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Assistive lower-limb exoskeletons (LLEs) have been recognized as promising tools for enhancing physical capacity in stroke survivors. Involving end-users in the early development stages is essential to ensure these technologies meet user needs. Co-design approaches, which actively engage end-users, support this goal. This study aims to (1) evaluate the impact of fatigue on daily living, (2) identify activities that could benefit from LLE assistance, (3) outline design and usability requirements for home-based LLEs, and (4) define physical parameters LLEs should monitor and assess. Discussions were structured using the PERCEPT co-design methodology, and thematically analyzed. Four chronic stroke survivors participated in three focus group sessions, each lasting approximately two hours. Fatigue was identified as a significant factor in daily life, underscoring the importance of assistive technology, such as LLEs, to help mitigate exhaustion. Participants recognized LLEs as valuable tools for enhancing physical performance, with benefits for muscle strength, balance, fatigue management, coordination, and general mobility. Design considerations included system modularity, battery efficiency, ease of donning and doffing, and practical needs for daily use. Our findings offer valuable insights into stroke survivors' design and usability concerns regarding LLEs and provide a foundation for advancing the development and adoption of new assistive technologies.

Keywords: exoskeleton; stroke; co-design; fatigue; assistive technology

1. Introduction

In previous years, research covering the use of lower-limb exoskeletons (LLEs) and robotics in the stroke population has primarily focused on gait rehabilitation [1, 2], showing their ability to improve walking [3, 4]. However, beyond rehabilitation, the use of LLEs may also show promise as assistive technology, directly compensating for physical capacity losses commonly seen in this population, such as decreased motor function and fatigue [5].

Several studies have examined the short-term effects of assistive LLEs on stroke survivors' physical functioning, particularly improvements in gait parameters such as walking speed, stride length, ground clearance, peak paretic propulsion [6-9], reduced energy costs [10], and increased walking distance [7]. However, their potential to address other major challenges faced by stroke survivors remains largely underexplored. Fatigue, for example, is one of the most debilitating consequences of stroke, affecting nearly half of all survivors and posing a major barrier to rehabilitation and executing everyday activities [11-13]. Yet, little to no studies have examined whether assistive LLEs might alleviate feelings of fatigue in this population. In clinical settings, fatigue management commonly involves optimizing energy expenditure [14]. In this sense, LLEs may hold promise, by reducing this expenditure with improving the efficiency of the performance of daily-life activities, such as stair climbing and walking.

However, before we can conclude if fatigue should be a key focus of LLE design, it is essential to first evaluate how fatigue impacts stroke survivors' daily lives from their own perspectives.

Apart from this, the current state of wearable assistive LLEs is widely considered as still being under development, with design and usability concerns such as weight, ease of use, adjustability, removal, and cost still posing challenges [15]. There is also a need for better evaluation of LLEs in relation to essential daily motor skills [16]. While LLEs support certain physical tasks like running [17], weight-bearing [18], and jumping [19], these are not necessarily critical for enhancing post-stroke independence. Similarly, LLEs are able to incorporate various integrated sensors that can measure human performance and physical state, for example walking ability, muscle strength and heart rate [20, 21]. However, the lack of user input makes it unclear which performance metrics are considered most relevant or valuable to stroke survivors. Addressing these concerns requires the active involvement of stroke survivors in the LLE development process to identify features that will improve design and functionality.

A previous meta-synthesis review identified the lack of end-user involvement in the design process as a barrier for the use of assistive technology in individuals with chronic conditions [22]. Involving end-users provides valuable insights that enhance the design, user-interface, functionality, usability, and overall quality of the device [23, 24]. While user engagement can be integrated at any stage of development, its inclusion during the early design phase, even before a system prototype exists, is particularly crucial and has been identified as a key factor in achieving product success and user satisfaction [25, 26]. The design approach has evolved from traditional user-centered methods, where users play a passive role, to a co-design model that treats users as active collaborators [27]. In co-design, end-users contribute to idea generation, knowledge sharing, and concept development [27]. One methodology supporting this co-design process is the Persona-Centered Participatory Technology (PERCEPT) approach from Bourazeri & Stumpf (2018), which engages target users in group discussions, and treats them as collaborators in the design process [28]. This method has proven effective in designing technology for neurological patients, as shown by a prior study co-designing smart home technology involving people with dementia and Parkinson's disease [28].

A more in-depth look at existing LLEs reveals that few have been developed using structured, user-centered approaches specifically tailored for individuals after stroke. Notably, only two studies have reported genuine participatory design efforts. The first is the *TWIN-Acta control strategy*, which adapted the TWIN exoskeleton—originally designed for individuals with spinal cord injury—using a four-phase process involving physiotherapists, engineers, and stroke survivors [29]. In phase one, physiotherapists and engineers held focus groups to discuss control strategy modifications. In phase two, three physiotherapists tested and assessed intermediate versions. Phase three involved testing the final version with five internal clinical experts and feasibility assessments by four external healthcare professionals. In the final phase, five individuals post-stroke tested the refined exoskeleton, rating their motivation and system usability [29]. The second example is the *NewGait exosuit*, aimed at improving functional mobility and correcting abnormal gait patterns, and was adapted from a prior device originally developed for sports performance enhancement [30]. This device was iteratively refined through two separate design sprints involving clinicians, stroke survivors, and caregivers, with each cycle addressing user needs and improving design features [30].While both studies demonstrate end-user involvement, they remain focused on gait rehabilitation. In contrast, assistive applications for daily life—particularly in a home environment—remain underexplored. Furthermore, existing systems have largely overlooked the early-stage involvement of stroke survivors in conceptual development.

Building on the importance of early end-user involvement, this study aims to gather insights from individuals post-stroke on user needs and requirements—prior to the development of a first prototype—to inform the design of future assistive LLEs for home use. Specifically, using the PERCEPT methodology, this study evaluates the impact of fatigue on everyday life (RQ1), and explores the activities that could benefit from LLE assistance (RQ2), the design and usability requirements for home-based LLEs (RQ3), and the key physical parameters that LLEs should monitor and assess (RQ4).

2. Methods

2.1 Study design

This early-phase, user-centered study is part of the larger interdisciplinary REVALEXO project (www.revalexo.be), with the overarching aim to develop LLEs for in-home and community use for post-stroke individuals. Ethical approval was granted by the University Hospital Brussels Ethics Committee (BUN: B1432023000271), and the study was registered on ClinicalTrials.gov (NCT06238206).

2.2 Participants

A total of four post-stroke individuals were recruited to take part in this study. Participants were recruited through purposive sampling. Eligibility criteria were carefully designed to select participants most likely to benefit from assistive LLEs. The inclusion/exclusion criteria are shown in Table 1. Participants received study information and signed informed consent before participating.

The number of participants is in line with the original PERCEPT framework [28, 31], and is based on the nature of this co-design study, which emphasizes deep collaboration with end-users as active contributors to the design process. Therefore, the number of participants is justified given the high level of involvement and expertise, combined with the complexity of the topic and the goal of getting a more in-depth understanding of the participants' perspectives [32]. Additionally, using different personas allows for discussions beyond the participants' own visions, leading to broader demographic perspectives [28].

