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The use of home-based digital technology to support post-stroke upper limb rehabilitation: A scoping review

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Abstract

Objective: To identify, map and synthesize the extent and nature of existing studies on the use of home-based digital technology to support post-stroke upper limb rehabilitation.

Data sources: A comprehensive literature search was completed between 30 May 2022 and 05 April 2023, from seven online databases (CINAHL, Cochrane Library, PubMed, ScienceDirect, IEEExplore, Web of Science and PEDro), Google Scholar and the reference lists of already identified articles.

Methods: A scoping review was conducted according to Arksey and O'Malley (2005), and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews. All English-language studies reporting on the use of home-based digital technology to support upper limb post-stroke rehabilitation were eligible for inclusion.

Results: The search generated a total of 1895 records, of which 76 articles met the inclusion criteria. Of these, 52 were experimental studies and the rest, qualitative, case series and case studies. Of the overall 2149 participants, 2028 were stroke survivors with upper limb impairment. The majority of studies were aimed at developing, designing and/or assessing the feasibility, acceptability and efficacy of a digital system for poststroke upper limb rehabilitation in home settings. The thematic analysis found six major categories: Tele-rehabilitation ($n = 29$), games ($n = 45$), virtual reality (n = 26), sensor (n = 22), mobile technology (n = 22), and robotics (n = 8).

Conclusion: The digital technologies used in post-stroke upper limb rehabilitation were multimodal, and system-based comprising telerehabilitation, gamification, virtual reality, mobile technology, sensors and robotics. Furthermore, future research should focus to determine the effectiveness of these modalities.

Keywords

Poststroke rehabilitation, upper limb rehabilitation, home-based technology, digital health

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Introduction

Poststroke rehabilitation is essential for stroke survivors to optimize and improve their function and enhance their quality of life, with the overall aim of achieving maximum independence in their everyday activities.[1] Over the past two decades, significant progress has been made in the development of interventions for stroke rehabilitation.[2] However, the global need for rehabilitation services is largely unmet, and services have been severely disrupted by the coronavirus disease 2019 (COVID-19) pandemic. As a result, today, more than half of stoke survivors in some low- and middle-income nations do not receive the rehabilitation service they require.[3] On the other hand, the current COVID-19 pandemic has caused a dramatic technological transformation in the way that a post-stroke rehabilitation service could be delivered to stroke survivors within their own homes.[4]

One of the long-term impairments after stroke is upper limb weakness. According to the study by Meyer et al.[5] the prevalence of upper-limb somatosensory impairment after stroke was estimated between 21% and 54%. Evidences indicates that the proportion of recovery of initial motor impairment in patients with a functional corticospinal tract made up to 63% (95% CI, 55%–70%).[6]

Traditionally, upper limb rehabilitation has been carried out in rehabilitation centres or hospitals, but due to the increasing demand for home-based rehabilitation, the use of digital technology has become a more accessible solution for patients. Thus, the recent advancements in digital and telecommunication technologies have created an unprecedented opportunity for post-stroke rehabilitation to adapt to new approaches to care using digital technology innovations. These digital technologies include telemedicine, artificial intelligence, machine learning, deep learning, fifth generation telecommunication networks, the Internet of Things, home monitoring devices, augmented and virtual reality (VR).[7]

Despite this, digital exclusion has also been reported as a challenge for health care digital transformation. For example, a recent report showed that 6% of households in the UK had no access to the internet by the end of 2021. This could be tackled by supporting users to get online and providing essential digital skills for less confident users.[8]

Nevertheless, the up-to-date evidence base about the use of digital technology for post-stroke upper limb rehabilitation in home settings is not well investigated and mapped. Therefore, the aim of this scoping review was to identify, map and synthesize the extent and nature of research activity on the use of home-based digital technology to support post-stroke upper limb rehabilitation.

Methods

A scoping review was conducted according to the Arksey and O'Malley,[9] which includes five sequential steps; (a) defining a research question, (b) identifying relevant studies, (c) selecting related studies (d) charting data, and (d) collating, summarizing and reporting the result. The reporting of our scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist.[10] Accordingly, the primary review question was 'What digital technology is used to support poststroke upper limb rehabilitation in home settings?'.

