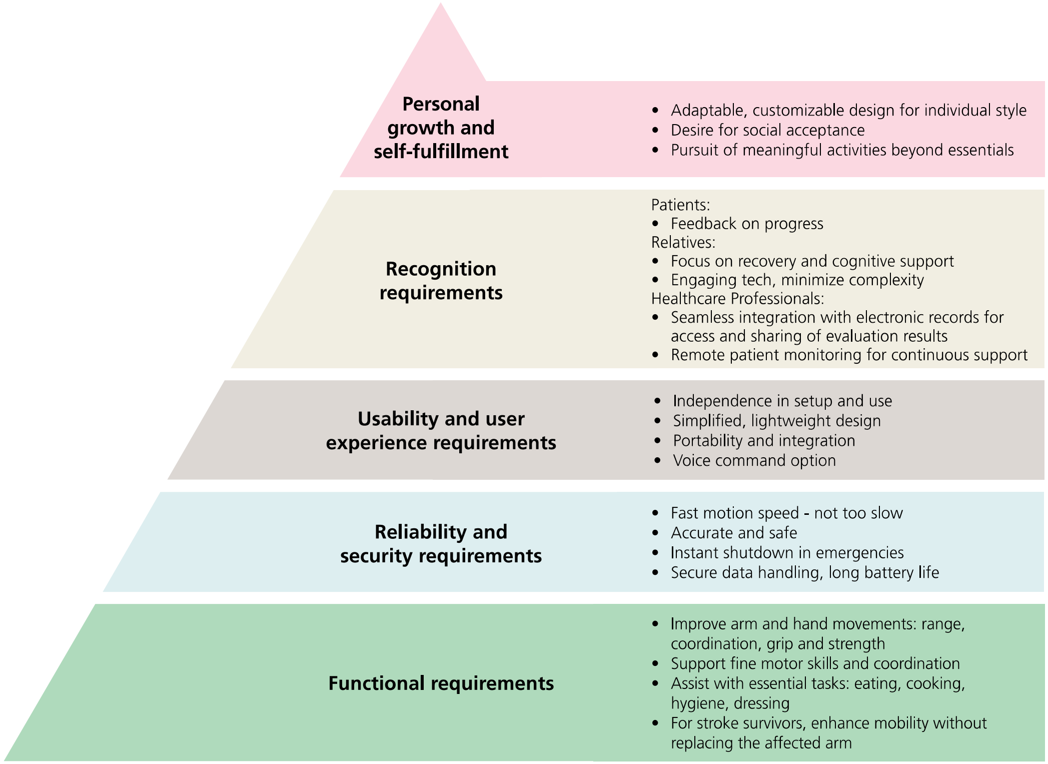

Fig. 2. Illustration of user requirements drawing on Maslow's hierarchy of needs.

SCI patients, relatives and healthcare professionals). The research activities involved 39 post-stroke patients with upper limb paresis, 39 individuals with SCI, 65 healthcare professionals and 38 relatives (Table 6). Notably, the average age of post-stroke patients exceeded that of individuals with SCI. The majority of the post-stroke and SCI patients were men, while most relatives and healthcare professionals were women.

4.1 A Hierarchy for User Requirements

The analysis revealed a hierarchical structure, similar to Maslow's hierarchy of needs [67], of user requirements of robotic limbs. Our findings suggest that users' needs and preferences undergo a hierarchical progression in which the foundational level of user requirements consists of functional requirements. Meeting these functional requirements, which are situated at the base of the hierarchy (Figure 2), is a prerequisite before other requirements can take precedence. According to all participants, the utilisation of any assistive technology becomes unlikely if functional requirements are not met. Progressing hierarchically, we identified reliability and security requirements. A technology must not only be functional but also safe and reliable for use and operation. If the reliability and security requirements are also met, usability and user experience requirements emerge as crucial. A technology has to be not only functional and reliable but also easy to use in terms of usage, setup and required training. Subsequently, recognition requirements became prominent as participants emphasised the need for recognition and progress tracking to sustain motivation for prolonged usage of assistive robotics. Our findings revealed that after recognition requirements,

