Post-Stroke Technologies-Based Rehabilitation for the Upper Limb Recovery: A Systematic Review of Systematic Reviews

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Table of Contents

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Abstract

Background: Stroke is one of the most common cerebral vascular diseases, usually affecting people aged 60 and over, leading to a variety of disabilities requiring motor and cognitive rehabilitation. Post-stroke rehabilitation has a lead role in the recovery of the patients, and it is never too late to start. It should be implemented in a structured approach to help patients regain their physical, cognitive, and functional abilities. Technological solutions offer a beneficial and effective alternative to conventional therapy, making rehabilitation more accessible.

Objective: This study maps and synthesizes the evidence from published systematic reviews that assessed the effectiveness of technology-based rehabilitation for the recovery of the upper limb in post-stroke individuals.

Methods: Separate literature searches were conducted in PubMed, Web of Science, Scopus and Embase databases and Google Scholar. The PICOS was used to define inclusion criteria. There was no restriction on publication dates. The PRISMA flowchart was used in the retrieval and selection process. Then, the final articles were appraised for their methodological quality using the AMSTAR 2.

Results: After the search process that identified 1450 records from the 4 databases and an additional 342 by Google Scholar, seven systematic reviews were included. The seven studies were published between 2019 and 2023.

Conclusions: This review indicated that the field of technology-based rehabilitation is still fragmented due to poor evidence of efficacy. This is probably due to the high heterogeneity of the experimental studies. When developing a technology-based rehabilitation program, it is crucial to carefully plan and link all relevant actors, user-driven design guidelines, and principles of neuroscience.
There is a need for further research to understand better the impact of technology interventions on stroke deficits and recovery-related outcomes, both alone and in combination with traditional rehabilitation. This field of research could benefit from standardized rehabilitation protocols provided to patients, enabling comparison and interpretation to discover evidence currently missing.

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Review

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Keywords: stroke; rehabilitation; technology-based interventions; upper limb.

Introduction

Background

A stroke event refers to the alteration in brain functions after a sudden disruption of brain blood flow. It has an incidence of 15 million people a year. Stroke is one of the most common cerebral vascular diseases, usually affecting the population aged 60 and over, leading to a variety of disabilities for about 5 million surviving patients that require motor and cognitive rehabilitation [1,2].

The consequences of stroke encompass a spectrum of disabilities, spanning physical impairments to cognitive challenges, including issues with language, social interactions, and emotional well-being [3]. In about 80% of cases, stroke patients experience motor impairments of the upper limbs [4], which are functionally complex and difficult to recover, making activities of daily living very difficult for the patients. Post-stroke disability negatively impacts the quality of life and health, and only 25% of patients recover with only minor impairments [5].
Post-stroke rehabilitation has a lead role in the recovery of the patients, and it is never too late to start [6]. The level of recovery varies from person to person, but with time, effort, and support, many stroke patients can significantly improve their function and quality of life [7]. For this, stroke rehabilitation should be planned and implemented in a structured and coordinated approach to help patients regain their physical, cognitive, and functional abilities. For instance, the increasing understanding of brain plasticity is relevant to the rehabilitation strategy and outcome after brain damage, and the principles of experience-dependent plasticity are valuable for treatment [8,9]. Indeed, rehabilitation requires multiple and varied therapeutic approaches at any stage of disease (acute and chronic phase) [10]. In addition, the quantity and quality of treatment are important for an effective recovery: rehabilitation after a stroke should be task-oriented, offered in large doses, and with an active learning component for providing intentional and more effective training [11]. Training several times daily is necessary to exploit the neuronal plasticity that ensures effective neurorehabilitation.
Nevertheless, high-intensity treatments are very expensive for the healthcare system, and hospital stays often must be reduced. This could mean that on the day of hospital discharge, patients could still have functional deficits [4], especially in the upper limb [11,12].
In addition, outpatient therapy is not feasible for many patients because of the high costs of individual specialized therapies and the logistical difficulties of transportation from/to the hospital.
Home rehabilitation is a good option to continue recovery from chronic diseases such as stroke and a good alternative to manage long-term rehabilitation problems. Home rehabilitation is, therefore, necessary to provide such a large amount of training [13] also because traditional rehabilitation programs do not usually comply with all the above-mentioned requisites.
Thus, to maintain progress in the recovery process, the conventional rehabilitation pathway must include self-administered home exercises, a home rehabilitation solution, and outpatient therapy.
However, even within these strategies, certain limitations exist. Patients often lack motivation or lose interest in performing exercises independently, e.g., they may consider them too difficult or too easy/monotonous, and the absence of external feedback does not stimulate them [14].
In this context, technology can bridge the gap between home rehabilitation and remote therapy by providing tools and platforms that make it feasible for stroke patients to receive therapy, guidance, and support without needing a physical presence in a healthcare facility [15].

Technology that impacts post-stroke rehabilitation

Attempting to reduce and overcome all the mentioned logistical and economic barriers of long-term rehabilitation, technological solutions offer a beneficial and effective alternative to conventional therapy, making rehabilitation more accessible to everyone. Rehabilitation technologies can significantly enhance the effectiveness and accessibility of stroke rehabilitation programs when incorporating principles of experience-dependent plasticity [8,9,16]. Advanced and simple technologies are more commonly explored and used in developed countries, mainly due to their readiness and availability [17].
Advanced technological interventions for post-stroke rehabilitation include robotics, transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), brain-

computer interface (BCI), and functional electrical stimulation (FES). These therapies, while effective, require a certain level of expertise and resources that may not be readily available in a home setting. Therefore, they are typically conducted in a clinical or rehabilitation centre under the supervision of trained professionals. Other current less invasive technologies are virtual reality (VR), augmented reality (AR), and activity trackers (such as accelerometers, gyroscopes, pedometers, breath sensing, heart-rate monitors, and calorie trackers) [18]. As a cutting-edge and computer-generated simulation technology, VR can create an enriched environment, facilitate task-specific training and provide multimodal feedback to augment functional recovery [19]. Users can use their hands or movement sensors, such as gloves or joystick, to interact with virtual objects. The development of low-cost sensors has allowed this technology to spread at the consumer level: the Sony Playstation 3™, Microsoft X-box 360™ and Nintendo Wii™ are examples of VR-based consoles [16]. AR technology combines real and virtual objects to provide an interactive real-time experience in a common environment [20]. Users can interact with AR through various devices such as smartphones, visors, display, or active mirrors. These devices use cameras, sensors and software to overlay digital information onto the real world. In contrast, FES or neuromuscular electrical stimulators have been used predominantly for stimulating lower and upper extremity functions [21].

