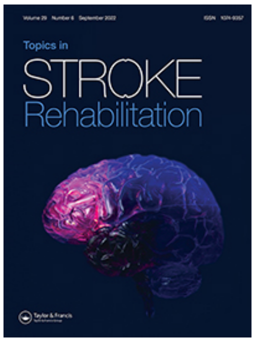

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REVIEW

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A scoping review of design requirements for a home-based upper limb rehabilitation robot for stroke

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ABSTRACT

Background: Home-based robotic therapy is a trend of post-stroke upper limb rehabilitation. Although home-based upper limb rehabilitation robots have been developed over several decades, no design specification has been published.

Objectives: To identify and synthesize design requirements considering user and technology needs for a home-based upper limb rehabilitation robot through a scoping review.

Method: Studies published between 1 January 2000 and 10 June 2020 in Scopus, Web of Science and PubMed database regarding design requirements for upper limb rehabilitation robots from of stroke survivors or therapists were identified and analyzed. We use 'requirement' as something that is needed or wanted. Two physiotherapists ranked the requirements identified from literature review.

Results: Nine studies were selected for review. They identified 42 requirements regarding functionality (n = 11, 26.2% of total requirements), usability (n = 16, 38.0% of total requirements), software (n = 14, 33.3% of total requirements) and safety (n = 1, 2.4% of total requirements). The main implementation barriers with respect to adherence and monitoring were space, operation, and cost.

Conclusion: This is the first research to summarize the design requirements for home-based upper limb rehabilitation robots for stroke survivors. The need for a safe, comfortable, easy to use device which can be individualized and promote specific movements and tasks emerged. The result of this paper captures the design requirements that can be used in future for the development of a design specification. It provides designers and researchers guidance about the real-world needs for home-based upper limb rehabilitation robots for stroke.

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KEYWORDS
Home-based; upper limb; rehabilitation robot; design requirement; implementation barriers

Background

Stroke is one of the most common and disabling health care problems in the world.[1] Annually approximately 33 million people suffer a stroke worldwide[2,3]; more than 1 million people suffer from stroke in Europe and 100,000 in the United Kingdom (UK).[4] Up to 85% of stroke survivors suffer upper limb weakness and recovery is often limited.[5–7] Therefore, improving functionality of the upper limb is a major aim of post-stroke rehabilitation. The most effective intervention to improve upper limb recovery is high repetition task-specific training,[8–10] however this is difficult to achieve as healthcare systems are resource limited, especially for stroke survivors who are unable to move their limb without assistance. One way to increase the intensity of practice is to use robotic devices to provide this assistance.[8,11]

Since the first use of MIT-MANUS in the clinical environment in 1994, robotic-assisted therapy has entered a new era[12,13] and several upper limb rehabilitation robots have been developed including the Mirror Image Motion Enable (MIME) and Automatic Recovery Arm Motility Integrated System (ARAMIS).[14–18] However, the evidence of the effectiveness of robotic-assisted therapy is mixed[17,18] and they have not as yet been widely adopted into clinical practice. One reason for this may be the logistics of their use. Patients for whom a rehabilitation robot is indicated are severely

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disabled and so regular clinic visits for treatment are difficult; expensive; time consuming and fatiguing and patients only receive relatively low doses of therapy. Post-hospital rehabilitation is primarily delivered in patients' home at present.[19] Thus, to be integrated into clinical practice, upper limb rehabilitation robots need to be suitable for deployment in patients' homes which will allow unlimited access to assisted therapy enabling higher frequency and higher intensity.

Several researchers have designed and shown the potential benefit of home-based rehabilitation robots, such as MARIONET, Bi-Manu-Track and hCAAR.[20–22] Although some studies collected or analyzed stroke survivors' or therapists' requirements for rehabilitation robots,[23–25] there is no systematic analysis of design requirement for home-based upper limb rehabilitation robots.

The aim of this scoping review is to identify the clinical and technology design requirements and the implementation barriers for home-based rehabilitation robots. The results of this research will help designers and researchers understand the real-world needs for home-based upper limb rehabilitation robots enabling them to develop new systems which are fit for purpose.

Method

Search strategy

Scopus, Web of Science and PubMed were searched using the following search categories:

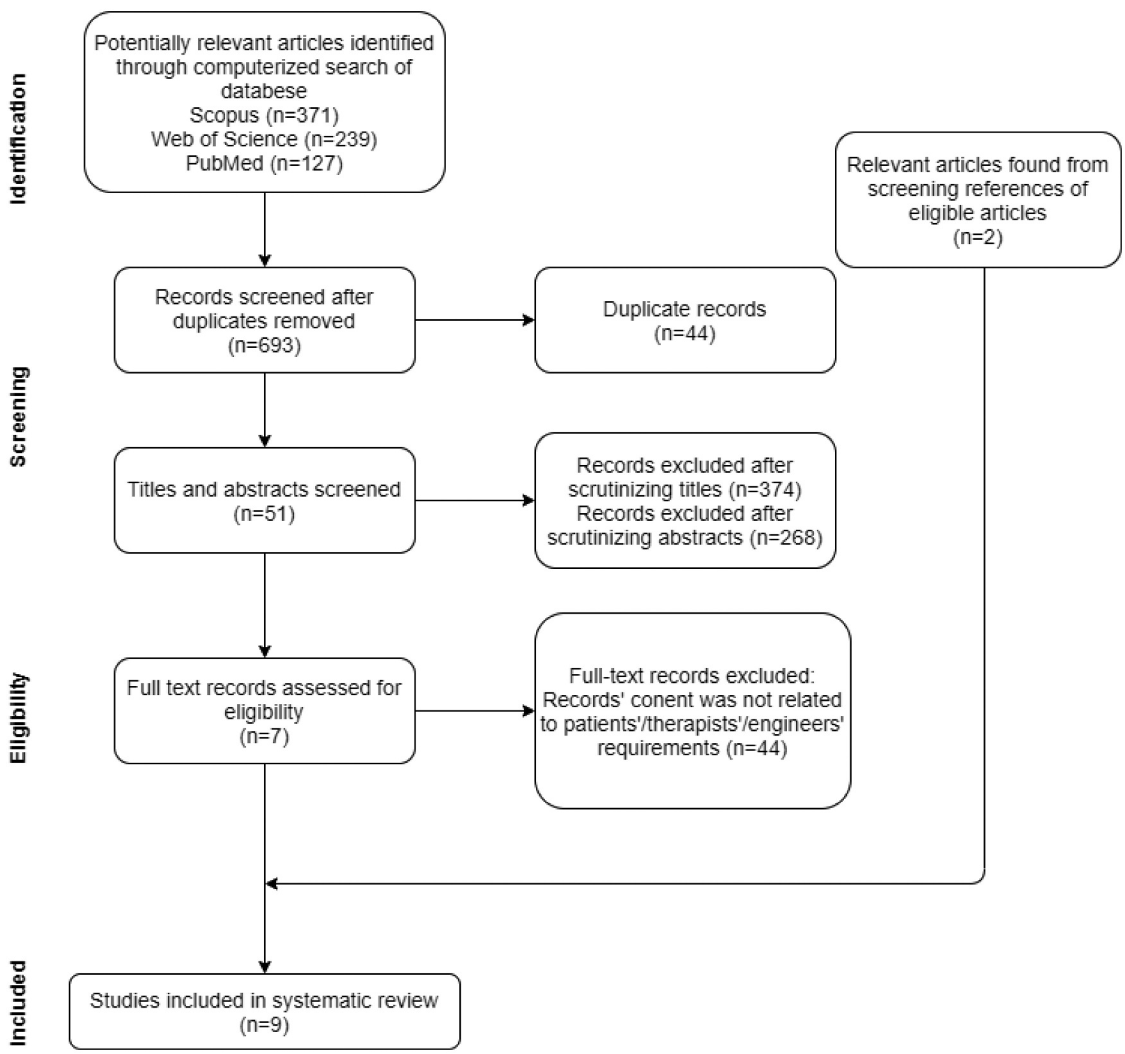

Figure 1. Flowchart of study selection.

Table 1. Overview of selected studies.

Study	Methodology	Participants or/and studies involved	Aim	Main findings A home-based upper limb rehabilitation robot needs to:
Hughes et.al, 2010[26]	Observation; interview; questionnaire	5 stroke survivors (average 4 years after stroke; 3 had a right hemiplegia and two on the left))	To design and develop a upper limb workstation by collecting users' perceptions	**Functionality requirements**: provide repetitive movement; be usable in seated, standing or recumbent position; promote movement related to ADL; promote finger movements; promote whole upper limb movement **Usability requirements**: be easy to set up; usable at home; easy to don and off. **Software requirements**: have a user-friendly appearance; have a graphical performance outcome which motivates users; have multiple games to enhance users' motivation **Barriers**: A home-based robot may reduce the frequency or timeliness of communication between stroke survivors and therapists; how to provide efficient and suitable robotic therapy at a users' home (should stroke survivors' treatment time at home be designed as a trial with a fixed duration, or should they be based on stroke survivors' progress?)
Lu et.al, 2011[32]	Questionnaire	233 therapists (72% physiotherapists, 27% occupational therapists); most based in Australia (48%) and Canada (28%); over half had more than 10 years' experience; most worked in clinical settings and 42% worked in the stroke survivors' home	To identify the therapist's requirements and preference for upper limb rehabilitation robot	**Functionality requirement**: be usable in any position (seated, standing or recumbent); facilitate arm movement in multiple planes (transverse and sagittal); **Usability requirement**: provide arm and hand stability; provide different handholds; be easy to transfer/move and store in users' home; be compact size; suitable for home environment; be adjustable to individual needs; keep trunk stable; include all device accessories for installation and set up **Software requirement**: virtual ADL specific activities; adjust resistance and alignment based on users' performance; provide fun games; provide feedback to users and therapists; provide separate interfaces for users and therapists; provide predefined functions.
Hochstenbach et.al, 2012[31]	Literature research; semi-structured interview	9 studies related to application of technology in upper limb rehabilitation of stroke survivors; 7 therapists mean experience >18 years in the Netherlands (6 worked in stroke rehabilitation, 1 worked in children's rehabilitation)	To identify and provide guidance on rehabilitation technology criteria	**Functionality requirement**: accommodate individualized training goals based on to the patient's ability; provide task-oriented ADL-related training; provide intense and repeatable training; **Usability requirement**: provide quick hardware installation and software setting; be portable or transferable but stable; be ergonomically acceptable; easy to operate **Software requirement**: provide variable type of, and difficulty of training or games; provide feedback on training performance to users and therapists; include games which motivate users; be easy and intuitive to use; have a clear introduction; be customizable to individual needs; provide pre-programmed training based on therapists' suggestions; a system which can save individual therapy settings and users' data; be human-friendly **Safety**: include an 'emergency stop' button; provide warning messages

(*Continued*)

Table 1. (Continued).

