Review

Factors That Contribute to the Use of Stroke Self-Rehabilitation Technologies: A Review

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Abstract

Background: Stroke is increasingly one of the main causes of impairment and disability. Contextual and empirical evidence demonstrate that, mainly due to service delivery constraints, but also due to a move toward personalized health care in the comfort of patients' homes, more stroke survivors undergo rehabilitation at home with minimal or no supervision. Due to this trend toward telerehabilitation, systems for stroke patient self-rehabilitation have become increasingly popular, with many solutions recently proposed based on technological advances in sensing, machine learning, and visualization. However, by targeting generic patient profiles, these systems often do not provide adequate rehabilitation service, as they are not tailored to specific patients' needs.

Objective: Our objective was to review state-of-the-art home rehabilitation systems and discuss their effectiveness from a patient-centric perspective. We aimed to analyze engagement enhancement of self-rehabilitation systems, as well as motivation, to identify the challenges in technology uptake.

Methods: We performed a systematic literature search with 307,550 results. Then, through a narrative review, we selected 96 sources of existing home rehabilitation systems and we conducted a critical analysis. Based on the critical analysis, we formulated new criteria to be used when designing future solutions, addressing the need for increased patient involvement and individualism. We categorized the criteria based on (1) motivation, (2) acceptance, and (3) technological aspects affecting the incorporation of the technology in practice. We categorized all reviewed systems based on whether they successfully met each of the proposed criteria.

Results: The criteria we identified were nonintrusive, nonwearable, motivation and engagement enhancing, individualized, supporting daily activities, cost-effective, simple, and transferable. We also examined the motivation method, suitability for elderly patients, and intended use as supplementary criteria. Through the detailed literature review and comparative analysis, we found no system reported in the literature that addressed all the set criteria. Most systems successfully addressed a subset of the criteria, but none successfully addressed all set goals of the ideal self-rehabilitation system for home use.

Conclusions: We identified a gap in the state-of-the-art in telerehabilitation and propose a set of criteria for a novel patient-centric system to enhance patient engagement and motivation and deliver better self-rehabilitation commitment.

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KEYWORDS

home rehabilitation systems; stroke rehabilitation; telerehabilitation; patient participation; motivation; comparative effectiveness research

Introduction

Background

Stroke has become a global problem [1]. One new case is reported every 2 seconds, and the number of stroke patients is predicted to increase by 59% over the next 20 years [2]. In the United Kingdom alone, more than 100,000 stroke cases are reported annually [1], with impairment or disability affecting two-thirds of the 1.2 million stroke survivors [1]. In the United Kingdom, only 77% of stroke survivors are taken directly to the stroke unit. Due to the high number of patients, in England, for example, the social care costs are almost £1.7 billion per annum. The social care cost varies with the age of the patient: the older the patient, the higher the cost. The cost for a person who has had a stroke was reported in 2017 to be around £22,000 per annum. Thus, cost is one of the main drives for service delivery practices. In that respect, early discharge units have been used due to better outcomes and greater success on rehabilitation. Early discharge units consist of specialized personnel who offer an intensive rehabilitation program to the patient. However, after this intensive program of relatively short duration, the patient is discharged and continues the rehabilitation at home. This is expected to reduce costs by £1600 over 5 years for every patient, according to a 2017 report [1].

Due to increasing pressure to discharge patients early from hospital [3], they rely increasingly on home rehabilitation to improve their condition after discharge. As a result, the need has been increasing for home rehabilitation systems that are not dependent on specialist or clinician operators [1,4,5] while providing service similar to a clinical environment. Technological advances in home rehabilitation have been mainly focused on motor control impairments due to their prevalence in the patient population (85% worldwide [1]).

Rehabilitation in a home environment can prove more efficient than that in a clinical environment, as the home environment supports patient empowerment through self-efficacy [6,7]. The presence of supportive family members and a familiarity with the space are significant contributors to motivation. Additionally, rehabilitation in cooperation or in competition with family members demonstrates higher level of engagement [8].

Though rehabilitation in the comfort of a patient's home seems an attractive option, home environments have limitations that can affect the use of clinical devices. The most prevalent limitations are related to space and the lack of qualified personnel to operate devices. The number of occupants; the patient's mobility, individual personality, and mood disorders following stroke; and sound insulation, home modification requirements, and cost [9,10] also contribute to limitations of home rehabilitation. Finally, different age groups react differently to technology and devices; for example, elderly survivors often do not engage with wearable devices or video games [11]. As a result, stroke rehabilitation requires a person-centric approach that is suitable for the home environment and that does not require infrastructure change in the home.

Enhancing Motivation

The success of stroke rehabilitation depends heavily on personal commitment and effort. Recent studies, for example, on applied psychology in behavior change theories for stroke rehabilitation [12-14], do support that the self-esteem of the patient is limited after stroke. In addition, there is an extended sedentary period due to disability and, thus, different programs of activities are set to motivate the patients. Thus, the patient's motivation and engagement have a critical impact on the success of any routine that is to be encouraged [15]. This is especially critical for devices used at home, since patients are usually interacting with them alone without frequent checks. Indeed, if a device does not provide a high level of engagement or motivation enhancement, it is more likely to be abandoned within 90 days [16]. Motivation levels depend on the individual, their achievements, and their needs at each given point in time. For example, once the patients achieve their physiotherapy exercise targets, they lose motivation for further practice. There are 3 main approaches to enhancing patients' motivation: (1) goal-setting theory, (2) self-efficacy improvement theory, and (3) possible selves theory.