Prior to identifying relevant literature and sources, two authors (GG, APA) agreed the key words to use during the search for articles and databases bases to be accessed. The search strategy for electronic databases was derived from the research question and key concept definitions. The electronic database search was performed from 30 May 2022 to 05 April 05 2023 in CINAHL, Cochrane Library, PubMed, ScienceDirect, IEEExplore, Web of Science, PEDro, and Google Scholar as relevant search engine for grey literature. In addition, articles were included through a review of the reference lists of already identified articles. The main terms used in database searches were 'home, digital Technology, Tele medicine, Tele health, eHealth, mHealth, Tele rehabilitation, upper limb rehabilitation, upper limb, stroke, rehabilitation' (Full search strategies can be found in Supplemental Table 1).

Table 1. The number of studies is based on their aims and thematic areas.

	Number of articles	References
Aims		
Feasibility	21	13,15,16,19,28,30,32,35,41,42,45,48,50,51,64,72,81,84,86,87,91
Design/development	14	18,20,28,29,41,43,46,53,54,61,67,69,80,89
Usability	12	14,15,19,24,25,37,40,55,73,74,78,82
Efficacy	8	13,23,28,61,65–67,84
Acceptability	7	59,61–64,86,91
Adherence	5	28,58–60,86
Thematic areas		
Games	45	15,17–21,23,26–29,33,35,36,40,42,43,45,46,49,52–56,61–66,68,69,71,72,74,77–79,82–85,89,91
Telerehabilitation	29	19,21,23,24,26–28,30,35–37,41,44,48,50,53,55,59,64,65,69,71,72,74,79,81,83,86,89
Virtual/mixed reality	26	12,15,18,20,28,29,33,35,36,38,40,42,45–47,51,56,58,69,72,78,79,82,84,89,91
Sensor	22	15,16,18,21,22,26,31,34,39,45,46,50,51,54,57,58,61,78,82,84,87,89
Mobile technology	22	12,14,20,21,24,25,30,34,37,48,50,51,60,61,67,73–75,80,86,91,94
Robotics	8	27,41,49,55,69,79,83,85

The process of article selection was assisted with Mendeley reference manager software version 1.19.4. After importing all search results into a single folder, duplicate search results were identified and merged. Two authors (GG, APA) scanned the titles and abstracts of all articles reporting on the use of home-based digital technology in upper limb post-stroke rehabilitation. Full-text articles were thoroughly read by the lead author to determine eligibility, and the decision whether to include an article was based on the consensus of two authors (GG, APA) (Figure 1). As per the Arksey and O'Malley publication, the selection of studies for review was based on their pertinence to the review question rather than their level of methodological rigour.[9] Articles were reviewed for eligibility based on the following inclusion and exclusion criteria;

Inclusion criteria

- Articles published in English between 1 January 2010 and 05 April 2023.
- Study population of individuals with any degree of upper limb weakness after stroke.
- Studies conducted in home settings.
- Studies conducted with any type of digital intervention to support upper limb rehabilitation.

Exclusion criteria

- Editorials, registers, opinion pieces, letters and conference papers.
- Articles with no separate report for the eligible study population in studies with mixed participants.

Next, a data-charting excel sheet was prepared to be able to capture relevant information on key study patterns and characteristics. Authors discussed and agreed on the content of the charting for and the following information was included: Author(s), year of publication, study location (country); digital technologies used/interventions involved, and duration (if any), study sample, study design, outcome measures and results relevant to the research question of this scoping review (Supplemental Table 2). The first and last authors tested the charting sheet using three articles, who also actually extracted data from all included articles. Any disagreements between the two authors were resolved by the middle author.

An inductive thematic approach was adapted for analysis and synthesis of results.[11] After a thorough reading of the final selected articles and fully understanding of patterns, and we identified certain characteristics and concepts out of the extensive and widely dispersed papers conducted on the use of