Study	Methodology	Participants or/and studies involved	Aim	Main findings A home-based upper limb rehabilitation robot needs to:
Cristina et.al, 2012[30]	Interviews; focus group; observation	9 stroke clinicians for interviews (4 medical doctors, 2 occupational therapists, 2 physiotherapists and 1 nurse); 11 therapists for focus group; 9 stroke survivors for observation	To identify the requirements for computer games for upper limb rehabilitation	**Functionality requirement**: include a workspace within the users' safe range of movement **Usability requirement**: be easy to use; **Software requirement**: actively involve the user; provide tasks or games with different levels of challenge; provide feedback of users' performance; involve games that are simple and easy to understand, fun, fulfil the rehabilitation goals and relate to ADL; monitor users' usage; the games should include clear introduction;
Prange et.al, 2015[29]	Literature research; Interviews	10 studies related to ADL tasks required for hand rehabilitation; 5 sub-acute stroke survivors (> 3 months post-stroke); 3 neuro-rehabilitation experts (1 movement scientist, 1 physiotherapist, 1 occupational therapist); 3 technology experts (1 biomechanical engineer, 1 medical devices developer, 1 prosthetics orthoptist)	To identify the users' requirements for a hand rehabilitation device	**Functionality requirement**: promote hand function; provide active power support for hand and upper limb movements within the safe range of speed and movement for each patient; only provide the required assistance for each individual; train cylinder grasp **Usability requirement**: easy to don and doff so patients can do it independently; be comfortable and protect the users' skin; be lightweight; promote smooth movement; be wireless; be low-cost. **Safety**: avoid any sharp parts; have a back driveable mechanism; easy and quick to stop and move in an emergency situation;
Shirzad et.al, 2015[27]	Observation; focus group	11 rehabilitation professionals (detailed information of therapists was not provided)	To develop a bimanual upper limb rehabilitation platform through User Centered Design	**Functionality requirement**: promote hand movement in both horizontal and vertical planes **Usability requirement**: To be simple to use; low cost **Software requirement**: provide enough introduction; be simple and easy to use; provide sufficient feedback for users; include a set up menu;
Popescu et.al, 2017[28]	Observation; interview; questionnaires	Therapists (the number of participants was not specified)	To identify the clinical and technology requirements for upper limb rehabilitation robot	**Functionality requirement**: promote upper limb movement close to ADL; allow users to move in three-dimensional space; keep the trunk stable; be usable in a seated position; promote task-oriented training; maintain joint alignment **Usability requirement**: be adjustable to individuals' size and abilities; easy to transport; easy to use; stable **Software requirement**: provide feedback to therapists and patients; include customizable game settings (duration time); include a redefined menu; involve a modular system **Safety**: be safe for both patients and therapists to operate

(*Continued*)

Table 1. (Continued).

Study	Methodology	Participants or/and studies involved	Aim	Main findings A home-based upper limb rehabilitation robot needs to:
Van et.al, 2018[25]	Systematic review of users' needs of assistive technologies for upper limb rehabilitation after stroke	9 studies (published from inception to August 2017; related to users' perspective for assistive technologies of rehabilitation; with the involvement of stroke survivors or professionals)	To identify the users', need for upper limb assistive technology after stroke	**Functionality requirement**: provide task-oriented, repetitive and intensive exercise; provide active support; promote upper limb function **Usability requirement**: should be easy to don and doff; be lightweight; adjustable for users; easy to use; low cost; easy to set up and maintain; comfortable to use; stable; portable **Software requirement**: motivate users; provide feedback; include introductions; include adaptable system settings and programmes; save individual user's data; provide individualized levels of support and game difficulty; involve a modular system **Safety**: meet safety regulations **Barriers**: Users may be unfamiliar with technology; need financial support if the device is incompatible with existing furniture; data privacy needs to be maintained
Wentink et.al, 2018[33]	Questionnaire	125 stroke survivors (average 30.6 months after stroke, 81% with cognitive impairments, 84% with physical impairments, 48% with aphasia); 43 informal care givers (mean age = 58 years); 105 health professionals (41%physiotherapists, 15% psychologist, 47% physician); 75% worked in rehabilitation center, 34% worked in general hospital and 10% worked in health center in primary care; 79% had more than 10 years' work experience)	To identify users' requirements for e-rehabilitation after stroke	**Functionality requirement**: Provide functional exercises; **Usability requirement**: Provide tailored system; usable in most common home environments; **Software requirement**: require no internet connection; quick to log in; record data on users' performance and health status; provide a customizable system interface including adjustable background and font; provide (audio) feedback; require no other webpage; avoid complicated options; provide video introduction of device/system usage to patients and therapists; provide frequently asked question menu and system helpdesk; monitor users' performance (duration time, use frequency); provide online agenda option; provide communication function with other stroke survivors; provide general information of stroke and stroke rehabilitation **Barriers**: Technology adaptability (users may be unfamiliar with technology or find the system too complicated to use); compatibility with space; cost

"stroke," "upper limb," "home-based," "rehabilitation robot," "user," and "requirement." The search terms used were (design or speci* or require* or consideration or need) AND (robot* or rehab* system or rehab* technology) AND (upper limb or upper extremity) AND (user or clinic* or patient or stroke survivor) AND (home based or setting or environment) AND (stroke).

The titles, abstract, and then full texts were screened for papers which met the following selection criteria:

(1) Related to a robot device or robotic-assisted system for stroke survivors with upper limb impairments.
(2) Including mechanical or medical device design requirements, specification or consideration for a home-based upper limb rehabilitation robot.
(3) Including patients', therapists' or users' requirements on home-based rehabilitation robot.
(4) Published from 1 January 2000 to 10 June 2020, because there was no research on design requirements of home-based rehabilitation robots before 1 January 2000.