Table 1. Inclusion/Exclusion criteria

Inclusion criteria	**Exclusion criteria**
Adults (> 18 years old)	Severe spasticity of the lower limbs

Dutch speaking	Serious speech disorders and/or cognitive problems which restricted them from actively contributing to the group discussions
Had a stroke more than 3 months ago	
Living at home	
FAC levels 3 (individual is dependent on verbal supervision or the presence of an additional person during walking) to 4 (individual can walk independently but only on level surfaces)	

FAC = Functional Ambulant Categories; Exclusion criteria were based on the input from medical doctors at the recruitment site.

2.3 Data collection

Data collection followed a co-design approach inspired by the PERCEPT methodology, where users co-create a set of personas that are used to thoroughly explore, prioritize, and refine user information, goals, and needs [28, 31]. Personas are hypothetical archetypes that represent a broad group of individuals (here, stroke survivors) [33], and are an effective tool in product development, offering benefits such as focusing on user goals, preventing self-referential design, challenging incorrect assumptions, providing a common language, and broadening the demographic [31, 34, 35]. This study was structured around three focus group workshops (W1, W2 and W3), each dedicated to a specific topic. During all workshops we deliberately did not elaborate on specific system types, such as the distinction between soft and rigid exoskeletons or single- versus multi-joint configurations, as our aim was to explore broad user needs and requirements without influencing participants' responses by emphasizing particular design characteristics. Beforehand, preliminary discussions with the REVALEXO consortium, including engineers and physiotherapists, took place and identified important points of interest. As a result, a set of relevant topics, related to the use of assistive LLEs, were compiled for the participants to rate (Appendix A). They were asked to collectively complete this questionnaire at the end of the final workshop to avoid influencing participants' perspectives or responses during the earlier, open-ended co-design discussions.

W1 aimed at getting to know the participants and developing personas, covering their backgrounds, technology use, physical difficulties, and activities of daily living (ADL). Together, the participants created two personas they felt accurately reflected the community-dwelling post-stroke population. These served as reference points for discussions in the subsequent workshops, helping to evaluate the relevance of statements against the broader population and ensuring the generalizability of findings. W2 refined and expended the personas, with emphasis on ADL, physical challenges, and life goals. This was followed by a discussion on the impact of fatigue on ADL (RQ 1) and activities that could benefit from LLE support (RQ 2). To ensure participants understood the concept of assistive LLEs, a brief 3-minute introductory video was shown, featuring five commercially available devices (Keeogo, Hybrid Assistive Limb, EasyWalk, Honda Walking Assist and Myosuit) across various ADL scenarios. The video provided limited details to encourage open-ended discussions.

In W3, participants received an in-depth introduction to LLEs through a detailed presentation. This included definitions, explanation on the types (assistive, rehabilitation, and augmentation), and introduction of 14 assistive LLEs (eLEGS, Myosuit, Ekso indigo, ReWalk, SMARCOS, Mina v2, ComEx, REX, Hybrid Assistive Limb, BEAR, Ascend, Keeogo, EasyWalk and Honda Walking Assist), supplemented by pictures and videos. This comprehensive overview ensured all participants had a clear understanding of the technology. Following this, discussions focused on the usability, design (RQ 3), and assessment possibilities (RQ 4) of LLEs. Finally, participants collectively rated the importance of each predetermined exoskeleton feature (Appendix A).

A non-suggestive, open-ended interview guide was used to guide persona development and discussions on the relevant topics (Appendix B). If needed, side questions were used to maintain focus and avoid irrelevant discussions. Focus groups were held at the Brubotics Rehabilitation Research Center, in Jette, Belgium, with each session limited to no more than two hours [36]. A moderator (R.C.) facilitated discussions, supported by an assistant (E.E.) who took notes and managed timing. Sessions were video- and audio-recorded for thematic analysis.

2.4 Data processing

Recordings were transcribed verbatim using Word (Microsoft, USA). A codebook was developed to standardize procedures prior to transcription [37]. Thematic analysis followed Braun & Clarke's six-phase methodology (i.e., becoming familiar with the data, generating initial codes, searching for themes, reviewing themes, defining themes, and writing the article) [38], and was conducted using NVivo 14 (QRS International, USA).

3. Results

Four chronic post-stroke individuals (2 male/2 female, age range: 49-68 years, time post-stroke: 8-80 months) participated in this study (Table 2). One participant (P3) had previously engaged with a rehabilitation LLE during their rehabilitation period, while the others were newly introduced to the concept. A total of three focus group discussions, each lasting approximately 1.5 to 2 hours and spaced about 3 to 5 weeks apart, were conducted. All participants actively contributed to all workshops, except for one individual who was unable to attend W1 due to illness. Consequently, W1's content was summarized in the beginning of W2, allowing all participants to exchange input and information.

Appendix C provides a visual overview of the personas that were created by the participants. These include: a short biography, some background information, use of technology, physical difficulties and activities of daily living.

Table 2. Characteristics of the study population.

	P1	P2	P3	P4
Sex	Male	Female	Female	Male
Age (years)	62	49	63	68
Type of stroke	Ischemic	Ischemic	Hemorrhagic	Ischemic & Hemorrhagic

Multiple strokes	No	No	No	Yes
Affected side	Right	Right	Right	Left
Time post-stroke (months)	8	80	23	17
FAC (0-5)	4	4	3	4
MoCA (0-30)	28	24	24	21
IPAQ-SF (low - moderate - high level)	High level	Moderate level	Low level	High level
Walking aid	/	/	Walking cane, rollator and/or wheelchair (dependent on the performed activity)	Walking cane (everyday use)

FAC = Functional Ambulation Category, MoCA = Montreal Cognitive Assessment, IPAQ-SF = International Physical Activity Questionnaire Short Form

Table 3 gives an overview of the key findings from the thematic analysis on LLE needs and requirements: which physical attributes need to be assisted, the potential to use LLEs as an assessment tool, the design and control requirements, the battery needs, the device aesthetics, the context during which LLEs need to be used and the practical needs for LLEs.

3.1 The impact of fatigue during everyday life

The feeling of fatigue was a recurrent theme and seems a common challenge for the population. The analysis revealed two primary themes: trait fatigue and fatigability.

3.1.1 Trait fatigue

The experience of a "general", overwhelming feeling of fatigue, which is not linked to the execution of challenging activities, was frequently described. To manage this, the need for regular rest throughout the day was mentioned, through taking breaks or power naps.

> *"The typical fatigue that overwhelms you and that cannot be linked to any activity, it just happens. And they both (persona 1 and persona 2) still have that." (P1, W2)*

Fatigue was reported to fluctuate throughout the day, generally increasing as the day progressed, with more prominent feelings of tiredness towards the evening (e.g., "your evening starts much earlier") which limits the involvement in evening activities. Additionally, participants highlighted that the overall energy levels are significantly lower compared to before the stroke. This requires more effective planning and management of daily activities, often spreading tasks throughout the day to conserve energy.