Table 6. Overview of Participants and Data Collection

Country	Condition	Method	Participants	Average age	Gender
Sweden	Post-stroke	Interview	15 patients	60	73% males
			7 relatives	59	100% females
			6 healthcare professionals	N/A we did not ask them about their age	50% males and 50% females
Sweden	SCI	Interview	8 patients	53	63% males
			8 healthcare professionals	N/A we did not ask them about their age	100% females
Italy	Post-stroke	Interview	10 patients	62	70% males
			10 relatives	51	70% females
			11 healthcare professionals	N/A we did not ask them about their age	90% females
Spain	SCI	Interview	10 patients	50	90% males
			10 relatives	41	70% females
			13 healthcare professionals	N/A we did not ask them about their age	92% females
Sweden	Post-stroke	Workshops	8 patients	66	63% males
			6 relatives	N/A we did not ask them about their age	83% females
			5 healthcare professionals	N/A we did not ask them about their age	60% females
Sweden	SCI	Workshops	9 patients	60	67%
			2 relatives	N/A we did not ask them about their age	50%
Italy	Post-stroke	Workshops	6 patients	55	83% males
			3 relatives	N/A we did not ask them about their age	67% females
			9 healthcare professionals	N/A we did not ask them about their age	67% females
Spain	SCI	Workshops	12 patients	47	83% males
			13 healthcare professionals	N/A we did not ask them about their age	85% females

the highest level requirements regarded personal growth and self-fulfilment such as increased independence through customisation and adaptability to individual design preferences.

4.1.1 Functional Requirements. The participants' primary needs were related to a range of *functional requirements*. Functional requirements emerged as the most dominant theme, with all participants highlighting the need for support in enhancing arm and hand movements to improve range of motion, coordination and dexterity, placing particular emphasis on enhancing grip, reach and strength. The loss of being able to grip and hold objects permeated almost every aspect of their lives. One participant, a relative of a post-stroke patient underscored the critical necessity for technology that supports hand grip. They elaborated, stating 'The most crucial requirement for us is technology that support hand grip. This is my mother's primary deficit'. Similarly, a participant with SCI shared the severe compromise in their ability to grip objects. They explained: 'My ability to grip objects has been severely compromised. I can no longer gauge the appropriate amount of force required, leading to difficulty in manipulating items'. Furthermore, another participant with SCI shared the emotional impact of their condition, stating: '...not having hands is brutal. Not being able to hold objects, not being able to grasp and use tools and utensils. I can't even hold a glass of water'.

All participants also emphasised the importance of assistance in fine motor skills and coordination involving both hands. In addition, the necessity of maintaining a secure grip during spasms or when one's attention is diverted. All participants noted a desire for robotic assistance in performing essential daily tasks such as eating, drinking, cutting and cooking. Other meaningful activities where assistive devices or robotic limbs were deemed beneficial included using the restroom, maintaining personal hygiene and dressing. As one of the post-stroke participants said: 'The stroke has had a profound impact on my daily life, both physically and mentally. I have lost my independence in various aspects. Dressing myself has become an insurmountable challenge and while I can manage using the restroom alone, pulling up my pants on the left side is often unachievable. Showering is now beyond my capabilities. Consequently, I am forced to rely heavily on human assistance. The psychological toll has been so severe that I have attempted to take my own life on two occasions since the stroke'. For post-stroke patients, it was important that robotic devices should enhance mobility and provide support without completely replacing the affected arm of the user.