Exclusion criteria were:

(1) Not written in English.
(2) Describing an exoskeleton device.
(3) Describing wheelchair-based devices, as this type device assists movement of disabled arm rather rehabilitation.

This research followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses – Extension for Scoping Reviews (PRISMA-ScR) (Appendix 1).

Ranking strategy

To identify the importance level for each requirement, two experienced physiotherapists ranked identified requirements through online questionnaire. We divided the importance level from high to low into four levels: 1) essential/non-negotiable; 2) important – usability or effectiveness would be comprised if not present; 3) desirable – nice to have but the robot would be functional without and it would increase attractiveness or breadth of application; 4) unnecessary – could live without it. In order to analyze the ranking results, we assumed the importance value of each importance level, from 4 to 1 representing from high to low. Final importance value was represented by the average of the two responses.

Results

From 737 studies identified through the initial database search, nine were included in the final scoping review. Studies were omitted, and additional papers included, through the processes given in Figure 1.

Among the nine selected studies, five research designs were used: observation,[26–28] interview,[26,28–31] questionnaire,[26,28,32,33] focus group[27,30] and literature review[25,29–31] involving 144 stroke survivors, 379 rehabilitation professionals, 43 informal caregivers and three technological experts (Table 1).

Data extraction and presentation

The information related to design requirements and implementation of a home-based rehabilitation robot was extracted and tabulated, then key themes were identified through thematic content analysis (Table 1).

Classification and synthesis of requirements and implementation barriers

Forty-two design requirements of home-based upper limb rehabilitation robots were identified from the nine selected studies (Table 1). After reviewing the design requirements, we categorized them into four main themes; Functionality (n = 11, 26.2%), Usability (n = 16, 38.0%), Software (n = 14, 33.3%) and Safety (n = 1, 2.4%) (Table 2). 'Functionality' requirements needed to support users' motor relearning; 'Usability' requirements ensured the robot would be feasible and acceptable to use in the home; 'Software' requirements included everything about programming such as recording or measuring the users' performance and the game design and 'Safety' requirements included relevant requirements to ensure safety of robot and to fulfill all relevant medical device regulations.

Functionality requirements

Effective motor re-learning after stroke depends on three main factors: task-specific training, intensity of practice and that the practice is challenging (but not overwhelming) for the patient.[8,34,35] Therefore, providing repetitive, intensive, challenging, adjustable goal-oriented exercise is one of the basic functions of an upper limb rehabilitation robot.[25,26,31,33] By 'task-specific,' stroke survivors and therapists meant that to be effective, the exercises and movements produced by the robot should be related to those used in Activities of Daily Living (ADL)[26,28,30,31] – motions such as grasping a spoon, holding a cup, shaving, etc., should be considered. Upper limb movements in daily life are three-dimensional, so the robot should promote upper limb movement in multiple planes.[27,28,32] As the robot needs to offer active assistance to patients who are able to produce little or no movement themselves, an active device was preferred to a passive system.[25,29]

Usability requirements

Usability requirements ensure the robot will be feasible and acceptable to use in the home by people with a wide range of sizes, disabilities, and environments. Adjustable features of the robot were a frequent priority for therapists and stroke survivors, such as providing different handles to promote different grips[25,29] and adjustability for different upper limb sizes,[28,31] so that the device can be adjusted for individual's needs. Users also preferred devices with simple installation and setup.[25,26,31] Small size, lightweight, portability, and easy storage of the robot are also important features to make a home-based upper limb rehabilitation robot more acceptable to users.[25,28,31]

Software requirements

A user-friendly interface was required for home-based rehabilitation systems, including clear and simple introduction and operating instructions.[25–28,31] Providing multiple games was important to maintain users' motivation to exercise.[26,32] However, as a device needs to accommodate a wide range of levels of ability, games with a wide range of difficulty and assistance are needed.[25,28,30,31,33] Recording users' performance and device usage (i.e. the dose of treatment) and making it available to users and therapists was a frequent feature for home-based upper limb rehabilitation robots. This was so therapists could evaluate stroke survivors' progress based on performance feedback,[25,32] and to increase patients' motivation with graphical or audio feedback when tasks or games were completed.[26–28,30,33]

Safety requirements

Safety is always paramount for a medical device; general safety requirements should be met for every medical device such as including an emergency button and warning messages, avoiding sharp edges and possible finger traps, and protecting users' skin.[28,29,31] In addition, as a commercial medical device, it should meet all safety regulations,[25] such as ISO standard, CE marking and IEC standard.[36–38]

Ranking result

Forty-two identified requirements of home-based upper limb rehabilitation robot were ranked by two physiotherapists (Table 3). For a home-based rehabilitation robot, the safety is the first priority, including providing safety speed and range of movement and weight support. Additionally, providing efficient functional training and being suitable for the home environment are also ranked as the most important requirements. For requirements related to robot operation and customized functions, although they are not ranked as essential levels, they are still the priority factors for home-based rehabilitation robots.

Implementation barriers

We identified four main barriers which need to be overcome for successful implementation of upper limb rehabilitation robots at home, namely "operation," "adherence and monitoring," "space" and "cost" (Table 4).

Operational barriers related to installation and usability of a rehabilitation robot at home, such as device installation, system set up and operation. Many stroke survivors are elderly and may not be familiar with technology.[25,33] Furthermore, many suffer from cognitive, communication, and visual problems, as well as motor impairments which means they will need assistance from others (such as informal caregivers or family members) to operate rehabilitation robot at home.[39] These issues may have an impact on the feasibility of, and users' motivation to use a home-based rehabilitation robot.

Table 2. Design requirements for home-based upper limb rehabilitation robots.