Telerehabilitation (TR), mobile health applications (mHealth apps), assistive technologies (AT), and gait training (GT) are simple technological interventions for post-stroke rehabilitation [18]. Home-based TR is a branch of telemedicine that consists of the use of a variety of telecommunication platforms (such as telephone visits, mobile applications, serious games, web-based self-care programs, internet-based video conferencing, and sensor-based telemonitoring) by healthcare professionals to provide necessary patient care and remote evaluation, supervision, and support for persons with disabilities living at home [11,22]. Home-based TR allows to meet the rehabilitation needs of stroke survivors living in rural areas with limited health services, especially in westernized countries, where the stroke burden is rapidly increasing [23]. Home-based TR implies access at any time and from any place to rehabilitation services to address stroke aspects: 1. Motor function: upper and lower extremities, balance, and gait; 2. Cognitive function: spatial neglect, cognition, memory; 3. Language: aphasia [24]. TR can be delivered synchronously or asynchronously depending on patients' needs, medical conditions, and treatment plans [25]. The choice between synchronous and asynchronous telerehabilitation depends on various factors, including the patient's needs, the nature of the therapy, and the available technology. Synchronous sessions are often used for live consultations, real-time feedback, and interactive exercises. Asynchronous sessions are more flexible and beneficial when patients need rehabilitation in their daily routines. Some telerehabilitation programs use a combination of both approaches to offer a well-rounded service that combines real-time interaction with flexibility and convenience.

Also, mHealth apps are defined as health and well-being mobile services for medical care delivered using a mobile app or other wireless technology. These are interesting for their mobility, multi-functional skills such as reminders and videos, and ability to support specific rehabilitation goals, promote self-management [26]. mHealth apps for stroke rehabilitation can target different aspects of the disease, and there are mobile apps designed as games to improve finger dexterity and programs to increase adherence to home rehabilitation exercises, for example, for upper limb rehabilitation [27,28].

Objectives

This study identifies and appraises published systematic reviews. The aim is to describe the quality, summarise and compare the conclusions, and discuss the strengths and weaknesses in the effectiveness of technology-based rehabilitation for the recovery of the upper limb in post-stroke individuals. This systematic review focuses on technology-based rehabilitation with interventions supported by synchronous (real-time care) or asynchronous (not real-time care) telerehabilitation, mobile health applications, or eHealth portable devices equipped with VR or AR applications.

Methods

Databases, criteria, and search strategy

Separate literature searches were conducted in PubMed, Web of Science, Scopus and Embase databases, and Google Scholar. The Population, Intervention, Comparison, Outcome, and Study Design framework-PICOS were used to define the following inclusion criteria: (P) the target population was composed of post-stroke persons, (I) we considered technological interventions for upper limb rehabilitation in stroke survivors (i.e., e-Health rehabilitation, at home telerehabilitation, smartphone-based rehabilitation, (C) studies were selected with or without control group comparison, (O) we considered upper limb function recovery outcomes, (S) we search for systematic reviews written in English that evaluated the effectiveness of technology-based intervention for the rehabilitation of the upper limb in post-stroke patients. The combination of key terms reported in Texbox 1 was used for the search.

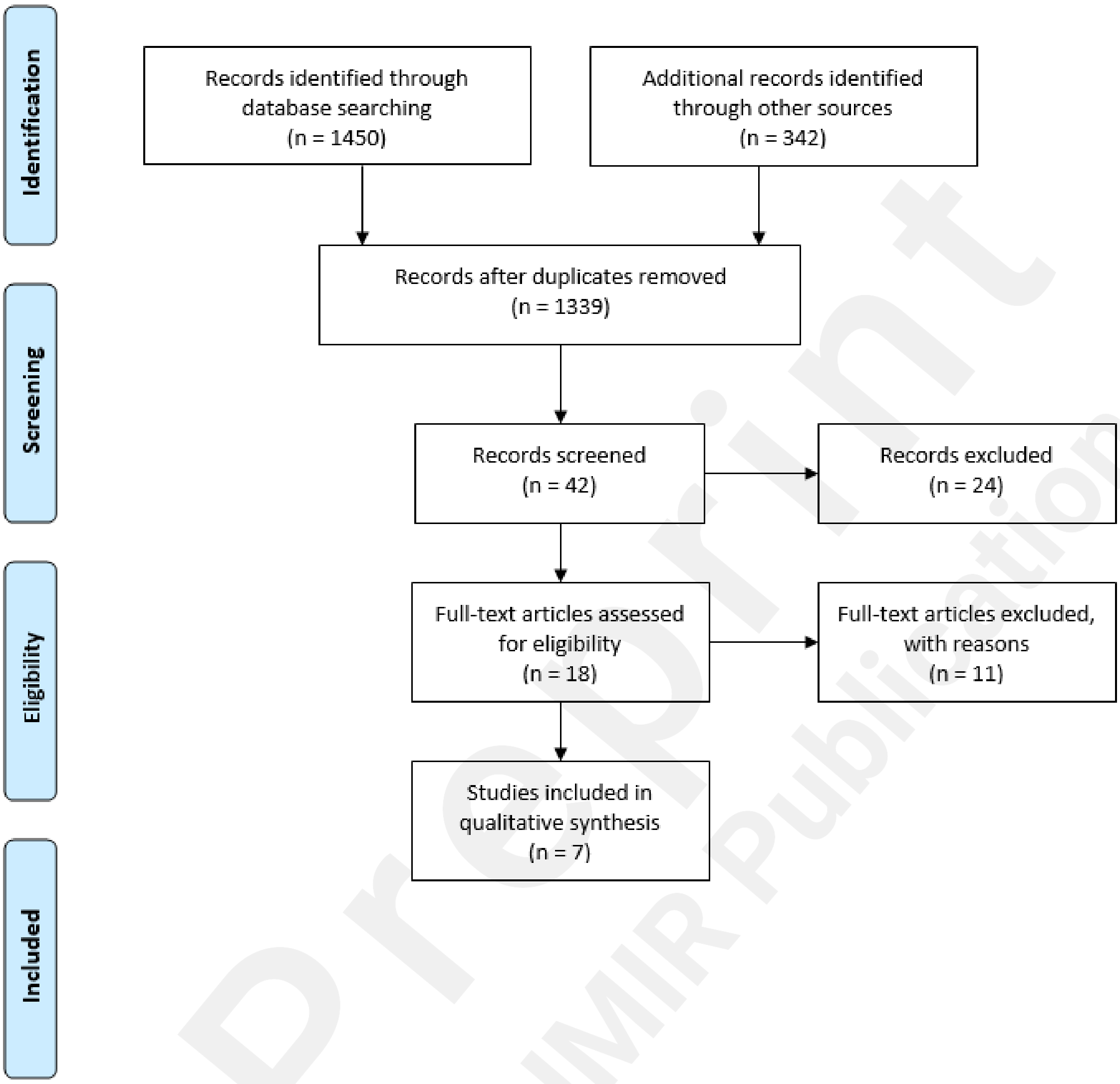
Textbox 1. Strings used for the search in each electronic database.