4.1.2 Reliability and Security Requirements. All participants highlighted the necessity of fulfilling several functional requirements before even considering the use of the robotic limbs. Furthermore, after addressing functional requirements, the majority of participants also emphasised reliability and security. This theme was frequently mentioned and highlighted the need for a device that is not too fast but not too slow, accurate and safe, able to turn off immediately, does not require frequent charging and does not collect personal data. A relative of a person with SCI expressed this sentiment: '...before it (a robot or robotic arm) does a thousand things and has a thousand of functions, it must do a few basic ones in a safe and reliable way...' In terms of *reliability and security requirements*, several key considerations were identified. For individuals with SCIs, the motion speed of robotic limbs holds a significant importance. Most participants with ULD highlighted that the use of wearable sensorimotor interfaces and supernumerary robotic limbs ought to be more effective in task performance compared to relying on another person. As one of the participants with SCI said: '...I always have assistance. Robotic limbs must be more efficient in carrying out tasks than having to ask another person for help...if it is time consuming or unreliable...I would not use it...I would ask for help instead'. A majority of participants insisted that the wearable sensorimotor interfaces and supernumerary robotic limbs must meet stringent criteria for accuracy and effectiveness, consistently performing as expected. According to most participants, the use of wearable sensorimotor interfaces and supernumerary robotic limbs should not cause any physical discomfort or harm. According to the majority of healthcare professionals and relatives' user safety was crucial. According to most participants, an emergency response feature is essential, allowing for immediate shutdown in case of inaccuracies or malfunctions. In addition, secure data handling procedures were perceived as necessary to safeguard user privacy and maintain confidentiality. Furthermore, ensuring long-lasting battery life and reasonable charging times was identified as a vital requirement.

4.1.3 Usability and User Experience Requirements. A broad and recurring theme was usability and user experience requirements, which included the desire to be able to set it up and use it without the help of others, a simple and lightweight design, the ability to move it or for it to be movable and familiar with voice commands. Many of the participants acknowledged the cognitive strain experienced by many individuals with ULD. As one of the post-stroke patients narrated: 'This physical strain has left me endlessly fatigued…my brain does not work as it used to do'. If we consider this quote, and we have many similar quotes in our dataset, the data imply that the setup and usage of wearable sensorimotor interfaces and supernumerary robotic limbs should not be overly complex to ensure actual usage. The design must enable users to independently set up, operate, deactivate or remove the robotic limbs and their interfaces. This was perceived as crucial for fostering independence and positively affecting the participants' emotional experience. There was an emphasis among many of the participants on wearable sensorimotor interfaces and supernumerary robotic limbs being both simple and versatile. Many participants desired to perform a range of tasks with the assistance of the wearable sensorimotor interfaces and supernumerary robotic limbs in various home and outdoor contexts. Additionally, a lightweight design was perceived as desirable, contributing to wearability, comfort and device portability. Furthermore, the seamless integration of wearable sensorimotor interfaces and supernumerary robotic limbs with existing technologies and the home environment, according to participants, would support more frequent use of the robotic limbs. Finally, many participants highlighted a preference for operating robotic limbs using voice commands, citing their familiarity with voice interfaces.

4.1.4 Recognition Requirements. We labelled the next set of requirements as *recognition requirements*. This theme, while less frequently mentioned than the other three, still provided important insights into the type of interaction and feedback desired from robotic limbs and their interfaces to facilitate long-term usage. In this theme, we noticed differences in the narratives of patients, their relatives and healthcare professionals. Some patients talked about the importance of encouragement and motivation in using robotic limbs and their interfaces, while some relatives highlighted the importance of support for recovery and cognitive functions. Some healthcare professionals emphasised the need for data integration and monitoring. Some stroke patients expressed a desire to receive regular updates on the improvement of their affected hand or side using robotic limbs and their interfaces. Similarly, some individuals with SCI sought feedback on their achievements and progress to encourage exercises and self-care practices. As an individual with a SCI said: 'I will need some motivation to use technology, like updates and progress reports…that would make me more inclined to use it'. Some relatives emphasised the importance of robotic limbs in aiding recovery by enhancing motor skills and addressing cognitive limitations. They stressed the need for prompts and reminders to encourage stroke patients to use their weaker side and prevent cognitive regression. Additionally, they expressed a preference for enjoyable and engaging assistive technologies to alleviate stress, fatigue and feelings of sadness or loss. Simplicity in usage was considered crucial to avoid reinforcing feelings of abnormality or incompetence. Some healthcare professionals underscored the significance of seamless integration with electronic medical records for immediate access to evaluation results presented in a clear and understandable manner, which can also be easily shared with patients. They also highlighted the importance of remote monitoring capabilities for healthcare professionals to track and support patients using robotic aids and tools in a home setting, ensuring continuous care and assistance.