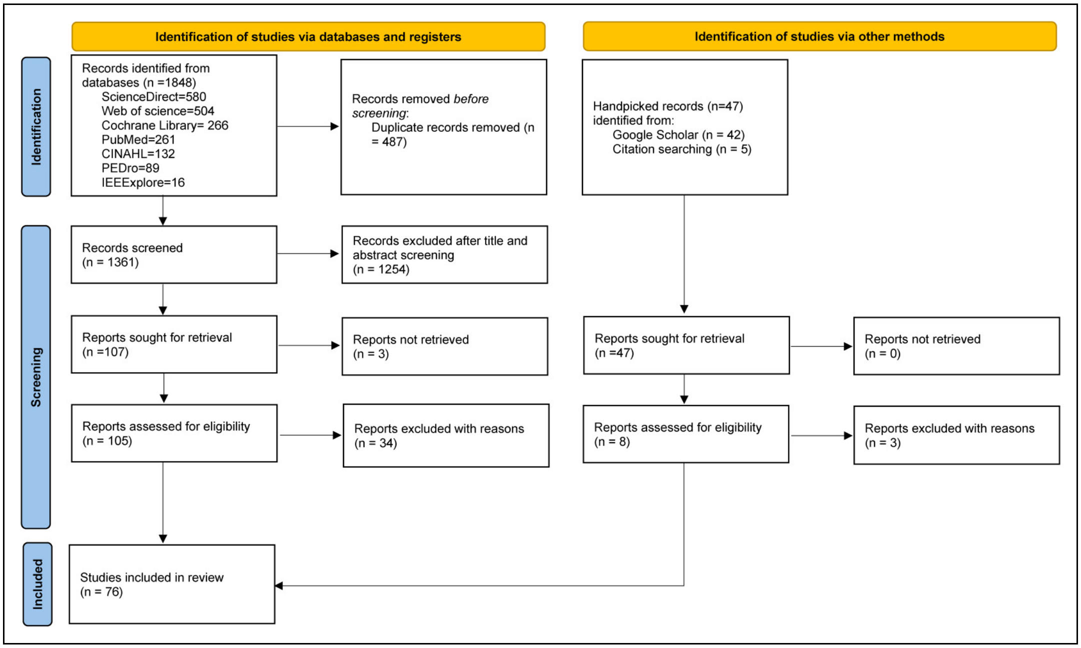

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram shows article selection process.

digital technologies for poststroke upper limb rehabilitation in home settings. Next, codes and themes were created using NVIVO. Furthermore, we mapped, summarized and presented the articles according to their aims, type of digital interventions, methods and main outcomes using texts, table and chart. All authors agreed on the findings, final thematic groups, and ways of result presentation. The trustworthiness of findings was enhanced by the research, clinical practice, and academic experience of the authors in the field.

Results

The search generated a total of 1895 records (1848 from online databases and 47 from other sources), of which 487 were removed for duplicates. Of the remaining, 1408 were excluded after title and/or abstract screening, leaving 113 articles for full-text review. Thirty-seven full articles were determined to be irrelevant in reporting the use of home-based digital technology for upper limb rehabilitation of stroke patients, leaving 76 articles[12–87] selected for inclusion in the review (Figure 1).

Overall, 76 articles met the inclusion criteria. Out of these, the majority were conducted in the USA ($n = 31$) and Europe ($n = 28$); 52 were experimental studies, and the rest, mixed, qualitative, case studies. The sample sizes in the studies ranged from 1 to 240, with a total of 2149 participants. Of these, 2028 participants were stroke survivors with upper limb impairment while the rest were non-stroke (control group) service users (Supplemental Table 2).

The papers mainly aimed to investigate the development or design (n = 14) feasibility (n = 21), usability (n = 12), efficacy (n = 8), acceptability (n = 7) and user adherence (n = 5), of home-based digital technologies for upper limb rehabilitation in stroke survivors. Furthermore, the thematic analysis identified six thematic areas of digital interventions for poststroke upper limb rehabilitation in home settings: Tele-rehabilitation, games, VR, sensor, mobile technology, and robotics (Table 1).

Themes

Tele-rehabilitation

Telerehabilitation can be defined as the delivery of rehabilitation services via various technologies remotely.[88] A total of 29 articles[19,21,23,24,26–28,30,35–37,41,44,48,50,53,55,59,64,65,69,71,72,74,79,81,83,86,89] discussed the use of telerehabilitation for upper limb in stroke clients in home settings. The majority of these articles showed a positive impact of telerehabilitation on its usability and acceptance for post-stroke upper limb rehabilitation at home. Overall, in the majority of the studies, participants showed upper limb improvement in training programme tasks, clinical and kinematic outcomes.