> *"Your load of energy is more limited and runs out quicker. You have to plan better …" (P1, W1)*

3.1.2 Activity-related fatigue or fatigability

Exhaustion was also related to the performance of activities, caused by prolonged tasks such as walking, standing or cleaning the patio, which increase the need for regular rest breaks.

> *"Cleaning the terrace is no longer possible … because she (persona 1) is too tired, it is too exhausting" (P3, W1)*

Fatigue also impacted stair climbing, making it more challenging and slow, and involved both physical (muscle strength) and mental components (reluctance to walk stairs and planning to minimize stair use).

> *"… very slowly going up the stairs" (P4, W2) – "And when you are upstairs … (P3, W2) – "You are tired" (P4, W2)*

Furthermore, a strong link to the cognitive aspect of fatigue was mentioned. Due to physical limitations, it was highlighted that post-stroke individuals remain more conscious and focused on their movements. Participants mentioned that activities like walking, functioning at work, and cooking become less spontaneous, and require constant attention to where and how one moves. They emphasized that this heightened need for control adds to the mental burden, further contributing to overall fatigue.

> *"It makes you feel physically exhausted way faster considering you constantly need to readjust and be careful not to fall or bump against something." (P1, W1)*

Lastly, the occurrence of motor compensations such as decreased gait symmetry and foot clearance were reported to occur after prolonged activities.

3.2 Increased physical performance from LLE use

The potential of LLEs to improve agility and coordination was recognized, being able to assist activities like walking down slopes and stairs. In addition, compensating for lost lower limb muscle strength was also acknowledged, with the need for assisting tasks such as standing up, sitting down, climbing stairs and slopes, crouching to pick up objects, and handling household chores like filling the washing machine (Table 3).

> *"… if he (persona 2) has to grab* something low to the *ground … bending the knees and getting back up, is difficult" (P4, W2)*

Furthermore, the potential benefit of LLEs to enhance balance was acknowledged, especially in countering the fear of falling. This was seen as helpful during daily activities (e.g., standing on a small ladder to change a light bulb), and fundamental tasks (e.g., bending through the knees). Moreover, LLEs were recognized for countering feelings of fatigue, allowing for longer walks and prolonged standing.

> *"She (persona 1) can no longer walk for long periods of time and perhaps with this (LLEs) she will be able to go again for longer walks. Maybe she will then be less tired, have less fear of falling and find it easier to keep her balance" (P1, W3)*

Lastly, LLEs were recognized useful for a wide variety of activities related to general mobility. This included walking on irregular surfaces (e.g., forest or garden), performing gardening tasks (e.g., mowing grass, plant care), overhead reaching, household chores (e.g., vacuuming, mopping), and simply moving around in home environments.

> *"I think that Laura (persona 1) would be able to perform long distance walks again (with the LLE), maybe even go for a forest walk. And for Bart (persona 2), mostly so that he can be back at home in his own yard" (P1, W2)*

3.3 Design and Usability of LLEs

Five general themes were identified regarding LLE design and usability were discussed: design and control of the system, battery system, aesthetics, context of use and practicality (Table 3).

3.3.1 System design and control

A common need for a modular exoskeleton system was identified. A customizable device was considered essential to meet the varying needs for levels of support and attachments.

> *"... it really should adhere to what you need (refers to customization towards the user), so you will use it more." (P4, W3)*

On the one hand, the ability to manually adjust the level of support based on the physical state was emphasized, with a preference for the control panel directly on the device rather than through an external device such as a smartphone. On the other hand, there was interest in how the exoskeleton could automatically adapt to the user's physical state or intention, adjusting the support according to energy levels or activities performed, thereby eliminating the need for manual adjustments (Table 3).

> *"The device knows when you are climbing stairs. The device senses that based on your muscle tone for example ..." (P1,W3) – "Yes, then you don't need to deal with that (the adjustment of assistance level) (P4,W3) – "... It automatically adjusts to what you ask from the device" (P1,W3)*

3.3.2 Battery system

The participants emphasized that the battery life of LLEs must accommodate daily living, and should last through an entire day of activities. A modular battery system, allowing multiple batteries to be switched throughout the day, is a possible practical solution.

> *"... most of the time you only need energy (battery-life) for one day. In the evening you may charge it when you go to bed. It may be an option to include a second (spare) battery. " (P4, W3)*

An essential aspect of the battery system seemed the clear communication of battery level, informing the user how long the device can continue to function at a given level of support, therefore ensuring that the system will not unexpectedly shut down. Additionally, it was preferred that the battery can be charged separately from the exoskeleton, simplifying the charging process.

> *"If you have to charge such a system, it would be easier if you just need to charge the battery (and not plug in the whole device). " (P2, W3)*

3.3.3 Aesthetics

Overall, it was concluded that while aesthetics are beneficial, they are not as important as the practicality of the device. The emphasis should be on functionality and effectiveness. A statement made by one participant, but supported by the whole group, was:

"… if it looks good, it would be nice, but should I go to buy one and there are five models, I will take the most practical and not the prettiest one" (P1, W3)

However, no consensus could be reached on whether the device should be discrete or not. One vision was a design that would be discrete and not attract too much attention, while the other was a visible device that might encourage others to be more considerate of your physical limitations. Nevertheless, a preference for neutral colors such as black was commonly expressed (Table 3).

3.3.4 Context of use

Overall, while the potential of LLEs to improve quality of life was recognized, the intended use varied. A distinction was made between wearing them to support specific challenging activities and wearing them for extended periods of time.

"Bart (persona 2) will need it (LLE) more often, as he will need more support and would use it for more activities. Laura (persona 1) would maybe use it more targeted, just to expand her abilities, to regain capabilities she lost a bit. … Bart will probably put it on in the morning to use throughout his day" (P1, W3)

Related to the adoption of LLEs, it was mentioned that the acceptance of one's physical condition grew over time, with longer post-stroke periods leading to greater openness to mobility aids, such as LLEs.

"Yes, but for Laura (persona 1), it (stroke incident) has already been 3 years and for Bart (persona 2) only 11 months. That makes a difference. Considering it is three times as long for Laura, we can expect she is already further in the level of acceptance." (P2, W3)

Furthermore, it was concluded that LLEs should be designed for versatile use, both inside and outside the home (Table 3).

3.3.5 Practicality

Practicality was a major concern, with the need for a lightweight, compact, quiet, and easy-to-use device. Small dimensions are crucial in settings like public transport, restaurants, and cafes. The importance of ease of donning and doffing was expressed, with simplicity over speed being emphasized, particularly for stroke survivors with hemiplegia and potential upper limb impairments. There was even a vision for an automatic device that could strap itself around the leg.

"I just think 'easy' is more important, it does not have to be fast (refers to donning and doffing)" (P2, W3)

"If we are allowed to dream, this is the ideal: that the LLE hangs against the wall, you put your leg against it, it says 'click clack' and you're gone." (P1, W3)

The device needs to tolerate unrestricted leg movement, remain comfortable when seated, avoid skin damage, and be weather-resistant. Freedom of movement was deemed essential to ensure wearers can perform activities smoothly without hindrance. Additionally, it should be portable for travelling, offering mobility and independence in various environments (Table 3).