Goal-Setting Theory

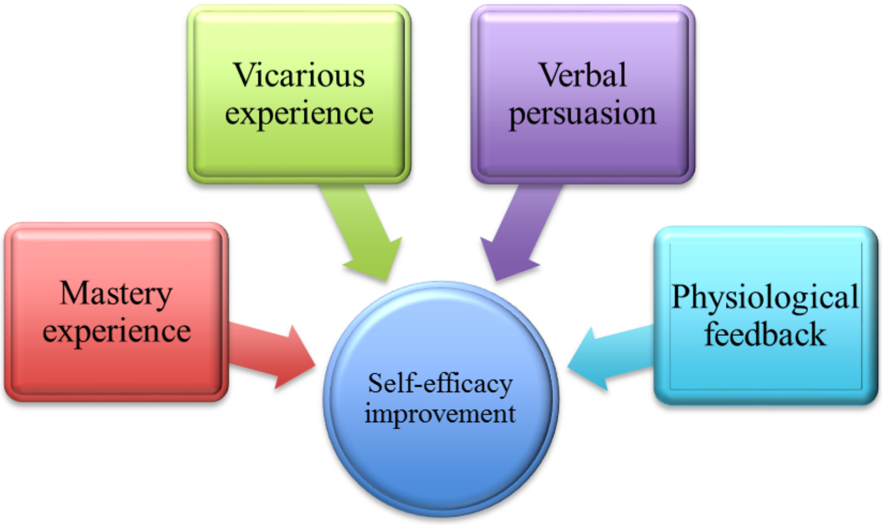
This approach has been proved effective for stroke survivors. According to the goal-setting theory, the patient's motivation can be increased through setting small goals or targets. These need to be realistic, manageable, and well defined for the individual patient. However, they also need to be sufficiently challenging for the patient to be engaged [15,17-19]. Figure 1 presents the main components contributing to motivation enhancement based on the goal-setting theory.

Figure 1. The main components of goal-setting theory.

Self-Efficacy Improvement Theory

Self-efficacy is the individual's ability to appreciate his or her capability to execute a set of actions to manage a situation or challenge [20]. According to this theory, self-efficacy makes patients feel more empowered and more comfortable to overcome difficulties. In the case of rehabilitation, this has been strongly linked with self-confidence in executing activities of daily living (ADL) [21,22] and with better future performance [23,24]. Figure 2 presents the main components contributing to self-efficacy improvement. Completing achievable goals supports mastery and allows engagement with more complex goals. The observation of others provides a vicarious experience, which supports enhanced confidence. Verbal appraisal provides the courage to tackle more difficult goals, while physiological feedback supports the will to improve.

Figure 2. Factors that contribute to self-efficacy enhancement.



Possible Selves Theory

The third theory focuses the patient's motivation on achieving a positive future image of themselves [25]. This approach is based on the patient's psychological condition and their ability to envisage a positive future and a successful recovery. When implemented successfully, this approach creates an optimistic environment leading to better engagement with rehabilitation and faster recovery. However, creating a pessimistic environment can have a negative impact.

Factors Affecting Motivation

Regardless of the approach implemented, several factors affect motivation positively (Figure 3) or negatively (Figure 4). The main contributor to a positive motivation effect is the information available to the patient. This includes acknowledgment of the condition, control of one's actions, achievement of goals, individualized care, overcoming an uncertain psychological condition, and receiving timely feedback [15,23,26]. Motivational feedback can be oral or visual. Also, receiving performance feedback is instrumental in maintaining motivation and engagement. Finally, self-selecting goals and having personal control is a major contributor. Negative factors usually arise from the patient's environment and, thus, care needs to be adapted to these environmental aspects to minimize their impact [27,28].

Additionally, constructive, supportive, and competitive motivational activities, such as specially designed games, can further enhance motivation and engagement with the required rehabilitation activity [8,22].

Based on the above approaches, motivation levels can be increased and engagement maintained at a high level. This is particularly important for home rehabilitation, as it reduces the requirement for caregiver engagement and provides greater control and independence to the patient. Thus, home rehabilitation has a direct impact on the cost of care and the requirement for physiotherapist visits.

Moreover, patients who have an increased capacity to perform daily activities are less dependent on other family members or care providers. This personal improvement in daily activities turns the home environment into a positive contributor to rehabilitation and recovery.

Figure 3. Factors that enhance motivation.

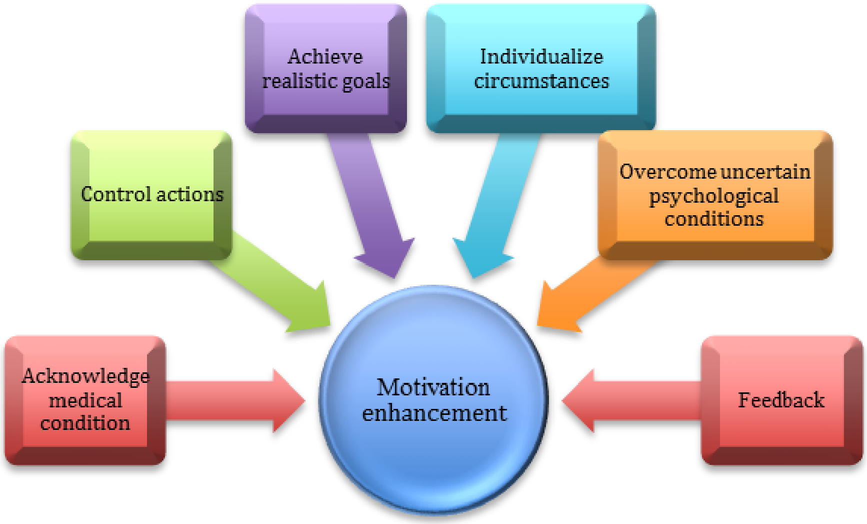


Figure 4. Factors that stop or decrease motivation.