Of these, eight articles[19,21,27,41,55,65,69,83] reported the usability of a remote robotic telerehabilitation system. For instance, Rozevink et al. found users' of a remote robotic system called HoMEcare aRm rehabiLItatioN that reported a high level of satisfaction, and the FMA-UE scores showed significant improvements in motor function from a baseline mean score of 36.3 to 43.1 after six-weeks of training.[27]

Six articles[37,48,59,64,71,74] reported the use of telecommunication in upper limb rehabilitation post-stroke. Three articles presented[48,59,64] a phone-monitored home exercise programme for upper limb rehabilitation following stroke. These studies confirmed the feasibility of the system and its positive impact on longitudinal improvement of motor function. The interventions rated high patient satisfaction and produced no adverse events. Furthermore, stroke patients provided high ratings of perceived usefulness and ease of use for remote mobile rehabilitation systems in home settings.[37]

Nevertheless, studies have also shown that in-clinic therapy was more effective than home-based telerehabilitation interventions for post-stroke upper limb rehabilitation. Gauthier et al. reported whilst both home-based Tele-Gaming and Self-Gaming produced clinically meaningful Motor Activity Log Quality of Movement gains, home-based Self-Gaming was less effective than in-clinic constraint-induced therapy.[74]

Games

Digital games have the potential to attract and engage stroke survivors with exercise whilst playing and subsequently supporting the rehabilitation process of the upper extremities. This can be achieved through repeated exercises of the hand and arm while the patient plays the game on a touchscreen or using a handheld device.[71] Often, serious games are designed to support upper limb rehabilitation. Serious games can be understood as games primarily used for educational, rehabilitative or therapeutic purposes.[90] A high level of acceptance and satisfaction was reported on the use of a gesture-based serious game for motor rehabilitation managed through a web platform.[43]

A total of 45 studies[15,17–21,23,26–29,33,35,36,40,42,43,45,46,49,52–56,61–66,68,69,71,72,74,77–79,82–85,89,91] deployed games for home-based upper limb rehabilitation following stroke. Of these, 15 articles[15,18,20,28,29,33,35,42,45,46,56,72,82,84,91] found a VR game to be a feasible, well-received, and safe intervention to use at home for people with chronic hemiparesis following stroke. These studies also demonstrated a positive impact of VR games on improving arm functioning and the number of reaching movements achieved. Likewise, three articles discussed the Nintendo Wii Sports™ for post-stroke upper limb rehabilitation.[18,62,66] Wii mote-mediated games perceived to be engaging in functional tasks and subsequently improved upper limb function.[18,62]

Virtual, augmented, or mixed reality

VR can be described as a type of graphical user interface that displays a computer-generated immersive, three-dimensional, interactive environment that can be accessed and manipulated using, for example, stereo headphones, head-mounted stereo television goggles, and data-gloves.[92] This emerging technology is widely being integrated in various medical fields.[93] Twenty-six articles[12,15,18,20,28,29,33,35,36,38,40,42,45–47,51,56,58,69,72,78,79,82,84,89,91] used or created a VR intervention or a virtual environment for home-based upper limb rehabilitation after stroke.

Of these, six articles reported on the creation of a virtual environment for rehabilitation gaming exercise specifically for the upper extremities.[29,47,56,79,82,89] Two articles[42,51] used a VR device (smart glove) for exercising the upper extremities as a rehabilitative intervention for stroke survivors.

Mobile technology

Twenty-two studies[12,14,20,21,24,25,30,34,37,48,50,51,60,61,67,73–75,80,86,91,94] used a mobile technology or a mobile application as part of their intervention for home-based upper limb rehabilitation with stroke patients. Mobile technology had been used more frequently by stroke patients for information searching, and reminders in comparison to non-stroke participants.[25]

In 5 studies,[14,20,24,37,73] a mobile technology was used to quantify quality of movement and provide feedback to augment upper limb rehabilitation, and improve functional mobility in stroke patients remotely from home. The phone-guided home exercise programmes were also reported as an effective method of upper limb rehabilitation following stroke.[48] Two studies also used a smartphone app equipped with a machine learning algorithm and evaluated the effectiveness of a home-based rehabilitation system in chronic stroke survivors.[67,86] In the study authored by Fusari et al.,[86] from baseline to 14 days, mean FMA-UE decreased from 37.7 to 36.4, VAS increased from 0.8 to 2.8 and EQ-5DL-5L increased from 0.462 to 0.606. While patients' activity correlated significantly with their daily activity target ($R = 0.164$), no significant correlation appeared with their weekly activity target ($R = -0.035$). Use of a mobile phone was also found to be feasible for a home-based, self-help telerehabilitation programme integrated with electromyography-driven wrist and/hand exoneuromusculoskeleton in stroke patients.[30,50]

Sensors

Sensors were also used to detect the motion or movement of the upper extremities during the practice of rehabilitative interventions. Twenty-two articles[15,16,18,21,22,26,31,34,39,45,46,50,51,54,57,58,61,78,82,84,87,89] discussed the use of upper extremity-sensing digital technologies in home rehabilitation of stroke patients.