Requirements	Source
Functionality requirements	
(1) Provide repetitive exercise	25,26,31,33
(2) Provide intensive exercise	25,31,33
(3) Provide goal-oriented exercise	25,28,31,33
(4) Movements produced to relate to ADL	26,28,29,31
(5) Apply assistive forces to aid practice of therapeutic movements	25,29
(6) Can be used in a seated position	26,28,32
(7) Suitable functional workspace to ensure users' safety	30
(8) Suitable and safe movement speed of each joint	28,29
(9) Provide arm weight support and arm stability	32
(10) Keep trunk stability/Ensure compensation stability	28,32
(11) Enables arm movement in all planes (three-dimensional movement)	27,28,32
Usability requirements	
(12) Intuitive to use	25,27,28,30,31
(13) Quick and simple to set up	25,26,31,32
(14) Quick and easy to install	31,32
(15) Easy to maintain	25
(16) Provide different handholds for different users' needs	26,29,32
(17) Easy to store	32
(18) Easy to transport/portable	25,28,29,31,32
(19) Adjustable to patient's arm size	25,28,31,33
(20) Comfortable	25,29
(21) Easy to don and doff	25,26
(22) Suitable for the home environment	26,33
(23) Stability of device base	25,28,31
(24) Reliability	25
(25) Compact size	28,32
(26) Lightweight	25,29
(27) Low-cost	25,27,29
Software requirements	
(28) User friendly interface	26,30
(29) Simple operation system	31,33
(30) Provide visual or audio feedback on handle movement and performance for patients	25–28,30,33
(31) Provide feedback on users' performance to therapists	25,28,30–33
(32) Monitor usage	25,31
(33) Customizable system, adjustable initial settings	25,28,31,33
(34) No internet connection requirements	33
(35) Multiple levels for assistance to accommodate differing patients' needs	25,30,32
(36) Simple and clear instructions for use	25,27,28,30,31,33
(37) Multiple games with differing levels of difficulty to accommodate patients' needs	25,30–32
(38) Have menu with frequently asked questions	27,28,33
(39) Provide online agenda option for patients and therapists to arrange the appointment	33
(40) Save individual users' data	25,33
(41) Modular the rehabilitation exercise (split the exercise into several small tasks)	25,28,31
Safety requirements	
(42) Meet all safety requirements	25,28,29

Adherence and monitoring barriers included the possible detrimental effect of the lack of direct supervision from a therapist at home, which may mean that patients lack confidence, or motivation, or do the robot mediated exercises in an ineffective way. Feedback to the patients' and therapists about the device's usage (i.e. the dose of treatment) and the patients' performance was considered important to monitor progress, and to maintain communication and motivation.[26]

Lack of space could act as a barrier to using rehabilitation robots in a home setting. Many stroke survivors have little spare space in their home to accommodate a rehabilitation robot. Consequently, a robot needs to be small, portable, and easy to store when not in use. Furthermore, to be used in everyday life, the robot needs to be compatible with existing furniture such as suitable table or chairs. It also needs to be suitable for use in different settingsfor example, some users may want

Table 3. Result of ranking the identified requirements.

Requirements (n = 42)	Ranking result: Importance level	Ranking result: Importance value
Functionality requirements (n = 11)		
(1) Provide repetitive exercise	Essential	4
(2) Apply assistive forces to aid practice of therapeutic movements	Essential	4
(3) Can be used in a seated position	Essential	4
(4) Suitable functional workspace to ensure users' safety	Essential	4
(5) Suitable and safe movement speed of each joint	Essential	4
(6) Provide arm weight support and arm stability	Essential	4
(7) Provide intensive exercise	Important – Essential	3.5
(8) Movements produced to relate to ADL	Important – Essential	3.5
(9) Provide goal-oriented exercise	Important	3
(10) Keep trunk stability/Ensure compensation stability	Desirable – Important	2.5
(11) Enables arm movement in all planes (three-dimensional movement)	Desirable	2
Usability requirements (n = 16)		
(1) Suitable for the home environment	Essential	4
(2) Stability of device base	Essential	4
(3) Intuitive to use	Important – Essential	3.5
(4) Provide different handholds for different users' needs	Important – Essential	3.5
(5) Adjustable to patient's arm size	Important – Essential	3.5
(6) Easy to don and doff	Important – Essential	3.5
(7) Reliability	Important – Essential	3.5
(8) Compact size	Important – Essential	3.5
(9) Easy to transport/portable	Important	3
(10) Quick and simple to set up	Desirable – Important	2.5
(11) Quick and easy to install	Desirable – Important	2.5
(12) Easy to maintain	Desirable – Important	2.5
(13) Easy to store	Desirable – Important	2.5
(14) Comfortable	Desirable – Important	2.5
(15) Lightweight	Desirable – Important	2.5
(16) Low-cost	Desirable – Important	2.5
Software requirements (n = 14)		
(1) User friendly interface	Important – Essential	3.5
(2) Provide feedback on users' performance to therapists	Important – Essential	3.5
(3) Customizable system, adjustable initial settings	Important – Essential	3.5
(4) Multiple levels for assistance to accommodate differing patients' needs	Important – Essential	3.5
(5) Simple and clear instructions for use	Important – Essential	3.5
(6) Simple operation system	Important	3
(7) Provide visual or audio feedback on handle movement and performance for patients	Important	3
(8) Monitor usage	Important	3
(9) Multiple games with differing levels of difficulty to accommodate patients' needs	Important	3
(10) No internet connection requirements	Desirable – Important	2.5
(11) Save individual users' data	Desirable – Important	2.5
(12) Modular the rehabilitation exercise (split the exercise into several small tasks)	Desirable – Important	2.5
(13) Have menu with frequently asked questions	Desirable	2
(14) Provide online agenda option for patients and therapists to arrange the appointment	Unnecessary – Desirable	1.5
Safety requirements (n = 1)		
(1) Meet all safety requirements	Essential	4

Notification: The importance value is the average value of two responses.

to use the robot in their living room or bedroom but store it elsewhere.