Objectives

We aimed to examine the state-of-the-art in home rehabilitation systems and to assess their suitability and functionality from a patient engagement perspective. Although several review (narrative and systematic) articles have been published on rehabilitation technologies focused on particular areas of the taxonomy (eg, wearable sensor systems review [21] and robotic systems review [29]), to our knowledge, no extensive narrative review of existing home-based rehabilitation technologies to identify criteria for designing future solutions has been done.

Our goal was to make the following contributions: (1) extend the state-of-the-art in assessment of home-based rehabilitation by combining research from 3 research domains: motivation enhancement as part of patient psychology, home rehabilitation technologies, and monitoring technologies through an interdisciplinary approach; (2) provide an in-depth narrative review of home rehabilitation systems that addresses both information and communication technologies and mechanical engineering solutions; (3) develop a patient motivation and engagement analysis of the reviewed technologies; and (4) identify a list of comparative criteria and successful device requirements to address patient motivation and engagement designed based on research findings from all 3 research domains.

Methods

We selected a list of articles and references for review of home rehabilitation systems and monitoring systems to be included in the comparative analysis. The data sources used to search for items to be included in this review were the following databases of academic references, journals with a particular focus on stroke rehabilitation, and web sources: (1) PubMed, (2) Elsevier, (3) IEEE, (4) Springer, (5) Hindawi.com, (6) *Journal of*

NeuroEngineering and Rehabilitation, (7) websites of stroke-related institutions and foundations presenting articles on rehabilitation found through a generic Google search, and (8) Google Scholar (including ResearchGate).

The search criteria included the following keywords and combinations thereof: stroke; devices for stroke rehabilitation; home rehabilitation; rehabilitation engagement; rehabilitation motivation; stroke rehabilitation; telerehabilitation; smart meter; pattern recognition; kinematic analysis; robotic systems; exoskeleton systems; virtual reality; games; mobile applications; individualization; gait analysis; upper limb rehabilitation; balance rehabilitation and/or training.

As the above combination of data sources and keywords returned a vast amount of results, we selected the following inclusion criteria to identify the most relevant sources. (1) Language: English. (2) Date range: within the past 20 years (1996-2018). The majority of articles were published within the past 5 years to reflect the state-of-the-art (since 2014). Older references were made to technologies that substantially shaped the future direction of home rehabilitation systems. (3) Relevance: home or self-rehabilitation was necessary.

Results

Literature Search

The literature search returned a total of 307,550 results after the inclusion criteria were applied as presented in Table 1.

We used the following exclusion criteria to identify the most relevant sources and reduce the number of literature search results: (1) no relevance to stroke rehabilitation in the home environment, (2) trained personnel required to operate the technology; (3) medication or other clinical intervention required, (4) no report of engagement or motivation as a result of using the technology or other form of patient feedback, (5) no description of the technology, (6) no report of usability especially for older people, and (7) no additional contribution to the review findings compared with the previously reviewed articles.

Overall, we read 420 sources, as we excluded the majority by reading the abstracts. A total of 96 sources remained for analysis after meeting the inclusion criteria and having not been eliminated through the exclusion process.

Table 1. Results of the literature search before and after inclusion criteria were applied.

Topic	Results of topic search	Results after inclusion criteria
Devices for stroke rehabilitation	325,000	6800
Home rehabilitation	1,150,000	36,200
Rehabilitation engagement	651,000	17,100
Rehabilitation motivation	128,000	17,300
Stroke rehabilitation	1,640,000	45,800
Stroke; telerehabilitation	8180	3110
Smart meter; pattern recognition	83,200	18,100
Stroke; kinematic analysis	105,000	15,700
Stroke rehabilitation; robotic systems	43,700	16,900
Stroke rehabilitation; exoskeleton systems	15,300	4440
Stroke rehabilitation; virtual reality	41,000	14,100
Stroke rehabilitation; games	47,100	16,900
Stroke rehabilitation; mobile applications	46,500	17,400
Stroke rehabilitation; individualized systems	35,800	17,300
Stroke rehabilitation; gait analysis	112,000	16,000
Stroke; upper limb rehabilitation	138,000	17,200
Stroke; balance rehabilitation	398,000	15,600
Stroke; balance training	799,000	11,600
Total literature search results	5,766,780	307,550

Home Rehabilitation Systems

Overview

To perform a systematic and comprehensive review, we proposed a taxonomy of rehabilitation systems, presented in Figure 5, based on the type of technology presented in the reviewed articles. We obtained the taxonomy on the basis of the therapeutic effect in combination with sensing technology.

Home rehabilitation mainly focuses on motor control impairments due to minimal or no clinical and medical intervention [30,31]. On the other hand, most clinical systems (see left-hand side of Figure 5) have dependencies and are difficult to implement at home. Therapy that requires either clinical or specialist personnel to assist in execution includes transcranial magnetic stimulation and transcranial direct current stimulation [32], regeneration of neural tissue stem cell therapy [33], and mirror therapy [34,35]. Similarly, treatment of aphasia and cognitive impairments is predominantly within a clinical environment or through specialist intervention [31,36]. As a result, these approaches would require regular home visits or would be impossible to perform away from the clinical environment.

The right-hand side of Figure 5 shows a variety of methods and approaches developed to support home rehabilitation focusing on locomotor training. They differ based on the individual's situation and disabilities [37].