> post stroke outpatient OR after stroke outpatient AND at home upper limb telerehabilitation OR at home paretic arm telerehabilitation OR home eHealth rehabilitation OR smartphone-based rehabilitation
>
> post stroke person OR after stroke person AND at home upper limb telerehabilitation OR at home paretic arm telerehabilitation OR home eHealth rehabilitation OR smartphone-based rehabilitation
>
> post stroke people OR after stroke people AND at home upper limb telerehabilitation OR at home paretic arm telerehabilitation OR home eHealth rehabilitation OR smartphone-based rehabilitation
>
> after hospital discharge patient OR after hospital discharge people AND at home upper limb telerehabilitation OR paretic arm telerehabilitation at home OR home eHealth rehabilitation OR smartphone-based rehabilitation

There was no restriction on publication dates. The searches were finalized in May 2023. Articles were excluded if they were not systematic review articles or were not written in English.
According to the predefined criteria, the screening phase was based on analysing titles and then abstracts. Later, full-paper articles of those titles/abstracts of screened publications were reviewed independently by MR and the SL. VS was involved in reaching a consensus in cases of disagreement. Studies that met the inclusion criteria were included, and the results of the

searches were summarized. We used the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [29] flowchart in the retrieval and selection process (Fig. 1).

Figure 1 The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flowchart.



Study quality assessment

Three authors independently appraised the final articles' methodological quality using the Assessment of Multiple Systematic Reviews (AMSTAR 2) [30]. AMSTAR 2 is composed of a 16-items evaluated either with "yes" or "no" (items 1, 3, 5, 6, 10, 13, 14, and 16); with "yes", "partial yes", or "no" (items 2, 4, 7, 8, and 9); or with "yes", "no", or "no meta-analysis conducted" (items 11, 12, and 15). A "yes" answer means the item is fulfilled and is considered a positive result. Each review was appraised by three authors (MR, SL, VR), and it is reported in Multimedia Appendix 1.

Results

The search process identified 1450 records from the databases and an additional 342 by Google Scholar. After duplicates (n=453) were removed, 1339 articles remained for initial screening by title. From this process, other 1297 were excluded because a) studies involved patients for general rehabilitation (n=18), b) the intervention was not specific for upper limb recovery functions (n=195), c) the intervention was performed using other technologies (n=402), d) studies dealt with other topics or disorders (n=682). This process resulted in 42 potentially eligible abstracts. Authors analysed the retained abstracts to obtain the final list of full-text papers to be reviewed. After analysing the abstracts, 24 were excluded, as they did not fit the established criteria of the target population and the specific technology-based intervention. A second screening step was performed for those full-text papers that matched all the criteria (n=18). The other 11 were excluded from this process because the type of studies were not systematic reviews.

Seven systematic reviews were included. Multimedia Appendix 2 presents a summary of the studies and their findings. The seven studies were published between 2019 and 2023.

Study design

Five of the selected reviews defined the study's design using the PICOS framework [31-35] whereas the other two defined the inclusion criteria [36,37]. Four reviews [31,32,36,37] were registered in the research protocol on the international database of prospectively registered systematic reviews in health and social care (PROSPERO). A total of 95 studies were included in the seven reviews that overall mapped RCTs [31,33,34,36,37], RCTs and non-RCTs studies [32,35] but also observational studies [33] and uncontrolled clinical trials [35]. 2995 patients were enrolled with a mean age of 58.78 years.

Reviews’ objectives

Four of the selected reviews [31-33,35] investigated the effectiveness of technology-based rehabilitation interventions on physical functioning compared to a combination of traditional treatments in stroke patients [31]; upper limb wearable technology for improving physical activity and social participation in adult stroke survivors [32]; Augmented Reality (AR) for the upper and lower limb functional recovery after stroke [33]; and mobile health applications (mHealth apps) containing a physical training in stroke rehabilitation [35]. Two reviews [34,36] examined the effects of home-based exergaming interventions on upper limb activity after stroke, compared with conventional therapy, in post-intervention and follow-up [34]; the use of mobile apps for stroke rehabilitation on stroke-related impairments (motor paresis, aphasia, neglect) and functional outcomes (adherence to exercise, activities of daily living (ADLs), quality of life, secondary stroke prevention, and depression and anxiety) [36]. Only one review [37] gathered evidence on virtual reality-based telerehabilitation for patients after stroke and compared it with conventional in-person rehabilitation.

Reviews’ outcomes and outcome measures

All seven reviews analysed Upper Limb (UL) function as an outcome and five of them also assessed Lower Limb (LL) function and walking [31,33,35-37]. Moreover, four of the latter five studies measured balance [31,33,35,37] and two physical activity and function [31,35].

Three of the selected reviews assessed the activity of UL function [32-34], LL function [33], and participation [32,33] after stroke according to the World Health Organization’s International Classification of Functioning, Disability and Health (ICF-WHO) framework [38].

The clinical scales used to measure UL function included the following: Late-Life Function and Disability Instrument (LLFDI) [39]; Fugl-Meyer Assessment – Upper Extremity (FMA-UE) scale [40]; Wolf Motor Function Test (WMFT) [41]; Manual Function Test (MFT) [42]; Box and Block Test (BBT) [43]; Action Research Arm Test (ARAT) [44]; Chedoke Arm and Hand Activity Inventory (CAHAI) [45]; Jebson-Taylor Hand Function Test (JTHFT) [46]; Motor Activity Log (MAL) [47]; Upper Extremity Function Test (UEFT) [48]; Disabilities of the arm, shoulder and hand (DASH) questionnaire [49] and the short version (QuickDASH) [50]; Ashworth scale (AS) and Modified Ashworth Scale (MAS) [51]; Stroke Upper Limb Capacity Scale (SULCS) [52]; Nine Hole Peg Test (NHPT) [53]; Barthel Index (BI) [54]; Grooved Pegboard Test (GPT) [55]; Purdue Pegboard Test (PPT) [56]; Canadian Occupational Performance Measure (COPM) [57]; ABILHAND scale [58]; Manual Muscle Test – Upper Extremity (MMT-UE) [59]; Brunnstrom stage – Upper Extremity (B-stage-UE) [60]; Range of motion (ROM) [61]; Wrist Extension (WE) and Wrist Flexion (WF) [62]; Finger Extension (FE) and Finger Flexion (FF) [63]; Motricity Index (MI) [64].