Cost barriers relate to the cost for rehabilitation robot (which needs to be as low as possible) and needs to consider the cost of usage (electricity and any other resources) and maintenance in addition to the cost of purchase or leasing.[25,33]

Discussion

This research has identified the design requirements and implementation barriers, for a home-based upper limb rehabilitation robot through a scoping review. In addition, the importance level for each requirement was ranked by therapists. The results of this research will be important to guide the design of acceptable, user-friendly, effective home-based upper limb rehabilitation robots.

Promotion of upper limb function is the basic requirement for a rehabilitation robot. We are aware that for training to carry-over into everyday function, the same movements need to be practised during robot training as those used in functional activities (i.e. three-dimensional movement of multiple joints).[26,28,29,31] However, most existing research home-based rehabilitation robots are

Table 4. Implementation barriers of home-based upper limb rehabilitation robots.

Implementation barriers	Derivation and supplement
Operation	
Lack of technology knowledge	Stroke survivors are often elderly and may not be familiar with using a computer and other technology.[25,33]
Need assistance	Many stroke survivors with severe upper limb weakness need help to set up and don and off a rehabilitation robot at home.[39]
System operation	Some systems (games) may be too complicated to stroke survivors to operation.[25,33]
Device installation and system set up	A cumbersome installation and setup procedure will be difficult for stroke survivors or their families, resulting less motivation to use the robot.[26]
Adherence and monitoring	
Lack of motivation	Stroke survivors may not persist with regular exercises.[26]
Lack of therapists' guidance	Rehabilitation at home involves less direct contact with therapists which may lead to the patients performing exercises less effectively than if they were directly supervised.[26]
Data privacy	Personal data privacy needs to be maintained.[25]
Space	
Storage space for device	Many stroke survivors do not have spare space in their homes for a large rehabilitation robot.[25,33]
Suitable table or chairs	Home-based rehabilitation may not compatible with users' furniture, such as the height of a table or chairs.[25]
Cost	
Cost of device	Some stroke survivors may need financial support to buy or rent a home-based rehabilitation robot.[25,33]

limited to planar movement of only a few (sometimes only one joint such as elbow flexion/extension), such as Bi-Manu-Track and hCAAR.[21,22] This limited functionality may have been chosen to minimize costs; however, if the movements produced by the robot are not those needed to promote recovery, the home-based robot is unlikely to be effective or adopted, however, inexpensive.

Customization features are another high priority design requirement. Stroke survivors with different levels of upper limb weakness will require different levels of assistance.[25,30,32] The robot system should allow users to choose the most suitable games, adapt the game difficulty and amount of assistance provided as the patient progresses. It also needs to record and monitor users' performance, and provide feedback to therapists and users. Therapists can then evaluate usage and progress and update the patient's training accordingly. In addition, users' motivation for using a home-based rehabilitation will depend on the choice for games, initial setting of the interface or program, and simplicity of operation. Complicated operating procedures will reduce the users' motivation, leading to abandonment of the robot.

The majority of stroke survivors are elderly[40] and may not be familiar with using computers (although this will change with time), and many have multiple system impairments.[41–43] Any home-based rehabilitation robot should therefore be as intuitive to use as possible. However, some users may, inevitably require assistance from others to either set up or operate the robot. Minimizing the amount of physical assistance required and the technical know-how needed to do so are important priorities.

Minimizing the size and maximizing the portability and storage of home-based robots are important but also a challenge. Many homes have limited space to accommodate robotic devices. Thus, a device needs to be as small as possible, easy to move and to 'pack down' to minimize storage space when not in use. However, this needs to be balanced against the need for the device to have sufficient power, stability, and functionality for a wide range of abilities.[44]

Limitations

In this review, the number of paper included is limited by the amount research in this field. Although the identified requirements were ranked by professionals, the sample size is small. The ranking result may vary with the increase of participants and/or relevant papers. Additionally, only therapists were involved in ranking phase, and the involvement of stroke survivors is also important. This will be addressed in future publications along with the engineering requirements, i.e. technology capabilities and limitations. These issues are important to find a balance between robot function and cost.

Conclusion

This scoping review identified the clinical and technical requirements of home-based upper limb rehabilitation robots, reflecting the actual needs and development trends for stroke survivors and their therapists. Four main requirement themes were identified; functionality, usability, software and safety. Four barriers to implementation have been detailed, namely operational details; adherence, space, and cost. A home-based upper limb rehabilitation robot needs to enable practice movements and tasks related to ADL; be suitable for wide range of users and settings but provide personalized therapy, be safe, easy and appealing to use, and small and easy to store, and inexpensive. These findings form the basis for the next stage of the authors' research; designing and developing a novel low-cost home-based upper limb rehabilitation robot which meets these requirements. The significance of the research we present provides clear guidance for designers and researchers about real-world needs for home-based upper limb rehabilitation robots enabling them to develop new systems which are fit for purpose.