Locomotor training [31,38-42] can be implemented through various methods. One approach is through the use of *exoskeleton devices* [43,44] for gait [45,46] or upper limb [47,48] training. Most large exoskeleton devices reduce clinic personnel costs [49-54] but are inappropriate for home use [55,56]. Some devices in this category have started to have feedback mechanisms incorporated, such as that described by Baran et al [5]. However, these are still very expensive systems requiring a caregiver to guide and support training. Thus, we did not review these systems.

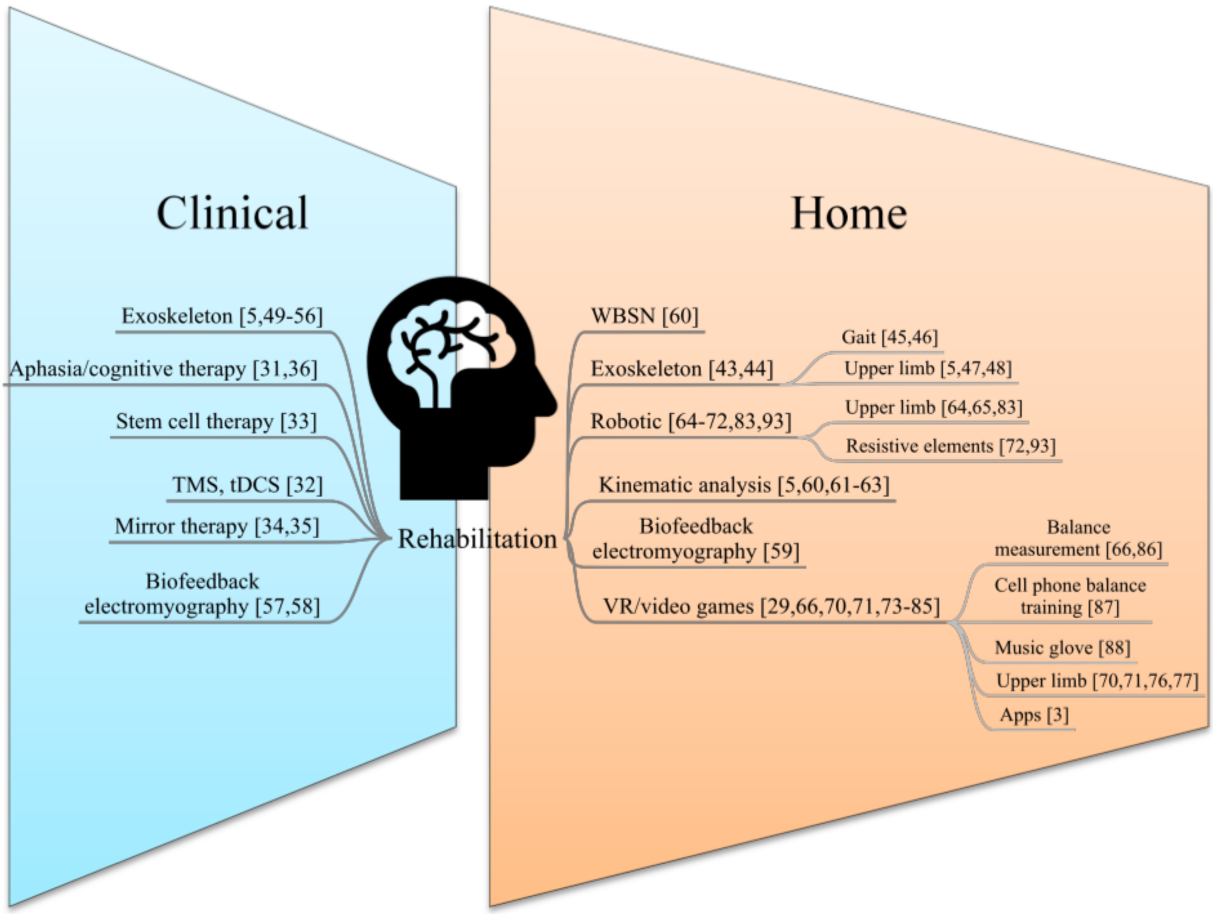
Biofeedback electromyography is based on feedback systems [57,58]. Though mainly designed for clinical use, some devices using this approach have been designed for home use, such as Biomove [59]. However, the disadvantage of this method [59] is the use of wearable equipment, which is not suitable for all patients and particularly the for the elderly [11].

The same challenge is faced by *wearable body sensor network systems* [60]. Additionally, observation by expert or clinical personnel is often needed and, thus, we did not investigate these 2 categories further in this review.

Another approach is to use cameras or wearable sensors for *motion* or *kinematic analysis* [60-63]. Cameras and wearables, however, are considered too intrusive for home use by many patients and individuals [11]. Many applications of cameras and wearables in home rehabilitation systems exist; thus, we reviewed these in detail.

Robotic systems have been heavily investigated [64-71] for home use. However, they face the same challenges of high complexity and cost. This includes systems such as low-cost resistive elements training [72]. However, these systems still do not avoid the requirement for supervision of the exercise. We reviewed systems in this category to identify their ability to enhance motivation and patient engagement.

Figure 5. Taxonomy of rehabilitation systems for stroke patients. VR: virtual reality; tDCS: transcranial direct current stimulation; TMS: transcranial magnetic stimulation; WBSN: wearable body sensor network systems.



Another area of research interest is the virtual reality and *video game* domain [3,73-84]. Although this is a promising area for home rehabilitation, there are still many challenges. The games are not individualized to the patients' needs; hence, patients lose motivation easily and are not engaged with the activities they need to perform [4,8,15,85]. In particular, elderly patients demonstrate very low engagement with this technology [11]. This category can be expanded to include balance measurement [86], cell phone balance training [87], and even a music glove, which motivates patients with the help of music [88]. We further analyzed systems in this category.