4.1.5 Growth and Self-Fulfilment. At the top of the pyramid of requirements, we have placed the need for personal *growth and self-fulfilment*. These requirements represent the overarching needs of users, which, despite their high-level nature, significantly influence user acceptance and long-term adoption of wearable sensorimotor interfaces and supernumerary robotic limbs, as indicated by a few of the participants. A few participants expressed a desire for adaptable and customisable designs of wearable sensorimotor interfaces and supernumerary robotic limbs, allowing them to align with their unique style and personality. Additionally, a few participants expressed a strong desire for these wearable sensorimotor interfaces and supernumerary robotic limbs to be embraced and desired by individuals without disabilities or impairments, as they would contribute to a sense of belonging and social integration. Thus, wearable sensorimotor interfaces and supernumerary robotic limbs should not only be designed for people with upper-limb disabilities but also beneficial for all individuals. Moreover, a few of the participants aspire to use wearable sensorimotor interfaces and supernumerary robotic limbs not only for essential tasks such as hygiene, eating, drinking and cooking but also to engage in a broader range of meaningful activities, enabling personal growth and self-fulfilment.

5 Discussion

The analysis of the large dataset derived from 108 in-depth interviews and 15 workshops with 73 participants demonstrated many nuances of the user needs of individuals with ULD. We identified a hierarchical structure of user requirements that can inform not only the design processes of wearable sensorimotor interfaces and supernumerary robotic limbs for individuals with ULD in particular but also the design processes for assistive robotics for individuals with disabilities in general. This is not the first hierarchical structure of user requirements that has been proposed; there are several [71–73], but to the best of our knowledge, this is the first study proposing an hierarchical structure of user requirements for assistive robotics for individuals with ULD.

Within psychology, Maslow's hierarchy of needs is well known [67]. The hierarchy presents a theory of motivation in which physical needs are at the foundation for all sorts of other needs as well. When physical needs are unsatisfied, all other needs are non-existent. In our study, the functional requirements took precedence. The participants found it difficult to envision that they would use any kind of assistive technology if the functional requirements were unmet. Once the functional requirements are satisfied and the technology is perceived as useful in terms of functionality, new requirements emerge, such as being reliable and secure to use. Then also the reliability and security requirements are met, subsequently usability and user experience requirements emerged. The usability and user experience requirements reflected desires influenced by emotions, acknowledging the significant impact of emotions on user acceptance [74]. Approaches such as affective design [75, 76], emotional design [74], design for pleasure [77] emphasise the pivotal role of emotions on user acceptance [78]. However, our findings indicate that participants prioritise functional, reliability and security requirements subsequently before needs related to usability and user experience. Thus, technology must not only to be functional and reliable but also easy to use in terms of the usage, setup and training required. Furthermore, when it comes to robotic limbs, participants wanted them to have a lightweight design that is desirable, contributing to wearability, comfort and portability. Despite technological advancements, our findings aligns with the challenge of assistive technology in adoption and acceptance [79]. Frauenberger suggested that for assistive technology to become an integral part of the everyday lives of individuals with disabilities, it must be versatile and work in conjunction with other technologies [79]. Similarly, [23] conclude that exoskeletons should have a sense of familiarity or affinity with existing technologies in order to get adopted. Our findings support these studies as many participants expressed reluctance to adopt assistive aids due to their narrow focus on solving specific tasks or supporting particular movements, while everyday life is inherently holistic.