Five studies[22,26,31,50,58] using an electromyography-controlled biofeedback system that targeted wrist muscle activation, achieved a significant change on post-intervention surface electromyography outcomes. In these studies, the measures of upper limb movement and motor function, such as the WMFT, ARAT and FMA-UE, of the stroke patients showed significant increment during the follow-up. Likewise, in six studies,[18,34,39,45,57,87] a wrist-worn system was effective in detecting upper limb movements.

Robotics

Prominent improvements in clinical outcomes were also evidenced in 8 studies[27,41,49,55,69,79,83,85] that explored the effectiveness of a robotic device, using a computer-assisted arm rehabilitation by stroke survivors with upper limb weakness. In the majority of the studies that involve robotic interventions, significant clinical outcomes were recorded. For example, Radder et al.[16] developed a wearable soft robotic glove to support grip and hand opening of affected fingers of stroke patients in a wide range of functional task performances. The system was found to be applicable, feasible and acceptable. However, according to Nijenhuis et al., a dynamic wrist and hand orthosis combined with a remotely monitored user interface and self-administered training in gaming environment showed no significant improvements as evidenced by the ARAT and MAL outcomes.[19]

Discussion

The aim of this review was to identify, map and synthesize the extent and nature of existing research literature on the use of home-based digital technology to support post-stroke upper limb rehabilitation. We found 76 papers that reported the use of digital technologies for post-stroke upper limb rehabilitation in home settings and six broad categories of technology emerged: Tele-rehabilitation, games, VR, sensor, mobile technology, and robotics. The aims of the majority of these studies were to develop, design and/or to assess feasibility, acceptability, user adherence and efficacy of a digital system for poststroke upper limb rehabilitation in home settings. Despite this, the methods applied to address aims across papers have been inconsistent. For instance, feasibility had been evaluated through participants' concordance,[32,35,48,51,81,86] clinical outcomes,[13,50] safety[13,15,32,45] and ease of use[16,28] to the given digital intervention.

In the majority of studies, the digital technology system used was multimodal and compromised of multiple digital devices delivered using laptops, desktops, tablets, and phone devices. Two categories of studies were found: Those that used technology to deliver an intervention focused on various stages of the patients' rehabilitation journey ranging from assessment, therapy and monitoring; to those that focused upon the technological capabilities of the system development and evaluation.

Twenty-nine papers evaluated the use of telerehabilitation for post-stroke upper limb rehabilitation in home settings.[19,21,23,24,26–28,30,35–37,41,44,48,50,53,55,59,64,65,69,71,72,74,79,81,83,86,89] The recent telecommunication advancements have boosted remote delivery of rehabilitation services via the internet of things, messaging services, telephone, videoconference, and other means of communication technology. Besides the convenience and flexibility of telerehabilitation, it has been reported to be advantageous in minimizing issues such as hospital acquired infection, fatigue and travel distance.[95] Telerehabilitation may also underpin an enhanced continuity of rehabilitation intervention, monitoring, and counselling from hospital to home for stroke survivors with upper limb impairment.[96,97] Furthermore, the dose and user adherence level to home-based digital rehabilitation might have better impact on the clinical outcomes. This can be observed on the study conducted by Benvenuti et al. where participants with high adherence to the telerehabilitation programme showed better upper limb improvement (WMFT, 9-Hole Peg Test) than those with a low adherence level.[59]

The review also highlighted the popularity of VR as a technology being used for home-based rehabilitation of upper limb after stroke. More than 1/3 of the articles included have used or created VR or virtual environment as part of their intervention.[12,15,18,20,28,29,33,35,36,38,40,42,45–47,51,56,58,69,72,78,79,82,84,89,91] VR enables the provision of rehabilitation offering rich experience and credibility in alternative environments such as at home. This minimizes auditory and visual distractions that possibly can happen in communal health care settings.[98] It could also stimulate the movements of upper limbs in stroke patients.[99] The augmentative or immersive nature of VR was suggested as being the reason for the enhancement of post-stroke upper limb recovery by encouraging more engaging and thus more intensive rehabilitation through daily use.[70,100]