We critically evaluated home-based rehabilitation technologies with a focus on patient engagement as the widely recognized key indicator of success of rehabilitation systems in the reviewed articles. In contrast with *usability*, which is a measure preferred in human-computer interaction studies, *engagement* is not the singular measure of the usability of an interface, but rather of the perpetual retention of the user's interest over a prolonged period of time as defined by Peters et al [14]. Engagement can be the effect of a successful human-computer interaction design in combination with the psychological motivation of stroke survivors for rehabilitation [14]. Based on the literature, engagement is more likely when the feedback is sufficient and well understood by the patient, and the system, apparatus, or device is easy and convenient to use without employing intrusive means and without complex requirements from the user [89].

Kinematic Analysis at Home

In their presentation of a representative example of kinematic analysis systems, Baran et al [5] proposed a home rehabilitation system for upper limb recovery after stroke. They used a specially designed desk and chair to monitor the patient's movement through sensors and cameras. Other examples of kinematic analysis used cameras for upper limb [61] and gait analysis [62,63]. The methods were based either on an expensive camera, to accurately capture fast motion [61,63], or on a laptop and Microsoft Kinect camera sensor, depth image processing, and machine learning [62], to extract the motion patterns, which is relatively difficult to set up and operate.

Wang et al presented another approach for kinematic analysis without the use of cameras. Instead, they proposed a wireless wearable body sensor network system with inertia sensors (accelerometers, gyroscopes, and magnetometers), implemented with 2 wearable sensors per arm to support upper limb rehabilitation. However, the study had several limitations, including the misrepresentation of the Brunnstrom method [90,91] and the lack of feedback provided to the patient.

Kinematic analysis systems rarely provided individualized feedback to the patient. They relied on wearable components or cameras and were of relatively high complexity, making them outside the scope of our review. These are disadvantages, as they contradict the motivation and engagement requirements identified above (see Enhancing Motivation).

Robotic Systems at Home

Robotic systems in this domain have been extensively researched. Zhang et al [64] described an exoskeleton device that they claimed was lighter than similar technologies, to support upper limb rehabilitation. However, the device did not provide feedback to the patient, which would render home rehabilitation impossible. The device was focused on receiving and acting on signals from the patient to increase the task's difficulty. But it did not demonstrate to the patient any positive or negative changes to their rehabilitation exercise.

Similarly, Amirabdollahian et al [65] focused on finger and wrist rehabilitation through a robotic system combined with a computer game to enhance motivation. Additionally, this system incorporated feedback to the health care professional caring for the patient. Nevertheless, the same issues as with wearable components, increased complexity and not being individualized to the needs of the patient, appeared in this device. Nijenhuis et al [83] presented an extension of this work, where individualization and bilateral training were used to enhance motivation. However, this approach still used wearable technology.

Mohamaddan et al [67] addressed ADL, but their device did not provide feedback or keep the patient engaged. The device did not have progressively more difficult or easier exercises to support different stages of the recovery process.

Kohler et al [72] used a simpler approach by combining resistive elements with goal-oriented training. However, the recorded data was presented to the patient in the form of a sinusoidal graph, which is often not understandable information for the patient [92]. Extending research in this direction, Nimmy and Hepsiba [93] provided individualized exercises based on patient monitoring and also provided feedback and comparison with reference exercises. However, the resistive elements used constricted the device's applicability.

Systems in this category demonstrated disadvantages similar to those of kinematic analysis systems. Robotic systems included wearable components, were highly complex, and when feedback was provided it was complicated and not tailored to the individual. These systems lacked engagement and motivation, especially when used by the elderly.

Video Games and Virtual Reality at Home

Some work on demonstrating engagement has been reported for video games and virtual reality approaches. Yano et al [66] presented a system for gait rehabilitation based on body balance training. The device supported slope and stair climbing training. The software received angle positioning data to determine position, but this feedback was not tailored to the patient. Thus, supervised rehabilitation was needed, and engagement was not supported. Similarly, González et al [86] combined balance training with a game environment through Nintendo Wii and Microsoft Kinect platforms. However, they did not investigate engagement with this platform, particularly for the elderly population.

Sivan et al [70] reported on a platform for upper limb rehabilitation in which the patient interacted with a leg support and a joystick and was offered 8 different games. The game became progressively more difficult. However, there was no detailed feedback to the patient when his or her actions did not fully meet the requirements of the game. Additionally, the presence of other people in the home during the game was not taken into account. The device was difficult to set up. Slijper et al [77] took a similar approach and extended their work to cover bilateral training to enhance engagement. This system supported individualization and feedback, but it was unclear how this system supported ADL.

Johnson et al [71] proposed a software system offering different tasks for upper limb rehabilitation, with extensive feedback, focusing on increasing engagement through individualization of therapy and including bilateral and unilateral therapy. However, the system had several components and used a game environment, which can lead to aversion to the rehabilitation process. Along the same lines, Gorsic and Novak [8] aimed to increase engagement and motivation through the use of competitive or cooperative gaming. However, the game was not individualized to support all users (patients and healthy users).

Friedman et al [88] used a different approach where the focus was on gamification of the patient music experience for motivation enhancement. The device also combined visual feedback through light-emitting diodes installed in the wearable musical glove. However, the study raised the well-known issue of elderly patients reacting negatively to wearable devices. Also, the device was not individualized to support different patient needs.

Wittmann et al [76] harnessed the concept of gradually increasing difficulty to support motivation, through a virtual reality system targeting upper limb rehabilitation and use of several wearable components. The patient's motion was continuously monitored and assessed to calibrate the device and to set tailored goals.