Once the usability and user experience requirements were satisfied; the participants expressed a desire for regular updates on the improvement of their affected hand/hands or side using robotic limbs and interfaces. Labelled as recognition requirements, participants emphasised the need for recognition and progress tracking to motivate long-term usage. Our findings reveal that first, after the recognition requirements are satisfied, then the highest requirements become important, such as customisation and adaptability to individual design. This finding is interesting as [80, 81] shows that customisation and individual design are important for adoption. However, our findings do not indicate that this is unimportant but that other requirements have to be met before this becomes important.

Hancock [72] suggested in his hierarchy of ergonomics and hedonic needs that safety is the foundation for promoting pleasure and preventing bad things from happening. In his pyramid, safety is the foundation, then followed by functionality, usability, pleasurable experience and individualisation [72]. His hierarchy is very similar to ours, but with the main differences in the foundation, which from our participants' point of view were functional requirements and not safety. For our participants to even consider using robotic limbs, they had to offer functionalities such as enhancing arm and hand movements to improve range of motion, coordination and dexterity, placing particular emphasis on enhancing grip, reach and strength. Only after these requirements are met will they require reliability and security. The reason for the differences between our findings and those of Hancock might be that the participants did not imagine using robotic limbs or any assistive robotics if they did not meet their functional requirements and with the prospect of non-use, they did not worry about safety. This may also be explained by their loss of functional capability due to an accident (individuals with SCI) or a stroke. A study on exoskeletons revealed that older people dislike being a burden and perceive exoskeletons as a possible solution to becoming more independent [82]. Since our participants also linked independence with upper limb assistive robotics, it is reasonable to speculate that this is why they stressed their functional impairments and tasks they used to handle, such as gripping, grasping and daily activities, resulting in a dominant focus on functional requirements. Similarly, a study exploring the user needs of potential users of external robotic arms and upper limb exoskeletons identified a significant demand for these devices to assist with various activities of daily living [83]. Their findings revealed high scores for the necessity of external robotic arms in tasks such as eating, hairdressing, cleaning, handling food, dressing and moving nearby items. Similarly, a study on the needs of individuals with tetraplegia identified functionality as the primary focus for the development of an exoskeleton arm [84]. In their study, participants prioritised tasks such as eating, drinking, itching, reading, brushing their teeth and shaving. Our study aligns with these findings. Furthermore, their findings, similar to ours, highlight the necessity for upper limb assistive robotics to be discreet, as participants preferred an arm that is neither bulky nor noisy to avoid drawing unwanted attention and feeling stigmatised. Additionally, both studies revealed that participants desired an arm that is simple, easy to clean and quick to mount. The reasons cited included the frequent change of caregivers and the considerable time required for getting in and out of bed [84].

5.1 Implications for Assistive Robotics Developers and Designers

This study underscores a hierarchical structure of requirements that demands careful attention from both robotics developers and designers. This hierarchy dictates the satisfaction of one level before the emergence of the next. Consequently, during user testing, it is crucial to recognise that users may primarily focus on basic requirements before offering insights into higher-level requirements. On the other hand, our prior studies in robotics have revealed that users often express preferences regarding design and aesthetics [85–88], classified as 'higher-level requirements' in the hierarchy of requirements. This may be explained by the fact that design is the most visually prominent aspect of any artifact, influencing users' emotions and perceptions, and shaping the user's perception of its usefulness [71, 73, 74]. However, our current study focuses on past experiences with assistive technologies, particularly within the context of individuals with ULD. Our aim was to identify factors influencing the use of assistive robotics based on ULD-specific needs and preferences. The analysis revealed a hierarchical structure of user requirements derived from gathered data.

It is important to note that users may articulate requirements hierarchically or across all hierarchy levels during user testing. Nevertheless, our study emphasises that successful and prolonged use of assistive robotics requires addressing various levels of requirements, with user needs evolving hierarchically during active engagement with assistive robotics. The specific number of levels that need to be met depends on the characteristics of the assistive robotics in question and its context of use. This emphasises the importance of an iterative approach to user testing, considering the diverse levels of requirements. The mere fulfilment of functional requirements is insufficient, as new requirements may continually surface once the existing ones are met. Equally, relying solely on user testing in laboratory environments may help to identify only the most basic levels of user requirements. In laboratory settings, the user's role is to assess a technical innovation in various scenarios. Here, functional, reliability, security, usability and user experience requirements may be evaluated. However, users' responses may not accurately reflect actual long-term usage or acceptance in everyday life as recognition, growth and self-fulfilment requirements likely need to be evaluated in real-life contexts and settings.