Even though most of the authors come to conclusion on the positive impact of mobile-based digital interventions for poststroke upper limb rehabilitation in home settings, Emmerson et al. could not find significant clinical outcome difference in its clinical trial that compared paper-based home exercise programme versus tablet-based home exercise, as indicated by the WMFT.[60] Of course, the application of a variety of digital interventions across studies could result in different degrees of clinical outcomes. Furthermore, the inconsistency in dose and period of interventions between studies might also influence the clinical outcomes.

Gamification, or game-based digital rehabilitation, is an advancing innovation with the potential to manage the limitations of in-person hospital-based rehabilitation. Patients have shown a high level of adherence, 97.8%, to gamification-mediated rehabilitative exercises.[101] This review identified [45,15,17–21,23,26–29,33,35,36,40,42,43,45,46,49,52–56,61–66,68,69,71,72,74,77–79,82–85,89,91] studies in which various types of digital games had been deployed as part of the intervention for home-based post-stroke upper limb rehabilitation. These games were augmented with/without virtual/immersive reality, and played via computer, mobile phone, and other digital devices and the participants were able to engage in rehabilitation activities based upon gamification within the home setting.

Sensors had been used as supportive components of the digital technology systems for providing effective home-based rehabilitation services among people with stroke. Twenty-two articles discussed the use of upper extremity-sensing digital technologies in the home rehabilitation of stroke patients.[15,16,18,21,22,26,31,34,39,45,46,50,51,54,57,58,61,78,82,84,87,89] Sensors do help with detecting body motions using physiological changes or physical stimulates.[102] This way, they can help to assess and monitor the effectiveness of therapeutic exercise of upper extremities in stroke clients.[103]

Robotics has also been applied in eight studies.[27,41,49,55,69,79,83,85] Robots have been used for upper limb rehabilitation in several ways. One common approach was the use of robotic devices that guide the movement of a patient's arm through a range of motion. These devices had been programmed to provide varied levels of resistance and assistance to help the patient regain strength and flexibility. Another way that robots were used for upper limb rehabilitation was through VR environments. These environments can simulate real-world activities and provide patients with a safe and controlled environment to practice their movements. As a result, robots can enhance motor activities and improve the daily functioning of stroke patients.[49,50,65,69]

This review was comprehensive and followed the Arksey and O'Malley steps.[9] In line with scoping review methodology, the studies were not evaluated for clinical effectiveness, methodological rigour or for overall quality. However, the authors note that many of the studies had small sample sizes, used a range of different outcome measurements and few articles were included from Asia and no studies were found from Africa. This may challenge the conclusion that home-based digital post-stroke rehabilitation is applicable and acceptable to all, particularly those residing in low-and middle-income countries.

In conclusion, this large scoping review has demonstrated that the digital technologies used in post-stroke upper limb rehabilitation were multimodal, and system-based comprising telerehabilitation, gamification, VR, mobile technology, sensors and robotics. The technologies were primarily used to assess, monitor, evaluate or provide therapeutic interventions for post-stroke upper limb rehabilitations within the home setting.

Furthermore, many aspects of technology use in rehabilitation, such as, whether home-based digital rehabilitation has advantages over, or is as effective as, hospital rehabilitation, in terms of treatment gains, adherence, patient satisfaction and cost, require further evaluation through interventional large-scale studies.

Clinical messages

- A wide range of digital technologies have been used in upper limb rehabilitation post-stroke incorporated at various stages along the patient journey including assessment, intervention, monitoring, and evaluation.
- Studies suggest the implementation of home-based digital rehabilitation as supporting the motor recovery of the upper limb is feasible and acceptable to the user with high ratings of perceived usefulness.
- Few studies explored key questions such as barriers to uptake and whether use of digital technology was more effective than in-person rehabilitation thus larger, more methodologically robust studies using a core outcome set to enable comparisons are required.

Author contribution

All authors meet the criteria for authorship.

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Supplemental material

Supplemental material for this article is available online.

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