Saposnik et al [3] developed a game as an iPad app that did not use wearable technology. However, the app had several limitations for a variety of patients to engage with this game (eg, age, familiarity, mobility, capacity to hold the device) and provided no explicit feedback to the patient.

Some evidence of motivation or engagement was provided for systems in this category. Some approaches also focused on individualization. However, the main disadvantage was the lack of incorporation into daily activities. Furthermore, the elderly were less engaged and motivation could be hindered, as the benefit in daily life was not directly perceived. Finally, the use of wearable devices or tools was a common trend in these systems.

Monitoring and Home Rehabilitation

Some rehabilitation technologies required renovation and other modifications in the patient's home [9,10,16]. Other challenges for the successful deployment and engagement with home assistive rehabilitation technologies were design and technical limitations [43], and many systems did not meet the acceptance and motivation criteria as reviewed above. Indeed, retrofitting infrastructure in existing homes can be significantly more challenging than designing a smart home that will already be equipped with embedded technology. To avoid these issues, research has mostly focused on smart home environment or monitoring devices that stand alone and do not require redesign of the home [94]. Such systems mostly focus on monitoring generic parameters and provide individualization through pattern recognition algorithms, but do not contribute to rehabilitation activities. Hence, monitoring systems can be tailored to the individual home environment [95-101] and to study individual patterns. To support rehabilitation, their scope would need to be altered to encompass rehabilitation goals, and patient motivation and engagement, while at the same time being transferable (supporting different application domains).

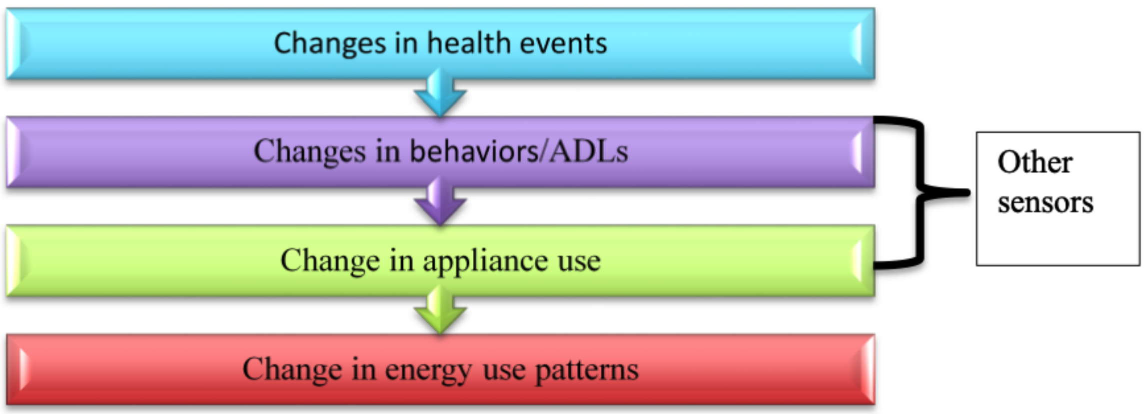
Systems for smart home environments have been proposed for various health-related applications [11,94-101]. They usually require extensive installation of sensors in several locations such as doors, windows, electrical appliances, and furniture. Monitoring devices can provide increasing understanding of the home environment, and of the patient and their condition; they can even provide a diagnosis. Such systems might be more appropriate to support rehabilitation based on performance of daily activities [21,22].

Research in this area has focused on machine learning for information extraction based on recorded data streams [11,94-101]. However, other challenges are introduced when such devices are used, including data security, data correctness, and device operational efficacy [22,101]. Cavallo et al [102] presented an example of such a system targeting rehabilitation. The system provided monitoring and remote supervision, but did not actively support rehabilitation. Some monitoring systems focused on specialist support [102] and behavior analysis [22]. Thus, rehabilitation, motivation, and engagement are outside the scope of these systems (leading to low scores in motivation).

According to Fell et al [22], there is a need for new monitoring devices that incorporate different sensors or input data streams. Figure 6 presents the additional information that can be used to support patient rehabilitation at home. The environment must be monitored and any deviation from the "normal" behavior must be identified. Changes in Figure 6 refer to identification of unexpected behavior, events, or abnormalities identified in the recorded data streams. "Other sensors" refers to the need for data fusion, acquisition of information from multiple sources, and a higher level of information extraction. For example, energy patterns can be identified through active power (smart meter) measurements; appliance use, though, might require other information such as time, temperature, location, and motion. Similarly, a health event may be recorded by a single monitoring parameter (eg, glucose level dropped below a threshold). However, changes in behavior and competence in daily activities require a series of additional measurements (eg, sound, motion, temperature, humidity, gases).

We found a gap in applying monitoring technologies (supported, for example, by machine learning, fusion, or pattern recognition) to rehabilitation that, at the same time, support patients in performing daily activities and enhance motivation. We suggest that, by using these monitoring technologies, *individualization* can be achieved for rehabilitation purposes, via providing appropriate feedback, applying machine learning to the individual patient, and focusing on daily activities, thus meeting the acceptance, motivation, and engagement requirements reviewed above (see Enhancing Motivation).

Figure 6. Monitored qualities for the health and care applications and the need for additional sensor input to monitoring devices [22]. ADLs: activities of daily living.



Comparative Analysis

Tables 2-4 summarize the criteria we selected for the comparative analysis. The methods for selecting the criteria were as follows. For Table 2, we selected these criteria based on the narrative review of motivation and engagement aspects we analyzed (see Enhancing Motivation). For Table 3, we selected these criteria according to commonly used and evaluated metrics in the majority of the reviewed articles. This was additionally informed by the conclusions outlined in the Enhancing Motivation and Home Rehabilitation Systems sections. For Table 4, we selected the criteria to meet other acceptability and economic aspects (including long term usability and transferability), as well as a separate category for the application area presented in the reviewed articles.