For measuring LL function, these were the most used clinical scales: Lower extremity domains of Late-Life Function and Disability Instrument (LLFDI) [39]; Motor Assessment Scale (MAS) [65]; Rivermead Motor Assessment (RMA) and Rivermead Mobility Index – Lower Extremity (RMI-LE) [66]; Fugl-Meyer Assessment – Lower Extremity (FMA-LE) scale [40]; Timed Up and Go (TUG) test [67]; Modified Ashworth Scale (MAS) [51]; Gastrocnemius muscle (GCM) [68]; Range of motion (ROM) [61].

The balance outcome was measured by: Berg Balance Scale (BBS) [69]; Mini Balance Evaluation Systems Test (Mini-BESTest) [70]; Function in Sitting Test (FIST) [71]; Trunk Impairment Scale (TIS) [72]; Postural Assessment Scale for Stroke Patients (PASS) [73]; Brunel Balance Assessment (BBA) [74]; Performance Oriented Mobility Assessment (POMA) [75]; Modified Falls Efficacy Scale (MFES) [76].

For the walking outcome, the tools used were the following: 10-Meter Walk Test (10 MWT) comfort and fast [77]; 6-Minute Walk Test (6MWT) [78]; 2-Minute Walk Test (2MWT) [79]; Functional Ambulation Category (FAC) [80] and Modified Functional Ambulatory Category (MFAC) [81].

Physical activity and function were measured by the physical activity subscales in Stroke Impact Scale (SIS) [82] and Health Promoting Lifestyle Profile-II (HPLP-II) [83]; National Institutes of Health Stroke Scale (NIHSS) [84]; Regional House-Brackmann Grading System (R-HBGS) [85].

Four reviews [31,34,36,37] assessed activities of daily living (ADLs) as outcomes, using the following measures: Barthel Index (BI) [54] and Modified Barthel Index (MBI) [86]; Modified Rankin Scale (mRS) [87]; Functional Independence Measure (FIM) [88]; ADL domain of Stroke Impact Scale (SIS) [82] and Nottingham Extended ADL (NEADL) scale [89]; Task Completion Time (TCT) [90].

While participation was included as outcomes in three of the selected reviews [31-33], the other three studies [35-37] evaluated the quality of life. The first was analysed by the participation subscales in Stroke Impact Scale (SIS) [82] and Late-Life Function and Disability Instrument (LLFDI) [39], and the second one by Stroke Specific Quality of Life (SS-QOL) scale [91] and EuroQol-5 Dimensions- 5 Levels (EQ-5D-5L) [92].

Only one review [36] examined adherence to exercise by Morisky Medication Adherence Scale (MMAS) [93], secondary stroke prevention by Functional Dysphagia Scale (FDS) [94] and Penetration-Aspiration Scale (PAS) [95], and depression and anxiety by Hospital Anxiety and Depression Scale (HADS) [96] as outcomes. Another review [37] also assessed cognitive function, using Montreal Cognitive Assessment (MoCA) [97] and Rivermead Behavioral Memory Test – Third Edition (RMBT-3) [98].

Reviews' types of interventions and technology used

Different technology-based interventions were reported in the seven reviews analysed. Online video monitoring and techniques for monitoring physical home exercises, goal settings or overall treatment, gamification and accelerometers are mapped in [31,34-36]. The tools used varied from smartphones, phones, tablets, digital video discs and programs via the Internet

[31], video game environments that required active body movements to control the game [34], to mobile health applications (mHealth apps) [35,36].

Looking at the details of the selected reviews, online video monitoring, phone calls, and messaging are the most common technologies used till now, as mentioned by [31]. They normally ensure a real-time therapist-patient interaction, with a "call" frequency ranging from 3-5 times per week to 1 per month. The therapist can also provide feedback, through the Internet and, when necessary, by scheduling virtual training (e.g., exercise videos) in advance [31].

Another option for remote technology-based rehabilitation, analysed by [34], is to provide exergames. We mean the use of video games requiring a physical interaction (active body movements) to play the game, so non-specific video game systems (e.g., Nintendo Wii, Xbox Kinect, etc.) need to be combined with specific rehabilitation systems (e.g., RGS, virtual gloves, etc.) or specific rehabilitation devices (e.g., Hand Mentor Pro, Polhemus 3, etc.). Patients, with a prescription usually ranging from 3 to 7 days per week, can use exergames systems independently, producing self-reported or observational measures (e.g., technological sensors, therapist telehealth visits) [34].

Leveraging everyday technologies, such as smartphones and tablets/PCs, has become increasingly prominent in rehabilitation. This is made possible through implementing mobile health applications, or mHealth apps, well investigated in [35]. These apps incorporate physical training components and offer a customizable approach tailored to individual patient requirements. This customization encompasses specific goals, desired difficulty levels, and the duration of app usage.

Moreover, these apps serve various purposes, including interactive gaming (e.g., FINDEX, ARMStrokes), prescription of exercise routines (e.g., CARE4STROKE), and progress monitoring (e.g., STARFISH). They can also be integrated with devices like IMU sensors and pedometers to enhance their effectiveness. This innovative use of technology complements traditional physiotherapy and widens the spectrum of rehabilitation possibilities.

Generally, the "gaming apps" require limb movement and interaction, aiming, for example, to improve upper limb and finger dexterity. In the "exercise prescription" app a therapist pre-selects a set of standardized exercises shown in the app, allowing the caregiver assistance, if necessary. "Monitoring" apps supervise and check patients' physical behaviour (e.g., number of steps per day, walking or sitting time, walking distance or speed, etc.).

For all the types of apps, the prescription is maximally 30 min per session, from one to seven times per week. The therapist's constant presence is not necessary, thanks to auditory and vibration feedback provided directly by the apps [35].