> *"For Bart (persona 2) it's going to be important that it is resistant to water and mud." (P4, W2)*
> *"It really should be comfortable to wear, there cannot be any areas where you cut your skin and so on" (P4, W3)*

3.4 LLEs as an assessment tool for physical parameters

While LLEs' potential for monitoring physical parameters was recognized, there was minimal interest in the specific measurements, with these features largely seen as "gadgets" rather than essentials. One mentioned option was a pedometer, although it was noted that this function is already available on other devices such as smartphones. However, there was interest in assessment features that could enable automatic control adjustments. Measuring inputs like physical input (e.g., "amount of energy") or detecting activities (e.g., stair climbing) could allow the system to automatically adapt support levels, therefore enhancing ease of use (Table 3). One participant's comment, later echoed by personas, stated:

> *"If you are using it (LLE) therapeutically, then measurements are very important. But if you are just using it as a support tool after your therapy is largely completed, then it does not need to analyze me every day. That doesn't really interest me." (P1,W3)*

Table 3. Key findings on lower-limb exoskeleton needs and requirements identified during the focus group discussions.

Which physical attributes need to be assisted?	LLEs as a possible assessment tool
Overcome decreased muscle strength	No interest to monitor own physical state
Improve balance	Potential of real-time assessment to improve functioning
Reduce fatigue	
Improve coordination	
Increase general mobility (e.g., irregular surfaces, household chores)	
Requirements for system design and control	**Thoughts on battery system**
Modular and customizable	Battery life for a whole day
Attached control panel	Clear visualization of battery life
Ability to manually change the assistance level	More than one battery that can be switched
Benefit of automatic adjustment of assistance level	Charge battery separate from device
Aesthetics of LLEs	**During which context would LLEs be used?**
Functionality is more important than aesthetics	Inside and outside use
Neutral colors	Some would use it for specific challenging activities versus others for a whole day
Practical needs for LLEs	
Lightweight and compact	Comfortable to wear while seated
Silent operation	No skin irritation
Easy donning and doffing	Weather/water resistant
Transportable by car	Does not restrict leg movements

3.5 Priority ranking of exoskeleton features

The ranking of predetermined exoskeleton features, as presented in Table 4, reflects the aspects that participants prioritized for using assistive LLEs in daily life.

There was a strong consensus that LLEs should support the common ADL. The maximum score of 9 was given to features related to mobility assistance, including walking long distances, sit-to-stand transitions, stair ascent and descent, walking on slopes, and crouching or kneeling. While walking assistance was highly rated, walking long distances received a higher score than walking short distances (score 9 vs. 7).

Several features related to comfort and daily usability also received the highest score of 9. These included unobstructed motion, comfortable cuffs, independent use, the ability to use the device for up to 8 hours, safety, hygiene, and toilet accessibility. Low noise levels followed with a score of 8.

Features with mid-range scores included lightweight design (score 6), feedback coupling to physiotherapists/physicians (score 5.5), the ability to walk with the device turned off (score 5) and the cost (score 5). Transportability was scored at 4.5. Cost was also more in-depth discussed, with subjects substantiating the differing views on what is considered 'expensive', but agreeing that the device should be reimbursable.

Notably, easy donning/doffing was scored higher compared to fast donning/doffing (score of 7 vs 4, respectively). Aesthetics received the lowest score of 2 and was the only feature ranked at that level.

When comparing the priority ranking of predefined LLE features (Table 4) to the key findings from the focus group discussions (Table 3), it becomes evident that the group discussions revealed a broader set of important design aspects than those initially anticipated by the consortium in the questionnaire. Nonetheless, several highly rated features—such as unobstructed leg movement, all-day usability, low noise levels, functionality over aesthetics, and ease rather than speed of donning/doffing—were consistently emphasized in both formats. Additionally, lightweight design and transportability were raised during the discussions and received priority scores of 6 and 4.5, respectively.

Table 4. Scores of the questionnaire assessing the importance of different LLE features.

Ranking	Score (1-9)	Topic:
1	9	Assist with walking (long distance)
	9	Assist with sit to stand
	9	Assist with stair ascent/descent
	9	Assist with walking up and down a slope
	9	Assist with crouching/kneeling
	9	No obstructed motions
	9	Comfortable cuffs
	9	Independent use
	9	Assistance for 8 hours
	9	Safety

	9	Hygiene
	9	Allow for toilet use
2	8	Low noise levels
3	7	Assist with walking (short distance)
	7	Easy donning/doffing
4	6	Lightweight
5	5,5	Feedback to physiotherapists/physicians
6	5	Able to walk with LLE when turned off
	5	Cost
7	4,5	Transportability
8	4	Fast donning/doffing
9	2	Aesthetics
The ranking is in ascending order, where rank 1 represents the most important feature and rank 9 the least important.		

4. Discussion

The present study aimed to collect critical insights from stroke survivors to inform the development of assistive LLEs. The study successfully implemented the PERCEPT co-design approach [28], and actively involved people post-stroke in the early stages of technology development.

4.1 User-centered design concerns for LLEs

Involving target users in the development process is well-recognized as a way to improve design and ensure that user needs are addressed [24, 26]. Despite this, to our knowledge, only two studies describe a user-centered LLE development approach for post-stroke individuals. Semprini et al. (2022) involved physiotherapists, engineers, clinical experts, healthcare professionals in the development of the 'TWIN-Acta' control strategy for the TWIN exoskeleton, and involved post-stroke individuals in evaluating the final version [29]. Additionally, Krishnan et al. (2024) refined the 'NewGait' exosuit through iterative design sprints involving stroke survivors, clinicians, and caregivers [30]. Although both studies successfully engage stroke survivors in the development process, their focus is more on refining a pre-existing device, rather than involving end-user to co-design a device from the ground up. In order to limit the chance that a device is developed based on wrong user assumptions, it is important to know beforehand what the expectations/concerns are of post-stroke individuals.

4.2 The impact of fatigue in stroke survivors

Our findings recognize fatigue as a prominent limiting factor in daily life for individuals post-stroke. This is supported by previous research showing that post-stroke fatigue is associated with reduced mobility [39], diminished functioning and participation in daily life [13], and an increased likelihood of dependency in ADL [40]. Participants in our study identified two key domains of fatigue that hinder task execution: *trait fatigue*, a persistent and generalized sense of exhaustion present over extended periods, and *fatigability*, which refers to task-induced exhaustion that arises in response to specific activities or circumstances [41]. Fatigability can be expressed both in a performance (e.g., reduced walking speed) and perceived component (e.g., increased perceived exertion) [41].

Based on promising findings from prior LLE research [7, 10], we suggest that assistive LLEs could serve as valuable tools to alleviate fatigue experienced during daily life. Given that trait fatigue and fatigability are distinct constructs [42, 43], we envision that assistive LLEs are particularly well suited to address *fatigability*, thereby enhancing stroke survivors' capacity to perform demanding or exhausting ADL.