We used the extracted information from the reviewed articles to establish the criteria and to identify whether the criteria were met by the proposed systems. For the engagement and motivation criteria, as well as acceptance, all of the reviewed articles reported results on a common basis; thus, we needed no additional steps to cross-validate the reported results.

Tables 2-4 present a detailed comparative analysis of all the aforementioned technologies that were applicable for use in the home environment. We selected the technologies as representative examples of each category we analyzed.

Table 2. Summative assessment of the reviewed systems for the selection of criteria for the comparative analysis: motivation.

First author, year, reference no.	Motivation method				Engaging	Supports daily activities
	Cooperative	Supportive	Constructive	General		
Baran, 2011 [5]	No	No	No	Yes	No	No
Zhang, 2016 [64]	No	No	No	No	No	No
Yano, 2015 [66]	No	No	No	No	No	No
Mohamaddan, 2015 [67]	No	No	No	No	No	No
Sivan, 2014 [70]	No	No	No	Yes	No	No
Johnson, 2007 [71]	No	No	No	Yes	No	Yes
González, 2015 [86]	No	No	No	No	No	No
Wang, 2017 [60]	No	No	No	No	No	No
Kohler, 2010 [72]	No	No	No	No	No	No
Friedman, 2011 [88]	No	No	No	Yes	No	Yes
Nimmy, 2013 [93]	No	No	No	No	No	No
Wittmann, 2015 [76]	No	No	No	Yes	No	No
Slijper, 2014 [77]	No	No	No	Yes	No	No
Nijenhuis, 2015 [83]	No	No	No	Yes	Yes	Yes
Saposnik, 2014 [3]	No	No	No	No	No	No
Gorsic, 2016 [8]	Yes	Yes	Yes	Yes	Yes	No
Fell, 2017 [22]	No	No	No	No	No	No
Cavallo, 2009 [102]	No	No	No	No	No	No

Table 3. Summative assessment of the reviewed systems for the selection of criteria for the comparative analysis: acceptance.

First author, year, reference no.	Individualized	Suitable for the elderly	Nonwearable	Nonintrusive
Baran, 2011 [5]	No	No	No	No
Zhang, 2016 [64]	No	No	No	Yes
Yano, 2015 [66]	No	Yes	No	Yes
Mohamaddan, 2015 [67]	No	Yes	No	Yes
Sivan, 2014 [70]	No	No	No	No
Johnson, 2007 [71]	Yes	No	No	Yes
González, 2015 [86]	No	Yes	No	Yes
Wang, 2017 [60]	No	No	No	Yes
Kohler, 2010 [72]	No	Yes	No	Yes
Friedman, 2011 [88]	No	Yes	No	Yes
Nimmy, 2013 [93]	No	Yes	No	Yes
Wittmann, 2015 [76]	No	No	No	Yes
Slijper, 2014 [77]	No	Yes	Yes	Yes
Nijenhuis, 2015 [83]	No	No	No	Yes
Saposnik, 2014 [3]	No	No	Yes	Yes
Gorsic, 2016 [8]	No	Yes	No	Yes
Fell, 2017 [22]	Yes	Yes	Yes	Yes
Cavallo, 2009 [102]	Yes	Yes	No	No

Table 4. Summative assessment of the reviewed systems for the selection of criteria for the comparative analysis: technological aspects.

First author, year, reference no.	Intended use			Cost-effective	Technologically simple	Transferable
	Monitoring	Rehabilitation	Diagnosis			
Baran, 2011 [5]	No	Yes	No	No	No	No
Zhang, 2016 [64]	No	Yes	No	No	No	No
Yano, 2015 [66]	No	Yes	No	No	Yes	No
Mohamaddan, 2015 [67]	No	Yes	No	Yes	Yes	No
Sivan, 2014 [70]	No	Yes	No	No	No	No
Johnson, 2007 [71]	No	Yes	No	No	No	No
González, 2015 [86]	No	Yes	No	Yes	Yes	No
Wang, 2017 [60]	No	Yes	No	No	Yes	No
Kohler, 2010 [72]	No	Yes	No	Yes	Yes	No
Friedman, 2011 [88]	No	Yes	No	No	Yes	No
Nimmy, 2013 [93]	No	Yes	No	Yes	Yes	No
Wittmann, 2015 [76]	No	Yes	No	No	No	No
Slijper, 2014 [77]	No	Yes	No	No	Yes	No
Nijenhuis, 2015 [83]	No	Yes	No	No	No	No
Saposnik, 2014 [3]	No	Yes	No	Yes	Yes	No
Gorsic, 2016 [8]	No	Yes	No	No	No	No
Fell, 2017 [22]	Yes	No	Yes	No	Yes	Yes
Cavallo, 2009 [102]	Yes	No	No	Yes	No	Yes

Our analysis identified 3 aspects of technologies that we used for comparison: (1) motivation, (2) acceptance of technology, and (3) technological aspects. We selected these aspects for their importance in supporting patients' motivation and engagement (motivation) and in being incorporated into patients' rehabilitation routines (acceptance, technology).

For each aspect, we identified several comparison criteria. Regarding *motivation*, the criteria are (1) the motivation method used, (2) the patient's *engagement* with the technology, and (3) whether the technology *supports daily activities* as an additional measure of motivation. There are 3 motivation methods: cooperative, supportive, and constructive. When the method used in a technology was not specified, we characterized it as *general*. With respect to *acceptance*, the criteria are (1) *individualization* of the device to meet patients' needs, (2) suitability of the device for *elderly patients*, (3) the use of *wearable components*, and (4) the use of *intrusive monitoring* methods (eg, wearable sensors, on-body sensors, cameras, microphones). Wearable and intrusive methods have a negative impact on acceptance. *Technological aspects* are (1) *intended use* for the technology (monitoring, rehabilitation, diagnosis), (2) *cost*, (3) *complexity*, and (4) *transferability* to other domains.