5.2 Study Limitations

As with all research, our study had limitations. Initially, we observed a substantial disparity between our target users, post-stroke and SCI patients and the ambitious research vision of wearable sensorimotor interfaces and supernumerary robotic limbs. While the intended target group were accustomed to basic, low-tech solutions, they had limited familiarity with advanced technology. This lack of familiarity posed a challenge in envisioning the integration of wearable sensorimotor interfaces and supernumerary robotic limbs into their daily lives. Some participants viewed these technologies as overly complex or belonging to the realm of science fiction, while others held overly optimistic expectations regarding their capabilities. To address this challenge, we focused on two key aspects: managing user expectations and effectively communicating the underlying concepts of wearable sensorimotor interfaces and supernumerary robotic limbs. However, due to our reliance on oral explanations, videos and sketches, the participants were unable to gain hands-on experience with the technologies. As a result, they based their understanding of wearable sensorimotor interfaces and supernumerary robotic limbs on their lived experience of ULD, which may be considered both a strength and a limitation.

In the field of HCI, discussions on power dynamics are frequent [89–91]. The ideal scenario involves intended users having equal power compared to other stakeholders. However, some of our study participants were recruited by their doctors and hospitals. Consequently, they may feel compelled to express positivity, having consented to participate. They may also fear missing out on the opportunity for more interactions with their healthcare professionals or causing disappointment [92–94]. To address this challenge, we recruited patients from hospitals in Spain and Italy, while in Sweden, the participants were recruited from patient organisations.

Another limitation, but also a strength, is that we used qualitative methods. In-depth interviews are dependent on the interaction between the interviewee and the interviewer. Furthermore, in-depth interviews provide insights into the participants' individual experiences and beliefs, which might not be generalisable to broader populations. To mitigate this, we also used participatory workshops to enable participants to interact, share ideas and build upon each other's experiences. By combining these methods, we hope to gather both individual experiences and collective experiences agreed upon in the workshops. However, our qualitative methodology is not easily replicable as the collaboration with the participants depends on the interviewer, the workshop moderator and the group setting. Future research could aim to verify our findings quantitatively through surveys or questionnaires.

Another limitation associated with qualitative research and interpretive analysis is that the analysis is shaped by the researchers' perspectives and preconceptions. To address this limitation, we involved researchers from different disciplines in the data analysis. Furthermore, we employed member checking as a crucial step in validating our qualitative data analysis. During these sessions, we presented our research findings to individuals with ULD, their relatives and healthcare professionals, actively seeking their feedback. This iterative process was employed to ensure the accuracy and validity of our data interpretation and analysis.

6 Conclusion and Outlook

This article presents a hierarchical structure of user requirements for wearable sensorimotor interfaces and supernumerary robotic limbs designed for individuals with ULD. Our data analysis reveals a progression in user priorities, starting with functional requirements as a primary concern. Once functional needs are satisfied, our participants emphasise the importance of reliability, security, usability and user experience. Subsequently, recognition requirements, such as the desire for progress updates and motivation for long-term use, become significant. Our empirical results identify customisation and adaptability as the highest level requirements, suggesting a hierarchy of user requirements that demands careful consideration from robotics' developers and designers. The findings underscore the importance of an iterative approach to user testing, recognising that users may prioritise basic requirements before expressing insights into higher-level needs.

We hope that the hierarchical structure of user requirements proposed in this article offers valuable knowledge to fellow researchers in the field of assistive robotics, serving as a cornerstone for the development of assistive robotics that align with the aspirations of individuals with upper-limb disabilities. Furthermore, we encourage fellow researchers to test and validate these findings, as a collaborative approach to advancing assistive robotics in line with user needs and preferences is needed.

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