The mobile apps can be on any operating system (IOS, Android, Windows) and on any aspect of stroke impairment rehabilitation (motor paresis, aphasia, neglect). Focusing more on their possible goals, we could have therapy apps (with users' active device interaction to complete activities) or rehab videos (exercises mobile guide), education apps (to learn about stroke), reminders (messaging to encourage compliance) or even a combination of them [36].

Parker et al. [32] described two types of wearable devices worn by the patients. The first device operated independently and functioned as a central connector for other devices, whereas the second one captured specific action or executed a measurement and then sent the info to a primary wearable device for analysis.

The "wearable technologies" are something portable to wear externally on the body and to be used independently of a therapist. They can be utilized in both clinical and nonclinical settings, to facilitate recovery, provide formative and real-time feedback, and measure intervention outcomes over long periods of time. They span from microelectromechanical systems (with accelerometers, gyroscopes etc.) to electromyographic biofeedback to robotics. This type of intervention can last 3 to 12 weeks, with various intensities [32].

AR- and VR-based rehabilitation systems providing games were reviewed by [33,37]. Such systems included using head-mounted displays (HMD), Leap Motion, HD webcam, Microsoft Kinect v2 sensors connected to a laptop or AR mirrors with visual tracking methods. AR technology is a real-time projection of virtual objects/scenarios in a common and real environment/place. During the game, the patients will interact with these virtual objects and receive automatic instructions, score, and visual and audio feedback via tracking devices (mouse, arm skate, HD Webcam, etc.). The AR systems usually allow the creation of a personal training program with various training intensities, and the treatment duration is between 30 min and 1 hour per session [33]. VR is a computer-generated simulation technology that requires patient interaction, providing multimodal feedback. VR systems are often installed at patients' houses and may include the remote supervision of a therapist (e.g., virtual-based telerehabilitation group, interfaces for patient and therapist remote communications). It is also used at hospitals/clinics, with a therapist's in-person supervision/instruction [37].

Reviews' results on the effectiveness of technology-based interventions

Even though all technology-based interventions included in these studies are economically favourable rehabilitation delivery models, no clear or direct evidence of impact on the recovery of function has been underlined.

Parker et al. [32] highlighted little evidence to support the use of wearable technologies to improve activity and participation in the recovery of the upper limb.

Even if all the other reviews [31,33-37] reported similar effectiveness to conventional treatments, results are interpreted and discussed cautiously. For example, Rintala et al. [31,35], Gelineau et al. [34] and Szeto et al. [36] discussed that rehabilitation technology, including mHealth apps, may have benefits as an additional treatment, but a lack of robust evidence does not consent authors to determine apparent effects.

Also, in the case of AR- [33] and VR- [37] based telerehabilitation, patients might still have a similar subjective experience of rehabilitation with therapists' supervision as in-person rehabilitation. According to Phan et al. [33], the use of AR significantly influenced the upper limb function (SMD = 0.657; 95% CI, 0.287 to 1.026; p = 0.000). AR-based applications could offer options for increasing treatment intensity and promoting motor recovery after a stroke used with conventional rehabilitation methods. Also, for Hao et al. [37], VR-based telerehabilitation is a promising avenue for patients with stroke that can potentially overcome the barriers of traditional in-person rehabilitation. VR-based telerehabilitation achieved comparable outcomes in the upper extremity function and equivalent effects on balance ability compared to in-person rehabilitation.

One aspect that holds significant clinical relevance is the duration of the intervention, which is measured in terms of both the quantity and intensity of the dosage. Studies suggested a positive correlation between the time allocated for therapy and the therapy outcomes [99]. In the seven reviews, the duration of the trials primarily ranged from 2 to 12 weeks.

According to Parker et al. [32], improvements were observed across some studies for both the control and intervention groups. The increase in the amount of rehabilitation has led to improvements in all the studies analysed. This observation could potentially suggest that a fundamental mechanism for improvement is the augmentation of the amount of rehabilitation administered. This concept has been acknowledged and incorporated into the national clinical guidelines for stroke.

Szeto et al. [36] concluded that the dosage and duration should be customized to address individual problems.

Some studies included in [34] reported follow-ups. However, in most of these cases, the duration of the follow-up is too short (4-24 weeks), leading to inconsistent results.

None of the selected reviews mentioned or reported any adherence to the principles of experience-dependent plasticity [8,9].

In conclusion, further research is necessary to differentiate between the mechanisms of dosage and intensity. This will aid in understanding the impact of the volume of rehabilitation activity and how it compares to the intensity, which is the amount of rehabilitation administered over a specific time period.

Limitations of the selected systematic reviews and implications for future research

The heterogeneity and the different quality levels of the studies included are the significant limitations claimed by almost all the selected reviews [31,32,34-37]. Each review performed the assessment of quality using Physiotherapy Evidence Database (PEDro) Scale [31,34,35,37], Cochrane Risk of Bias (CRoB) for RCTs [32,36], Downs and Black Instrument for non-RCTs [32,35] and QualSyst [33]. Due to these differences in assessment quality, results should be interpreted and generalized with caution.

Given these limitations, future research is called to frame a more robust methodology with a larger sample size [32-37] and valid measurement tools [32,35] as well as deeper investigation on different gender and age groups [32,33] as well as other impacts depending on the stroke stage [34,36]. Also, the trial length and the study follow-up time were mentioned [36,37]. Gelineau et al. [34] highlighted the need for a gold standard for future research in the field. Regarding technology readiness level, different issues were underlined to overcome the drawbacks of the reported technology-based rehabilitation interventions. For example, the integration and interoperability with intelligent infrastructure, the design of an attractive, user-friendly, portable and low-cost system [33,35,36].

Discussion

There are more than 15 million cases of stroke every year, of which about 40% require motor and cognitive rehabilitation, leaving 5 million new patients requiring treatment every year and more than 33 million chronic patients worldwide [1,2].

This massive incidence puts tremendous pressure on healthcare systems to satisfy the need for effective and sustainable solutions for rehabilitation post-stroke after hospital discharge.

User-friendly, portable, and low-cost systems could improve long-term recovery while allowing hospitals to reduce the length of outpatient treatment and its associated costs of infrastructure and staff while maximizing the treatment capacity of therapists.

Technology-based interventions should provide affordable and scalable science-based telerehabilitation to cope with this pressure.

In this Systematic Review of Systematic Reviews, seven reviews were selected, with 95 studies examined and a combined enrolment of 2.995 patients.