Regarding intended use, besides our focus of rehabilitation, we also included 2 systems that perform monitoring and diagnostics.

"Yes" in the table highlights that the system met the criteria, which was demonstrated in the published work, subject to our interpretation. "No" indicates that the system did not meet the criteria.

We assessed a system to be individualized or personalized or person centric when it learned or adapted to the needs of a particular patient by incorporating some type of feedback loop mechanism where the device adjusted the requested task(s) to the ability of the patient. Examples of such mechanisms are machine learning approaches and increasing task difficulty. We assessed suitability for the elderly based on Debes et al [11]. We classified nonwearable (on-body sensors, wearable components) and nonintrusive (cameras, microphones) systems according to the system inputs that were used. The intended use of the system can be for rehabilitation, smart home monitoring, or smart home diagnosis of a health condition.

In the analysis, we considered systems that could be purchased by an average household in the United Kingdom to be cost-effective. We considered systems that would require a high capital investment, and thus reimbursement from the health care provider, to be not cost-effective. We considered technologically complex systems to be those that had a significant number of components, required significant training before use, or required extensive installation to be usable in a household. Finally, transferable systems were those that could be used for other rehabilitation purposes and were not restricted to stroke rehabilitation.

As the tables show, no technology met all the selected criteria. Most of the technologies were suitable for the elderly and were nonintrusive. However, most technologies lacked motivation and engagement enhancement through the use of a variety of motivation methods. The developed approaches were technology centric, whereas a person-centric approach is necessary to keep patients engaged and motivated in achieving their rehabilitation goals. Several devices claimed to enhance motivation but produced little or no evidence of patient engagement [5,8,70,71,74,75,81,86]. None of the devices intended for rehabilitation were transferable to other uses. Devices intended for monitoring or diagnosis had the desired transferability features [22,102]. Only 1 of the reviewed technologies proposed for rehabilitation supported individualization [71]; however, it did not meet the requirements for elderly patients and it used wearable components. On the other hand, individualization was supported by monitoring devices that were not intended for rehabilitation use [22,100]. Several technologies we reviewed were inappropriate for home rehabilitation, as they were technologically complex and expensive.

Discussion

Principal Findings

The first rows of Tables 2-4 list all the selected criteria, drawn from our extensive literature review, that must be met for a home rehabilitation system to be engaging and enable stroke recovery patients to meet their progressively ambitious goals or targets. Based on the above analysis, an ideal home rehabilitation device should meet all the identified criteria and requirements. The device needs to avoid wearable or intrusive components. It needs to support enhanced motivation and engagement by being incorporated into the daily activity routine. It must be cost-effective and not complex to install, maintain, and use. It needs to support the needs of all patients, regardless of age and background. Moreover, it needs to be portable and transferable to other domains.

The successful design of an assistive technology or rehabilitation device should take under consideration what the individual should and can achieve during rehabilitation [16]. Quantification and further analysis of the present and future conditions of the patient could overcome difficulties and unforeseen circumstances and could result in better assistive technology design.

Data and patterns from electronic databases are quite important to tailor rehabilitation, as the device can learn patients requirements and goals, adapt to their individual needs, and provide suitable challenges, for example, through machine learning. Individual choice and personal control are mandatory for success (see Monitoring and Home Rehabilitation). Technology design has to follow a person-centric approach considering technology ability levels. Given the developments in smart devices, algorithms, and information extraction, devices can adopt a person-centric approach while meeting the requirements for cost and complexity.

Contributions from the patient's environment can be used to enhance motivation and engagement with the activity. Members of the family or others can provide a competitive or cooperative stimulation. Additionally, rehabilitation incorporated into the completion of daily activities could enhance motivation. Finally, the continuous adjustment of the technology or device to the patient's changing requirements has a more beneficial effect. The device should adapt to increased levels of difficulty to provide stimulation for achieving higher targets.

Thus, a system catering to every occasion, individualized and adapted to support the patient's daily activities in their home environment, has a higher potential for successful acceptance and engagement. This system should incorporate a device, hardware, and additional software. However, developing such a system for the full range of impairments and rehabilitation tasks is an unrealistic goal. This is due to the requirement for different types of inputs for each condition, the range of rehabilitation goals, the differences between patients, and the differences between home environments. Hence, the successful system should focus on supporting specific daily activities that have measurable outcomes specified in recognized health care rehabilitation tests (see Comparative Analysis).

Conclusion

We reviewed rehabilitation devices for stroke patients in detail. The focus was on systems that are intended for use within the home environment for self-rehabilitation routines. We reviewed several technology domains under the criteria of motivation and engagement enhancement for continued use without the need for clinical or specialist involvement. We demonstrated that the existing approaches do not meet all the criteria in the motivation, acceptance, and technological categories. However, there is evidence that some devices proposed for monitoring instead of rehabilitation might provide solutions to individualization and thus wider engagement and acceptance. We identified the criteria for a device and system that will provide the required level of self-rehabilitation commitment as nonintrusive, nonwearable, motivation and engagement enhancing through a list of motivation methods, individualized, supporting daily activities, suitable for the elderly, cost-effective, simple, transferable, and intended for use in rehabilitation.

Conflicts of Interest

None declared.

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Abbreviations

ADL: activities of daily living

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