List of abbreviation

ADL: Activities of Daily Living

MIME: Mirror Image Motion Enable

ARAMIS: Automatic Recovery Arm Motility Integrated System

PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses—Extension for Scoping Reviews

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

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References

1. Murray CJ, Vos T, Lozano R, et al. Disability-adjusted life years (DALYs) for 291 diseases and injuries in 21 regions, 1990–2010: a systematic analysis for the global burden of disease study 2010. *Lancet*. 2012;380(9859):2197–2223.
2. Murray CJ, Barber Rm, Foreman KJ, et al. Global, regional, and national disability-adjusted life years (DALYs) for 306 diseases and injuries and healthy life expectancy (HALE) for 188 countries, 1990–2013: quantifying the epidemiological transition. *Lancet*. 2015;386(10009):2145–2191.
3. Lozano R, Naghavi M, Foreman K, et al. Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the global burden of disease study 2010. *Lancet*. 2012;380(9859):2095–2128. doi:10.1016/S0140-6736(12)61728-0.
4. Warlow CP, Van Gijin J, Dennis MS, et al. *Stroke: Practical Management*. John Wiley & Sons; 2011.
5. Kwakkel G, Kollen BJ, Wagenaar RC. Therapy impact on functional recovery in stroke rehabilitation: a critical review of the literature. *Physiotherapy*. 1999;85(7):377–391. doi:10.1016/S0031-9406(05)67198-2.
6. Langhorne P, Bernhardt J, Kwakkel G. Stroke rehabilitation. *Lancet*. 2011;377(9778):1693–1702. doi:10.1016/S0140-6736(11)60325-5.
7. Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: a systematic review. *Lancet Neurol*. 2009;8(8):741–754. doi:10.1016/S1474-4422(09)70150-4.
8. Veerbeek JM, Langbroek-Amersfoort AC, Van Wegen EE, Kwakkel G. Effects of robot-assisted therapy for the upper limb after stroke: a systematic review and meta-analysis. *Neurorehabil Neural Repair*. 2017;31(2):107–121. doi:10.1177/1545968316666957.
9. Lohse KR, Hilderman CG, Cheung KL, Tatla S, Van der Loos HM. Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS One*. 2014;9(3):e93318. doi:10.1371/journal.pone.0093318.
10. Veerbeek JM, van Wegen E, van Peppen R, et al. What is the evidence for physical therapy poststroke? A systematic review and meta-analysis. *PloS One*. 2014;9(2):e87987.
11. Mehrholz J, Pohl M, Platz T, Kugler J, Elsner B. Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and

arm muscle strength after stroke. *Cochrane Database of Systematic Reviews*. 2018(9).

12. Gassert R,Dietz V. Rehabilitation robots for the treatment of sensorimotor deficits: a neurophysiological perspective. *Journal of Neuroengineering and Rehabilitation*. 2018;15(1):46.
13. Krebs HI, Hogan N, Aisen ML, Volpe BT. Robot-aided neurorehabilitation. *IEEE Trans Rehabil Eng*. 1998;6 (1):75–87. doi:10.1109/86.662623.
14. Johnson MJ, Wisneski KJ, Anderson J, Nathan D, Smith RO. Development of ADLER: the activities of daily living exercise robot. *The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006. BioRob 2006*. 2006. IEEE.
15. Burgar CG, Lum PS, Shor PC, Van der Loos HM. Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience. *Journal of rehabilitation research development*. 2000;37(6):663–674.
16. Maciejasz P, Eschweiler J, Gerlach-Hahn K, Jansen-Troy A, Leonhardt S. A survey on robotic devices for upper limb rehabilitation. *Journal of Neuroengineering and Rehabiltation*. 2014;11(1):3. doi:10.1186/1743-0003-11-3.
17. Rodgers H, Bosomworth H, Krebs HI, et al. Robot-assisted Training Compared with an Enhanced Upper Limb Therapy Programme and with Usual Care for Upper Limb Functional Limitation after Stroke: The RATULS Three-group RCT. *Health technology assessment (Winchester, England)*. 2020; 24(54):1-232.
18. Lo AC, Guarino PD, Richards LG, Haselkorn JK, Wittenberg GF, Federman DG. Robot-assisted therapy for long-term upper-limb impairment after stroke. *N Engl J Med*. 2010;362(19):1772–1783. doi:10.1056/NEJMoa0911341.
19. Sentinel Stroke National Audit Programme Annual report 2020, Intercollegiate Stroke Working Party Sentinel Stroke National Audit Programme (SSNAP).
20. Sulzer JS, Peshkin MA, Patton JL. Design of a mobile, inexpensive device for upper extremity rehabilitation at home. *2007 IEEE 10th International Conference on Rehabilitation Robotics*. 2007. IEEE.
21. Ivanova E, Kruger J, Steingraber R, Schmid S, Schmidt H, Hesse S. Design and concept of a haptic robotic telerehabilitation system for upper limb movement training after stroke. *2015 IEEEInternational Conference on Rehabilitation Robotics(ICORR)*. 2015. IEEE.
22. Sivan M, Gallagher J, Makower S, et al. Home-based Computer Assisted Arm Rehabilitation (hCAAR) robotic device for upper limb exercise after stroke: results of a feasibility study in home setting. *J Neuroeng Rehabil*. 2014;11(1):163. doi:10.1186/1743-0003-11-163.
23. Hughes AM, Burridge JH, Demain SH, et al. Translation of evidence-based assistive technologies into stroke rehabilitation: users' perceptions of the barriers and opportunities. *BMC Health Services Research*. 2014;14(1):124.
24. Prange GB, Smulders LC, van Wijngaarden J, et al. User requirements for assistance of the supporting hand in bimanual daily activities via a robotic glove for severely affected stroke patients. *2015 IEEE International ConferenceonRehabilitation Robotics (ICORR)*. 2015. IEEE.
25. van Ommeren AL, Smulder LC, Prange-Lasonder GB, Buurke JH, Veltink PH, Rietman JS. Assistive technology for the upper extremities after stroke: systematic review of users' needs. *JMIR Rehabil Assistive Technol*. 2018;5(2):e10510. doi:10.2196/10510.
26. Hughes A-M, Burridge J, Freeman CT, et al. Stroke participants' perceptions of robotic and electrical stimulation therapy: a new approach. *Disabil Rehabil*. 2011;6 (2):130–138. doi:10.3109/17483107.2010.509882.
27. Shirzad N, Valdes BA, Hung CT, Law M, Hay J, Van der Loos HFM. *FEATHERS, A Bimanual Upper Limb Rehabilitation Platform:* A Case Study of User-centred Approach in Rehabilitation Device Design. *Proceeding of the 20th International Conference on Engineering Design*.2015.
28. Popescu D, Manta F, Rusu L, Avramescu TE, Zavaleanu M. Upper limb rehabilitation robotic system requirements analysis. In: Ferraresi C, Quaglia G, eds. *Advances in Service and Industrial Robotics*. Vol49.2018:919-927.
29. Prange GB, Smulders LC, van Wijingaarden J, et al., User requirements for assistance of the supporting hand in bimanual daily activities via a robotic glove for severely affected stroke patients. In: Yu HY, Braun D, Campolo D, eds. *Proceedings of the Ieee/Ras-Embs International Conference on Rehabilitation Robotics*. 2015:357–361.
30. Rodriguez-de-pablo C,Perry JC, Cavallaro FI, Zabaleta H, Keller T, Ieee. Development of computer games for assessment and training in post-stroke arm telerehabilitation. *2012 Annual International Conference of the Ieee Engineering in Medicine and Biology Society*. 2012:4571–4574.
31. Hochstenbach-Waelen A, Seelen HA. Embracing change: practical and theoretical considerations for successful implementation of technology assisting upper limb training in stroke. *J Neuroeng Rehabil*. 2012;9 (1):52. doi:10.1186/1743-0003-9-52.
32. Lu EC, Wang RH, Hebert D, Boger J, Galea MP, Mihailidis A. The development of an upper limb stroke rehabilitation robot: identification of clinical practices and design requirements through a survey of therapists. *Disability and Rehabilitation: Assistive Technology*. 2011;6(5):420–431. doi:10.3109/17483107.2010.544370.
33. Wentink MM, Van Bodegom-Vos L, Brouns B, et al. What is important in E-health interventions for stroke rehabilitation? A survey study among patients, informal