Most of these studies used Advanced technologies with AR- and VR-based technologies and Simple technologies with telerehabilitation (TR), mobile health applications (mHealth apps), assistive technologies (AT), and gait training (GT). Overall, the variability in interventions, study designs, participant demographics, and measured outcomes contributed to heterogeneity across the studies. Nevertheless, despite these differences, all seven reviews reached a unanimous conclusion, highlighting the ineffectiveness of the examined technologies in restoring lost upper limb function. This underscores the need for future research to establish rehabilitation intervention principles that can inform the development of targeted innovative technologies [31-37].

A central theme addressed in each review was the potential of technology-driven interventions to enhance at-home post-stroke rehabilitation. Collectively, these interventions were recognized for their ability to motivate survivors through interactive, user-friendly, engaging, and cost-effective tools. As reported, all the selected reviews did not mention or report any adherence to the principles of experience-dependent plasticity [8]. Recent literature suggests that stroke affects the entire brain and its network properties, making it a network disease. Therefore, stroke-related neurological deficits and their recovery depend on neural network interaction patterns and follow principles of network plasticity [100]. In addition, the observation that network interactions are correlated with current and future neurological function directly leads to whether their modulation through therapy might be feasible and clinically useful [101]. This evidence could open new frontiers for developing technology-based rehabilitation in post-stroke individuals.

The feasibility of modulating brain networks through technology-based therapy may depend on several factors inherently linked to neurorehabilitation principles. According to these principles, exposure to specific training experiences in a recovery pathway leads to an improvement in impairment precisely because of the activation of these mechanisms of neuronal plasticity and remodelling [8]. The following neurorehabilitation principles should guide the selection of training experiences and rehabilitation technologies to optimize effectiveness [16]: massed practice, spaced practice, dosage, task-specific practice, goal-oriented practice, variable practice, increasing difficulty, multisensory stimulation, rhythmic cueing, explicit feedback/knowledge of results, implicit feedback/knowledge of performance, modulate effector selection, action observation/embodied practice, motor imagery, and social interaction. On the contrary, interventions with online video monitoring and phone calls [31] do not always have a clear dosage, whereas some virtual training programs [32] discuss real-time feedback [102] or exercise progression and the increasing difficulty of the training [103].

The AR analysed in [33] combined the capabilities of specific sensors [104] and viewers [105] to provide, through specific games, exercises in both clinical and home settings. With neurorehabilitation principles such as feedback (game score, social interaction, etc.), variable practice and training intensity can be guaranteed after obtaining approval from patients and clinicians. AR systems, however, present some limits: they are not always user-friendly, portable and low-cost. They are, therefore, a good rehabilitation option but not always very convenient to use as an upper limb home solution.

Gelineau et al. [34] reported heterogeneity in exergames-based rehabilitation, including supervision and treatment dosage. Exergames are thus another example of good technology to promote recovery after stroke and good support for telerehabilitation, but they are still too generically investigated from a clinical and neurorehabilitative point of view.

Rintala et al. [35] and Szeto et al. [36] evaluated the effectiveness of mobile health applications (mHealth app) in stroke rehabilitation that provided visual and auditory feedback, but the dosage prescriptions were not always indicated. Their descriptions confirm a poor application of neuroscience principles.

Mobile apps, particularly when combined with in-person rehabilitation, offer advantages such as improved adherence and functional gains. However, additional research is warranted for two primary reasons. Firstly, the studies included here exhibit considerable variability. Secondly, there is a notable absence of consideration in the technological applications of the valuable principles that underlie traditional face-to-face therapy, including concepts like mass practice, task-specific practice, feedback, and goal-oriented practice, among others [9].

In VR-based telerehabilitation [37], some systems provide synchronous supervision of the patient, while others provide only asynchronous setting options; activity feedback and patient supervision can be ensured in each case. However, the dosage prescription of these telerehabilitation systems remains to be better explored.

Implications for clinical practise and future research

This review indicated that the field of technology-based rehabilitation is still fragmented due to poor evidence achieved in terms of efficacy. This is probably due to the high heterogeneity of the experimental studies. We mapped various study designs, outcomes, and quality levels that demonstrate only the potential to assist with stroke recovery and augment face-to-face rehabilitation. When developing a technology-based rehabilitation program, it is crucial to carefully plan and link all the relevant actors, user-driven design guidelines, and principles of neuroscience.

With this potential, there is a need for further research to understand better the impact of technology interventions on varying types of stroke deficits and related outcomes, both alone and in combination with traditional rehabilitation.

This field of research could benefit from standardized protocols provided to patients, enabling comparison and interpretation to discover evidence currently missing [16].

Limitations

Data sources were drawn from PubMed, Web of Science, Scopus and Embase databases and Google Scholar. Even if The Population, Intervention, Comparison, Outcome, Study Design framework-PICOS was used to define the inclusion criteria, the combination of key terms to target the population and the specific technology-based intervention could have omitted some results from the search.

Conclusions

This review pooled the findings of seven systematic reviews. It found heterogeneity of interventions and measures, but the commonality of no clear or direct evidence of impact on recovery of function has been underlined. Advanced and simple technologies used for stroke rehabilitation allow for overcoming financial, physical, and attitudinal barriers while providing engaging, specific, low-cost exercises with constant feedback and supervision. These technologies serve as a valuable enhancement to traditional rehabilitation methods, particularly for the upper limb [106]. Unfortunately, demonstrating the efficacy of such interventions for restoring function after a stroke is still a challenge. Recent research indicated that the recovery of brain networks is essential for regaining motor and cognitive function after a stroke. This recovery can be facilitated through advanced non-invasive technologies such as brain stimulation techniques like TMS and tDCs [107,108]. Combining these technologies with interventions that follow neurorehabilitation principles may be more effective in promoting the recovery and retention of motor and cognitive functions after a stroke.

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Conflicts of Interest

None declared.