4.3 LLEs to support physical performance

This study identified various activities where LLE support could enhance physical performance in stroke survivors. Overall, our findings state the need for LLEs to compensate for the loss in muscle strength (e.g., crouching/stooping, sit-to-stand and stand-to-sit transfers, stair and slope ascending), decreased balance (e.g., bending through the knees and standing on small/unstable surfaces), fatigue (e.g., prolonged walking and standing upright) and reduced coordination (e.g., stair and slope descending). In support, Dorsch et al. (2016) identified bilateral lower limb muscle weakness in ambulatory chronic stroke survivors, particularly in the hip extensors, knee flexors, and ankle dorsiflexors [44]. This could suggest that LLEs should prioritize supporting these muscle groups to counter the lack of muscle strength in post-stroke individuals.

Furthermore, participants also addressed fear of falling to be linked with impaired balance, a finding consistent with Tian et al. (2024), who reported a high prevalence (42%–93.8%) of fear of falling among stroke survivors, with balance as a key risk factor [45]. Additionally, our finding on the perceived reduction of lower limb coordination, potentially affecting stair and slope descent, aligns with Menezes et al. (2017), who observed impaired motor coordination in both the paretic and non-paretic lower limbs of ambulatory chronic stroke survivors compared to healthy controls [46]. As both balance and coordination are still poorly considered in the evaluation of LLEs [16], future research is needed to address these physical attributes.

We conclude that LLEs aimed at improving functional independence in stroke survivors should focus on enhancing muscle strength, balance, fatigue management, and coordination. Future research should explore the ability of LLEs to support these attributes during more functional activities, as current evaluations focus primarily on walking on flat surfaces [16]. These functional activities include walking on inclines, stair navigation, sit-to-stand/stand-to-sit transitions, as well as less frequently targeted movements such as lateral stepping, crouching, turning, and standing [16]. As assistive LLEs should be a versatile tool for both indoor and outdoor use, it needs to be able to navigate real-world environments, including uneven terrains like those in forests or beaches [16].

For LLEs to be effective in mitigating fatigue, our findings suggest they must be designed for extended use, aimed at increasing both the amount and duration of activities while potentially reducing cognitive load by facilitating movement. While previous studies have demonstrated positive effects on objective outcomes that are considered related to fatigue (such as reduced energy cost [10] and increased walking distance [7]), evidence on their impact on perceived exertion remains limited. Indeed, given that fatigue is a highly complex construct, involving various physiological, central, and peripheral mechanisms that ultimately lead to a subjective response, and is therefore difficult to evaluate using one objective measurement, it is crucial to consider self-perceived fatigue as a significant outcome in these studies. Future research should evaluate whether assistive LLEs can mitigate perceived fatigue during ADL, such as household tasks and walking within stroke survivors' life-space mobility, to evaluate its real-world potential.

4.4 Design and usability requirements

Participants in our study expressed the need for a modular, customizable system to accommodate the diverse needs of stroke survivors. This in line with Cumplido-Trasmonte et al. (2023), who emphasized that future overground exoskeletons should be considered as sets of modular joint components, allowing users to choose a configuration based on their functional ability [15]. Other key design concerns raised by participants included a lightweight, compact device that is quiet, easy to don and doff, comfortable while seated, and water-resistant. Similarly, in the study of Vaughan-Graham et al. (2020) stroke survivors identified independent donning/doffing, the time required, and the device's weight as critical concerns, with the additional need to withstand inclement weather in order for the device to be usable during daily life [47]. While previous research emphasized the importance of fast donning and doffing [48], participants in our study prioritized ease of use over speed. Perhaps this difference is due to the intended context of use: where quick donning is essential in rehabilitation settings to preserve therapy time [47, 48], this seems less relevant for assistive LLEs for home use. To aid donning/doffing, automatic strapping systems should be explored to facilitate independent use [49]. Furthermore, existing assistive LLEs often incorporate a back module (e.g., Myosuit, TWIICE, UGO220) that could interfere with a comfortable seated position. Therefore, we suggest the reduction of the back system to its smallest possible form, a way to remove this module while seated, or even dismissal of the back module entirely.

Battery life emerged as an important consideration, with participants suggesting a full-day battery capacity and modular, swappable batteries. Prior studies confirm the importance of battery life and indicators [47, 50]. Regarding control systems, participants expressed interest in both manual and automatic modes. Manual control allows users to adjust support based on their subjective state but increases cognitive load [51]. Automatic control systems, which adjust assistance based on the user's physical condition or intended activity (e.g., stair climbing), were deemed useful to reduce human intervention, an interest echoed in Vaughan-Graham et al. (2020) [47]. Artificial intelligence methods are being increasingly explored to support automatic control [51]. Although participants in this study expressed interest in assessment to guide control strategies, there was little to no interest for using integrated sensors to monitor their own physical status. A prior study in rehabilitation context reported that stroke survivors saw wearable sensors as motivating when combined with personalized goals [52], suggesting that physical monitoring might be more useful when aligned with individualized rehabilitation goals, and less relevant for assistive use.

Our finding that functionality is prioritized over aesthetics, aligns with the study of Wolff et al. (2014), where wheelchair users rated "overall appearance" as the least important design feature [50]. However, our findings suggest that opinions on device visibility appear to be divided: while some stroke survivors may prefer a discreet LLE to encourage quicker adoption, others may be more accepting of visible designs that function as social cues, signaling the need for caution. Similar findings were reported by Vaughan-Graham et al. (2020), where one stroke survivor preferred a low-profile design, while another was willing to compromise for improved mobility [47]. Additionally, Swinnen et al. (2015) showed that for neurological patients, functionality and comfort outweighed aesthetic concerns for lower-limb orthotics [53]. However, Bashir et al. (2022) showed that appearance remains a barrier for adopting lower-limb assistive devices in certain populations [54]. Overall, we suggest that the current primary focus in LLE development should be on improving functionality and practicality for home use, after which aesthetics and discreetness could be explored to reduce barriers to adaptation.

5. Strengths, limitations and future directions

A key strength of this co-design study is the early involvement of stroke survivors in the design process, even before a prototype exists, to ensure effective product design. This approach enabled us to gather detailed insights on user priorities, including those not addressed in the survey (e.g., standing support, swappable batteries, seated comfort, water resistance). A limitation is the exclusion of individuals with cognitive impairments, which are commonly present in this population [55], due to the focus group methodology, leaving their perspectives unrepresented. However, we anticipate similar physical support needs, with the primary differences likely present on the usability level. Additionally, the visions of healthcare professionals were not included but could offer valuable insights. Further research should assess whether they share similar concerns.

Our study lays a solid foundation for future LLE development by identifying clear, user-informed design requirements *before* the creation of any physical prototype. By doing so, we created what could be described as a "pink world"—an idealized vision shaped entirely by users' goals and expectations, rather than constrained by existing technologies or prototypes. While this approach enables a fresh perspective, it also highlights the risk of designing based on assumptions that may not hold once real-world limitations come into play (e.g., technical limitations). Nevertheless, this early-stage co-design methodology offers valuable insight into how assistive technology can be better aligned with user needs from the start. It can guide critical hardware and software decisions, potentially reducing the need for fundamental and costly redesigns later in the development process.