caregivers and health professionals. *Int J Telerehabil*. 2018;10(1):15–28. doi:10.5195/ijt.2018.6247.
34. Lohse KR, Hilderman CG, Cheung KL, Tatla S, Vander Loos HM. Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS one*. 2014;9(3):e93318.
35. Veerbeek JM, van Wegen E, van Peppen R, et al. What is the evidence for physical therapy poststroke? *Syst Rev Meta-anal*. 2014;9(2):e87987.
36. Kramer DB, Xu S, Kesselheim AS. How does medical device regulation perform in the United States and the European Union? A systematic review. *PLoS Med*. 2012;9(7):e1001276. doi:10.1371/journal.pmed.1001276.
37. Horton LR. Medical device regulation in the European Union. *Food Drug Law J*. 1995;50:461.
38. Kramer DB, Xu S, Kesselheim AS. Regulation of Medical Devices in the United States and European Union. In: *The ethical challenges of emerging medical technologies.*Routledge; 2020:41-48.
39. van der Veen DJ, Dopp CM, Siemonsma PC, Nijhuis-van Der Sanden MW, de Swart BJ, Steultjens EM. Factors influencing the implementation of home-based stroke rehabilitation: Professionals' perspective. *PloS one*. 2019;14(7).
40. State of the Nation Stroke statistics 2018, Stroke Association: Stroke Association.
41. Wingham J, Adie K, Turner D, Schofield C, Pritchard C. Participant and caregiver experience of the Nintendo Wii sportsTM after stroke: qualitative study of the trial of WiiTM in stroke (TWIST). *Clin Rehabil*. 2015;29(3):295–305. doi:10.1177/0269215514542638.
42. Casserly DM, Baer GD. Effectiveness of commercially available gaming devices in upper limb stroke rehabilitation. *Phys Ther Rev*. 2014;19(1):15–23. doi:10.1179/1743288X13Y.0000000098.
43. van der Veen DJ, Dopp CM, Siemonsma PC, Nijhuis-van der Sanden MW, de Swart BJ, Steultjens EM. Factors influencing the implementation of home-based stroke rehabilitation: Professionals' perspective. *PloS One*. 2019;14(7):7. doi:10.1371/journal.pone.0220226.
44. Chen Y, Abel KT, Janecek JT, Chen Y, Zheng K, Cramer SC. Home-based technologies for stroke rehabilitation: a systematic review. *Int J Med Inform*. 2019;123:11–22. doi:10.1016/j.ijmedinf.2018.12.001.

Appendix

Appendix 1. PRISMA-ScR checklist

Table A1.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	page 1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	page 2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	page 3
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	page 3
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	Not done
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	page 3-4
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	page 3
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	page 3
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	page 4
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	page 4
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	page 3-4
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	Not done
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	page 4

Table A1.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	page 4 (Figure 1)
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	page 5-6 (Table 1)
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	Not done
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	page 4-6 (Table 1, Table3)
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	page 4-6
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	page 7-8
Limitations	20	Discuss the limitations of the scoping review process.	page 8
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	page 8
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	page 9 (no funding)