Abbreviations

JMIR: Journal of Medical Internet Research
RCT: randomized controlled trial

Multimedia Appendix 1

References

1. Wu D, Zhang H, Leng Y, Li K, Li S, Lo WLA. A bibliometric analysis of telerehabilitation services for patients with stroke. Front Neurol 2023 Jan;13:1026867 [FREE Full text] [doi: 10.3389/fneur.2022.1026867] [Medline: 36698904]
2. Moradi V, Babaee T, Esfandiari E, Lim SB, Kordi R. Telework and telerehabilitation programs for workers with a stroke during the COVID-19 pandemic: a commentary. World 2021 Jan;68(1):77-80 [FREE Full text] [doi: 10.3233/WOR-203356] [Medline: 33427710]
3. National Institute of Neurological Disorders and Stroke. Post-stroke rehabilitation. NINDS Publications. 2020. URL: https://catalog.ninds.nih.gov/publications/post-stroke-rehabilitation [accessed 2023-06-16]
4. Rozevink SG, Van der Sluis CK, Garzo A, Keller T, Hijmans JM. HoMEcare aRm rehabiLItatioN (MERLIN): telerehabilitation using an unactuated device based on serious games improves the upper limb function in chronic stroke. J NeuroEngineering Rehabil 2021 Mar;18(1):1-12 [FREE Full text] [doi: 10.1186/s12984-021-00841-3] [Medline: 33726801]
5. Virani SS, Alonso A, Benjamin EJ, Bittencourt MS, Callaway CW, Carson AP, et al. Heart disease and stroke statistics—2020 update: a report from the American Heart Association. Circulation 2020 Jan;141(9):e139-e596 [FREE Full text] [doi: 10.1161/CIR.0000000000000757] [Medline: 31992061]
6. Zeiler SR. Should we care about early post-stroke rehabilitation? Not yet, but soon. Curr Neurol Neurosci Rep 2019;19(3):13 [doi: 10.1007/s11910-019-0927-x] [Medline: 30788609]
7. Ostrowska PM, Śliwiński M, Studnicki R, Hansdorfer-Korzon R. Telerehabilitation of post-stroke patients as a therapeutic solution in the era of the COVID-19 pandemic. Healthcare 2021;9(6):654 [FREE Full text] [doi: 10.3390/healthcare9060654] [Medline: 34072939]
8. Kleim JA, Jones TA. Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. J Speech Lang Hear Res 2008 Feb;51(1):S225-239 [doi: 10.1044/1092-4388(2008/018)] [Medline: 18230848]
9. Maier M, Rubio Ballester B, Verschure PFMJ. Principles of neurorehabilitation after stroke based on motor learning and brain plasticity mechanisms. Front Syst Neurosci 2019 Dec 17;13:74 [FREE Full text] [doi: 10.3389/fnsys.2019.00074] [Medline: 31920570]
10. Platz T. Clinical pathways in stroke rehabilitation: evidence-based clinical practice recommendations. Greifswald, Germany: Springer; 2021. ISBN:9783030585044
11. Cramer SC, Dodakian L, Le V, See J, Augsburger R, McKenzie A et al. Efficacy of home-based telerehabilitation vs in-clinic therapy for adults after stroke: a randomized clinical trial. JAMA Neurol 2019 June;76(9):1079-1087 [FREE Full text] [doi: 10.1001/jamaneurol.2019.1604] [Medline: 31233135]

12. Rajsic S, Gothe H, Borba HH, Sroczynski G, Vujicic J, Toell T, et al. Economic burden of stroke: a systematic review on post-stroke care. Eur J Health Econ 2019;20:107-134 [FREE Full text] [doi: 10.1007/s10198-018-0984-0] [Medline: 29909569]
13. Forman CR, Nielsen JB, Lorentzen J. Neuroplasticity at home: improving home-based motor learning through technological solutions. A review. Front Rehabil Sci 2021 Dec 21;2:789165 [FREE Full text] [doi: 10.3389/fresc.2021.789165] [Medline: 36188793]
14. Neibling BA, Jackson SM, Hayward KS, Barker RN. Perseverance with technology-facilitated home-based upper limb practice after stroke: a systematic mixed studies review. J NeuroEngineering Rehabil 2021;18:1-26 [FREE Full text] [doi: 10.1186/s12984-021-00819-1] [Medline: 33627126]
15. 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 Mar;123:11-22 [doi: 10.1016/j.ijmedinf.2018.12.001] [Medline: 30654899]
16. Maier M, Rubio Ballester B, Duff A, Duarte Oller E, Verschure PFMJ. Effect of specific over nonspecific VR-based rehabilitation on poststroke motor recovery: a systematic meta-analysis. Neurorehabil Neural Repair 2019 Feb;33(2):112-129 [FREE Full text] [doi: 10.1177/1545968318820169] [Medline: 30700224]
17. Ferreira B, Menezes P. Gamifying motor rehabilitation therapies: challenges and opportunities of immersive technologies. Information 2020 Feb;11(2):88 [FREE Full text] [doi: 10.3390/info11020088]
18. Selamat SNS, Che Me R, Ahmad Ainuddin H, Salim MS, Ramli HR, Romli MH. The application of technological intervention for stroke rehabilitation in Southeast Asia: a scoping review with stakeholders' consultation. Front Public Health 2022 Feb;9:783565 [FREE Full text][doi: 10.3389/fpubh.2021.783565] [Medline: 35198531]
19. Laver KE, Lange B, George S, Deutsch JE, Saposnik G, Crotty M. Virtual reality for stroke rehabilitation. Cochrane Database Syst Rev 2017 Nov;11 [FREE Full text] [doi: 10.1002/14651858.CD008349.pub4] [Medline: 29156493]
20. Gorman C, Gustafsson LA-O. The use of augmented reality for rehabilitation after stroke: a narrative review. Disabil Rehabil Assist Technol 2022;17(4):409-417 [FREE Full text] [doi: 10.1080/17483107.2020.1791264] [Medline: 32663112]
21. Sousa AS, Moreira J, Silva C, Mesquita I, Macedo R, Silva A et al. Usability of functional electrical stimulation in upper limb rehabilitation in post-stroke patients: a narrative review. Sensors 2022 Feb;22(4):1409 [FREE Full text] [doi: 10.3390/s22041409] [Medline: 35214311]
22. Peretti A, Amenta F, Tayebati SK, Nittari G, Mahdi SS. Telerehabilitation: review of the state-of-the-art and areas of application. JMIR Rehabil Assist Technol 2017;4(2):e7511 [FREE Full text] [doi: 10.2196/rehab.7511] [Medline: 28733271]
23. Chen J, Sun D, Zhang S, Shi Y, Qiao F, Zhou Y et al. Effects of home-based telerehabilitation in patients with stroke: a randomized controlled trial. Neurology 2020;95(17):e2318-e2330 [doi: 10.1212/WNL.0000000000010821] [Medline: 32999058]
24. Nikolaev VA, Nikolaev AA. Recent trends in telerehabilitation of stroke patients: a narrative review. NeuroRehabil 2022;51(1):1-22 [FREE Full text] [doi: 10.3233/NRE-210330] [Medline: 35527574]
25. Morse H, Biggart L, Pomeroy V, Rossit S. Exploring perspectives from stroke survivors, carers and clinicians on virtual reality as a precursor to using telerehabilitation for spatial neglect post-stroke. Neuropsychol Rehabil 2022 Jun;32(5):707-731 [doi: 10.1080/09602011.2020.1819827] [Medline: 32942950]
26. Zhou X, Du M, Zhou L. Use of mobile applications in post-stroke rehabilitation: a