By capturing end-user priorities—such as joint modularity, comfort while seated, toilet accessibility, and pleasant cuff materials—our findings provide a valuable starting point for developers. The next step is to translate these insights into LLE prototypes and engage users in iterative testing to optimize usability, safety, and perceived benefit. These stages will gradually shape the “pink world” into a balanced reality that reflects both user needs and technical/practical constraints. Importantly, prototype testing should move beyond controlled lab settings and evaluate LLE use during a wide range of ADL, ideally in the end-user's home environment and over extended time periods. Evaluations should combine objective metrics (e.g., metabolic cost) with subjective experiences, like perceived effort and satisfaction, to ensure practical relevance and long-term adoption.

6. Conclusion

This study successfully implemented a co-design approach to gather insights from stroke survivors during the early design phases of LLE development. Fatigue mitigation emerged as a key focus area for assistive technology. Overall, participants expressed enthusiasm for integrating assistive LLEs to improve physical functioning, enhance quality of life, and promote functional independence. Our findings offer valuable insights into the design and usability concerns of stroke survivors regarding LLEs and serve as a critical foundation for advancing the development and adoption of new assistive technologies.

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8. Disclosure of interest

The authors report there are no competing interests to declare.

9. Appendix

Appendix A. Questionnaire rating the importance of LLE features.

Score (1-9)	Topic:
	Assist with walking
	Assist with sit to stand
	Assist with stair ascent/descent
	Assist with walking up and down a slope
	Assist with crouching/kneeling

	Able to walk with LLE when turned off
	No obstructed motions
	Comfortable cuffs
	Independent use
	Fast donning/doffing
	Easy donning/doffing
	Assistance for 8 hours
	Feedback to physiotherapists
	Safety
	Lightweight
	Transportability
	Noise
	Cost
	Hygiene
	Aesthetics
	Toilet use

Appendix B. Interview guide.

Workshop 1	
Introduction	*General introduction on the purpose of today's session, and an explanation what the concept of personas are.*
Co-creating the personas: background information	
Transition question	In order to get to know each other we would like you to introduce yourself addressing the following topics: name, residence, current or last profession, living situation, experience with technology, interests and hobbies.
Instruction	*Similar to the information we just heard from each other, we are going to do the same exercise for our first persona. So think about a typical person from your demographic, someone who has suffered a stroke in the past. You can draw inspiration from yourself but also from people from your environment.*
Key question	What could be a good name for the persona?
	What is the age of the persona?
	What is the residence of the persona?
	What is his/her current or last profession?
	What is the living situation of the persona?
	Is the persona surrounded by friends and family?
	How long ago did our persona had a stroke?
	Is the persona experienced in using technology?
	Does somebody have an idea what the interests and hobbies could be of the persona?
Co-creating the personas: activities of daily living	

Transition question	Before we go further with the personas we would like to know what activities you perform throughout the day. This covers everyday activities both inside and outside the house. We are going to discuss this by collectively going through the day: when you wake up, in the morning, at noon, in the afternoon and in the evening.
Key question	Now we want to do the same exercise for the persona. So what activities do you also expect to see with him/her? This could be activities we already heart but this could also be activities that we haven't said yet.
Co-creating the personas: physical difficulties	
Transition question	As today's last topic, we are going to talk about physical difficulties and complaints. This can include difficulty in performing activities or actions, as well as having certain physical complaints. What are difficulties or complains you experience during everyday life?
Key question	Now we also want to discuss the physical difficulties and complaints of the personas. This can be things we just listed, but this can also be aspects we didn't hear from you but that we expect to see in a classic individual after a stroke with some physical problems.

Workshop 2	
Introduction	*General introduction on the purpose of today's session.*
Co-creating the personas: reflect on the personas	
Instruction	*In the previous workshop we created these personas (visually represented). First we are going to verbally revise each one of them, afterwards we are going to take time to reflect on them, possible changing or adding information.*
Key question	Based on your own experience but also looking at stroke survivors in your environment are there topics that need to be additionally addressed or that need to be refined?
	Do you feel like this forms a good representation of the demographic of stroke survivors, or do we wat to create/expand the personas?
Co-creating the personas: the same structure in questions is then used to make the following persona(s) (if stated necessary)	
Questioning the impact of fatigue	
Instruction	*In the next section, we will take a closer look at the feeling of fatigue. We will use our personas to discuss this. The aim is to define the concept of fatigue from the typical image of a stroke survivor who is functionally limited to some extent. So we try to think not only from our own perspective, but also more broadly.*
Transition question	In general, do you think that one or more of the personas experience fatigue?
Key question	During which activities do they experience fatigue?
	Are there known strategies or helping aids to counter the feelings of fatigue?
	On the table you see a combination of common daily activities and daily activities we stated during the previous workshop. Do you feel like any of these could cause fatigue?
Questioning the potential of LLEs to support challenging activities	
Introduction	*In order to make sure all participants understand what a LLE is, a brief introductory video was shown, featuring five commercially available LLEs in various ADL scenarios. The video provides limited details to encourage open-ended idea generation. Afterwards the personas are again used to open the discussion.*
Key question	Do you envision activities that would benefit from exoskeleton support?

	Based on the physical difficulties we discussed, could the use of LLEs be of potential help?

Workshop 3	
Introduction	*General introduction on the purpose of today's session. In depth presentation on the concept of LLEs, with many examples of devices using videos and photos.*
Design and usability of LLEs	
Introduction	*A moment ago, you were shown a wide variety of exoskeletons. Now the idea is to reflect on what you like and dislike about the design and usability of the device. We are again using the personas to discuss this.*
Key question	First, we start with the design, what is there to like and dislike? So related to how the device looks, and how it is drafted?
	Second, we are interested in how convenient it is to use?
Assessment using a LLEs	
Introduction	*Within the exoskeleton there is the possibility that we can measure different parameters. Think about the possibilities that exist using a smartwatch of smartphone but with more options.*
Key question	Are there parameters that are relevant/interesting to assess?
	With the parameters we addressed, how would it be best to visualize them in an interface?
Questionnaire scoring the importance of LLE features	
Introduction	*Beforehand, based on what the researchers expected to be of interest, we made a questionnaire with different topics related to exoskeleton features. We are going to score each topic collectively, again taking the perspective of the personas into account.*
Key question	How important (1 through 9) is the following topic?

Appendix C. Visual representation of the co-created personas Laura and Bart.

Laura

Bio: Laura, 52, lives with her partner in Halle, Belgium. As a former teacher, she has a solid basic knowledge of technology. Three years ago, she suffered a stroke, as a result she now experiences some physical challenges, especially in the areas of long-distance walking, gardening and maintaining balance.

Background information:

Gender: female
Age: 52 years old
Diagnosis: CVA on the left (3 years ago)
Residence: Halle (small town in Belgium), semi-detached house with small garden
Occupation: teacher (early retirement)
Family: husband, 2 children (1 boy aged 29, lives in the USA and 1 girl aged 22, attends college and is a final-year physical therapy student), a dog and 2 goldfish
Hobbies and interests: nature (fauna and flora), walking the dog (well-behaved, trained dog), cycling, swimming
Dreams/Motivator: preventing relapse, maintaining her current condition and capabilities, performing long walks (10-15 km)

Technology use:

- Basic level
- Indicates the importance of fine motor skills (e.g., typing)
- Is patient with herself when handling technology
- Devices: iPad, PC/Laptop

Physical difficulties:

- Walking:
    - Fear of falling: she needs company to walk greater distances
    - Long distance: limited to 3-4 km, suffers from fatigue, difficulties with irregular surfaces
    - Helping aid: walking cane with build-in seat
- Gardening: too tiring, gross (e.g., stooping/kneeling) and fine (e.g., hand manipulating) motor skills
- Balance problems: situational
- Stressful situations trigger physical problems: coordination, fine motor skills
- Getting on- and off a bike

Common daily activities:

- Morning: get up, eat breakfast, read the newspaper (iPad), walking the dog, cooking
- Noon: eating hot meal
- Afternoon: household chores (ironing, cleaning and laundry), physiotherapists visit (2x/week), meeting with friends, rest breaks
- Evening: watching TV, crocheting/knitting, social visits
- Weekend: hobbies, longer walks in a club (± 3-4 km), coffee breaks

Bart

Bio: Bart, 64 years old, is a widower and lives in Peer, Belgium. He lives with his eldest son, who is taking over Bart's farm. His son also helps him with technology, as Bart has no experience in this area. 11 months ago, Bart suffered a stroke and as a result he now has some physical challenges in his daily activities.

Background information:

Gender: male
Age: 64 years old
Diagnosis: CVA on the right (11 months ago)
Residence: Peer (town in Belgium), lives on a farm
Occupation: farmer (retired, but still active)
Family: wife deceased (widower), 2 sons (boy aged 39, who continues the business; boy aged 35, who lives in Hasselt, Belgium), 3 grandchildren, dog, cat and pigeons
Hobbies and interests: agriculture (animal husbandry), Cycling races (follows on TV on Sundays), Pigeon fancier
Dreams/Motivator: regain independence, improve in functions/activities, maintain a successful business

Technology use:

- Doesn't understand technology (his son is taking care of this)
- No interest in technology

Physical difficulties:

- Walking:
  - Careful + requires more time
  - Influence of the ground surface (e.g. slipping)
  - Helping aid: elbow crutch (right arm): crutch is disabling and frustrating
- Putting on boots:
  - In sitting position: left boot is difficult due to bending and pulling
  - In standing position: standing on 1 leg is difficult due to balance problems
  - Cannot control his left leg very well
- Tacking of boots: helping aid: boot jack
- Transition from sitting to standing, squatting to standing and getting in and out the tractor
- Stairs:
  - Slow speed, strength and coordination difficulties
  - Fear of falling

Common daily activities:

- Morning: get up, help from home care, bring grandchildren to school, help on the farm, coffee and newspaper
- Noon: eating dinner
- Afternoon: nap, eat cake, physiotherapy at home, inspection of the stables/ paddock
- Evening: eating dinner, watch TV, self-care routine

10. References

1. Hsu, T.H., et al., *Effect of wearable exoskeleton on post-stroke gait: A systematic review and meta-analysis*. Ann Phys Rehabil Med, 2023. **66**(1): p. 101674.
2. Calafiore, D., et al., *Efficacy of robotic exoskeleton for gait rehabilitation in patients with subacute stroke : a systematic review.* Eur J Phys Rehabil Med, 2022. **58**(1): p. 1-8.
3. Rodriguez-Fernandez, A., J. Lobo-Prat, and J.M. Font-Llagunes, *Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments*. J Neuroeng Rehabil, 2021. **18**(1): p. 22.
4. Calabro, R.S., et al., *Shaping neuroplasticity by using powered exoskeletons in patients with stroke: a randomized clinical trial.* J Neuroeng Rehabil, 2018. **15**(1): p. 35.
5. Grimmer, M., et al., *Mobility related physical and functional losses due to aging and disease - a motivation for lower limb exoskeletons*. J Neuroeng Rehabil, 2019. **16**(1): p. 2.
6. Firouzi, M., et al., *Immediate effects of the honda walking assist on spatiotemporal gait characteristics in individuals after stroke.* Medicine in Novel Technology and Devices, 2022. **16**.
7. Awad, L.N., et al., *Walking faster and farther with a soft robotic exosuit: Implications for post-stroke gait assistance and rehabilitation.* IEEE Open J Eng Med Biol, 2020. **1**: p. 108-115.
8. Chuang, Y.C., et al., *Effects of soft robotic exosuit on ambulation ability in stroke patients: a systematic review.* Biomed Eng Online, 2023. **22**(1): p. 88.
9. Pan, Y.T., et al., *Effects of Bilateral Assistance for Hemiparetic Gait Post-Stroke Using a Powered Hip Exoskeleton.* Ann Biomed Eng, 2023. **51**(2): p. 410-421.
10. Tang, X., et al., *A Wearable Lower Limb Exoskeleton: Reducing the Energy Cost of Human Movement.* Micromachines (Basel), 2022. **13**(6).
11. Zhan, J., et al., *Global prevalence estimates of poststroke fatigue: A systematic review and meta-analysis.* International Journal of Stroke, 2023. **18**(9): p. 1040-1050.
12. Yang, S.Y. and K.H. Kong, *Level and predictors of participation in patients with stroke undergoing inpatient rehabilitation.* Singapore Med J, 2013. **54**(10): p. 564-8.
13. Vollertsen, J., et al., *The impact of post-stroke fatigue on work and other everyday life activities for the working age population - a registry-based cohort study.* Ann Med, 2023. **55**(2): p. 2269961.
14. Blackwell, S., et al., *Management of post-stroke fatigue: an Australian health professional survey.* Disability and Rehabilitation, 2023. **45**(23): p. 3893-3899.
15. Cumplido-Trasmonte, C., et al., *Satisfaction analysis of overground gait exoskeletons in people with neurological pathology. a systematic review.* J Neuroeng Rehabil, 2023. **20**(1): p. 47.
16. Pinto-Fernandez, D., et al., *Performance Evaluation of Lower Limb Exoskeletons: A Systematic Review.* IEEE Trans Neural Syst Rehabil Eng, 2020. **28**(7): p. 1573-1583.
17. Cherry, M.S., et al., *Running With an Elastic Lower Limb Exoskeleton.* Journal of applied biomechanics, 2016. **32 3**: p. 269-77.

18. Panizzolo, F.A., et al., *A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking.* J Neuroeng Rehabil, 2016. **13**(1): p. 43.
19. Ben-David, C., B. Ostraich, and R. Riemer, *Passive Knee Exoskeleton Increases Vertical Jump Height.* IEEE Trans Neural Syst Rehabil Eng, 2022. **30**: p. 1796-1805.
20. Moeller, T., et al., *Use of Lower Limb Exoskeletons as an Assessment Tool for Human Motor Performance: A Systematic Review.* Sensors (Basel), 2023. **23**(6).
21. Netukova, S., et al., *Lower Limb Exoskeleton Sensors: State-of-the-Art.* Sensors (Basel), 2022. **22**(23).
22. Howard, J., et al., *Exploring the barriers to using assistive technology for individuals with chronic conditions: a meta-synthesis review.* Disabil Rehabil Assist Technol, 2022. **17**(4): p. 390-408.
23. Stehle, C. and C. Albrecht-Buehler, *Developing more desirable products for stroke survivors.* Top Stroke Rehabil, 2008. **15**(2): p. 109-17.
24. Shah, S.G. and I. Robinson, *Benefits of and barriers to involving users in medical device technology development and evaluation.* Int J Technol Assess Health Care, 2007. **23**(1): p. 131-7.
25. Kujala, S., *User involvement: A review of the benefits and challenges.* Behaviour & Information Technology, 2003. **22**(1): p. 1-16.
26. Shah, S.G. and I. Robinson, *User involvement in healthcare technology development and assessment: structured literature review.* Int J Health Care Qual Assur Inc Leadersh Health Serv, 2006. **19**(6-7): p. 500-15.
27. Sanders, E.B.N. and P.J. Stappers, *Co-creation and the new landscapes of design.* CoDesign, 2008. **4**(1): p. 5-18.
28. Bourazeri, A. and S. Stumpf, *Co-designing smart home technology with people with dementia or Parkinson's disease*, in *Proceedings of the 10th Nordic Conference on Human-Computer Interaction*. 2018. p. 609-621.
29. Semprini, M., et al., *User-centered design and development of TWIN-Acta: A novel control suite of the TWIN lower limb exoskeleton for the rehabilitation of persons post-stroke.* Front Neurosci, 2022. **16**: p. 915707.
30. Krishnan, C., et al., *Human-centered design of a novel soft exosuit for post-stroke gait rehabilitation.* J Neuroeng Rehabil, 2024. **21**(1): p. 62.
31. Neate, T., et al., *Co-Created Personas: Engaging and Empowering Users with Diverse Needs Within the Design Process*, in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019. p. 1-12.
32. Morgan, D., *Planning Focus Groups*. 1998, SAGE Publications, Inc.: Thousand Oaks, California.
33. Cooper, A., *The Inmates are Running the Asylum*, in *Software-Ergonomie '99: Design von Informationswelten*, U. Arend, E. Eberleh, and K. Pitschke, Editors. 1999, Vieweg+Teubner Verlag: Wiesbaden. p. 17-17.
34. Miaskiewicz, T. and K.A. Kozar, *Personas and user-centered design: How can personas benefit product design processes?* Design Studies, 2011. **32**(5): p. 417-430.
35. Nielsen, L. and K. Storgaard Hansen, *Personas is applicable - A study on the use of personas in Denmark*, in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 2014. p. 1665-1674.

36. Morgan, D.L., R.A. Krueger, and J.A. King, *Developing Questions for Focus Groups*. 1998: SAGE Publications.
37. Azevedo, V., et al., *Interview transcription: conceptual issues, practical guidelines, and challenges.* Revista de Enfermagem Referência, 2017. **IV Série**(Nº14): p. 159-168.
38. Braun, V. and V. Clarke, *Using thematic analysis in psychology.* Qualitative Research in Psychology, 2006. **3**(2): p. 77-101.
39. MacIntosh, B.J., et al., *Post-stroke Fatigue and Depressive Symptoms Are Differentially Related to Mobility and Cognitive Performance.* Front Aging Neurosci, 2017. **9**: p. 343.
40. Glader, E.L., B. Stegmayr, and K. Asplund, *Poststroke fatigue: a 2-year follow-up study of stroke patients in Sweden.* Stroke, 2002. **33**(5): p. 1327-33.
41. Van Geel, F., et al., *Measuring walking-related performance fatigability in clinical practice: a systematic review.* Eur J Phys Rehabil Med, 2020. **56**(1): p. 88-103.
42. Rahamatali, M., et al., *Post-stroke fatigue: how it relates to motor fatigability and other modifiable factors in people with chronic stroke.* Acta Neurol Belg, 2021. **121**(1): p. 181-189.
43. Tseng, B.Y., et al., *Exertion fatigue and chronic fatigue are two distinct constructs in people post-stroke.* Stroke, 2010. **41**(12): p. 2908-12.
44. Dorsch, S., L. Ada, and C.G. Canning, *Lower Limb Strength Is Significantly Impaired in All Muscle Groups in Ambulatory People With Chronic Stroke: A Cross-Sectional Study.* Archives of Physical Medicine and Rehabilitation, 2016. **97**(4): p. 522-527.
45. Tian, X., et al., *Contributing factors and interventions for fear of falling in stroke survivors: a systematic review.* Topics in Stroke Rehabilitation, 2024: p. 1-16.
46. Menezes, K.K., et al., *Lower-limb motor coordination is significantly impaired in ambulatory people with chronic stroke: A cross-sectional study.* J Rehabil Med, 2017. **49**(4): p. 322-326.
47. Vaughan-Graham, J., et al., *Exoskeleton use in post-stroke gait rehabilitation: a qualitative study of the perspectives of persons post-stroke and physiotherapists.* J Neuroeng Rehabil, 2020. **17**(1): p. 123.
48. Morris, L., et al., *The-state-of-the-art of soft robotics to assist mobility: a review of physiotherapist and patient identified limitations of current lower-limb exoskeletons and the potential soft-robotic solutions.* J Neuroeng Rehabil, 2023. **20**(1): p. 18.
49. van Vlerken, C., et al., *Development of an Active Physical Interface for Physical Human-Robot Interaction: Investigation of Soft Pneumatic Actuator Straps for Automatic Enclosure System.* Actuators, 2023. **12**(6).
50. Wolff, J., et al., *A survey of stakeholder perspectives on exoskeleton technology.* J Neuroeng Rehabil, 2014. **11**: p. 169.
51. Baud, R., et al., *Review of control strategies for lower-limb exoskeletons to assist gait.* J Neuroeng Rehabil, 2021. **18**(1): p. 119.
52. Demers, M., et al., *Understanding stroke survivors' preferences regarding wearable sensor feedback on functional movement: a mixed-methods study.* J Neuroeng Rehabil, 2023. **20**(1): p. 146.

53. Swinnen, E., et al., *Neurological patients and their lower limb orthotics: An observational pilot study about acceptance and satisfaction.* Prosthet Orthot Int, 2017. **41**(1): p. 41-50.
54. Bashir, A.Z., et al., *Patient Compliance With Wearing Lower Limb Assistive Devices: A Scoping Review.* J Manipulative Physiol Ther, 2022. **45**(2): p. 114-126.
55. Douiri, A., A.G. Rudd, and C.D. Wolfe, *Prevalence of poststroke cognitive impairment: South London Stroke Register 1995-2010.* Stroke, 2013. **44**(1): p. 138-45.