systematic review. Top Stroke Rehabil 2018;25(7):489-499 [FREE Full text] [doi: 10.1080/10749357.2018.1482446] [Medline: 30209991]
27. Chung BPH, Chiang WKH, Lau H, Lau TFO, Lai CWK, Sit CSY, et al. Pilot study on comparisons between the effectiveness of mobile video guided and paper-based home exercise programs on improving exercise adherence, self-efficacy for exercise and functional outcomes of patients with stroke with 3-month follow-up: a single-blind randomized controlled trial. Hong Kong Physiother J 2020;40(01):63-73 [FREE Full text] [doi: 10.1142/S1013702520500079] [Medline: 32489241]
28. Grau-Pellicer M, Lalanza J, Jovell-Fernández E, Capdevila L. Impact of mHealth technology on adherence to healthy PA after stroke: a randomized study. Top Stroke Rehabil 2020;27(5):354-368 [FREE Full text][doi: 10.1080/10749357.2019.1691816] [Medline: 31790639]
29. Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann Intern Med 2009;15(4):264-269 [FREE Full text] [doi: 10.7326/0003-4819-151-4-200908180-00135] [Medline: 19622511]
30. Shea BJ, Reeves BC, Wells G, Thuku M, Hamel C, Moran J et al. AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. BMJ 2017;358:j4008 [FREE Full text] [doi: 10.1136/bmj.j4008] [Medline: 28935701]
31. Rintala A, Päivärinne V, Hakala S, Paltamaa J, Heinonen A, Karvanen J et al. Effectiveness of technology-based distance physical rehabilitation interventions for improving physical functioning in stroke: a systematic review and meta-analysis of randomized controlled trials. Arch Phys Med Rehabil 2019 Jul;100(7):1339-1358 [FREE Full text] [doi: 10.1016/j.apmr.2018.11.007] [Medline: 30529323]
32. Parker J, Powell L, Mawson S. Effectiveness of upper limb wearable technology for improving activity and participation in adult stroke survivors: systematic review. J Med Internet Res 2020 Jan 8;22(1):e15981 [FREE Full text] [doi: 10.2196/15981] [Medline: 31913131]
33. Phan HL, Le TH, Lim JM, Hwang CH, Koo KI. Effectiveness of augmented reality in stroke rehabilitation: a meta-analysis. Appl Sci 2022;12(4):1848 [FREE Full text] [doi: 10.3390/app12041848]
34. Gelineau A, Perrochon A, Robin L, Daviet JC, Mandigout S. Measured and perceived effects of upper limb home-based exergaming interventions on activity after stroke: a systematic review and meta-analysis. Int J Environ Res Public Health 2022 Jul 26;19(15):9112 [FREE Full text] [doi: 10.3390/ijerph19159112] [Medline: 35897472]
35. Rintala A, Kossi O, Bonnechère B, Evers L, Printemps E, Feys P. Mobile health applications for improving physical function, physical activity, and quality of life in stroke survivors: a systematic review. Disabil Rehabil 2023 Dec;45(24):4001-4015 [FREE Full text] [doi: 10.1080/09638288.2022.2140844] [Medline: 36325613]
36. Szeto SG, Wan H, Alavinia M, Dukelow S, MacNeill H. Effect of mobile application types on stroke rehabilitation: a systematic review. J Neuroeng Rehabil 2023;20(1):1-18 [FREE Full text] [doi: 10.1186/s12984-023-01124-9] [Medline: 36694257]
37. Hao J, Pu Y, Chen Z, Siu KC. Effects of virtual reality-based telerehabilitation for stroke patients: a systematic review and meta-analysis of randomized controlled trials. J Stroke Cerebrovasc Dis 2023 Mar;32(3):106960 [doi: 10.1016/j.jstrokecerebrovasdis.2022.106960] [Medline: 36586244]
38. Raghavendra P, Bornman J, Granlund M, Björck-Åkesson E. The World Health Organization's international classification of functioning, disability and health:

implications for clinical and research practice in the field of augmentative and alternative communication. Augment Altern Commun 2007;23(4):349-361 [FREE Full text] [doi: 10.1080/07434610701650928] [Medline: 19925317]
39. Jette AM, Haley SM, Coster WJ, Kooyoomjian JT, Levenson S, Heeren T et al. Late life function and disability instrument: I. development and evaluation of the disability component. J Gerontol A Biol Sci Med Sci 2002;57(4):M209-M216 [FREE Full text] [doi: 10.1093/gerona/57.4.M209] [Medline: 11909885]
40. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient1, a method for evaluation of physical performance. Scand J Rehabil Med 1975;7(1):13-31 [FREE Full text] [doi: 10.2340/1650197771331] [Medline: 1135616]
41. Wolf SL, Catlin PA, Ellis M, Archer AL, Morgan B, Piacentino A. Assessing Wolf motor function test as outcome measure for research in patients after stroke. Stroke 2001 Jul;32(7):1635-1639 [FREE Full text] [doi: 10.1161/01.STR.32.7.1635] [Medline: 11441212]
42. Michimata A, Kondo T, Suzukamo Y, Chiba M, Izumi SI. The manual function test: norms for 20-to 90-year-olds and effects of age, gender, and hand dominance on dexterity. Tohoku J Exp Med 2008;214(3):257-267 [FREE Full text] [doi: 10.1620/tjem.214.257] [Medline: 18323695]
43. Mathiowetz V, Volland G, Kashman N, Weber K. Adult norms for the box and block test of manual dexterity. Am J Occup Ther 1985;39(6):386-391 [FREE Full text] [doi: 10.5014/ajot.39.6.386] [Medline: 3160243]
44. Yozbatiran N, Der-Yeghiaian L, Cramer SC. A standardized approach to performing the action research arm test. Neurorehabil Neural Repair 2008;22(1):78-90 [FREE Full text] [doi: 10.1177/1545968307305353] [Medline: 17704352]
45. Barreca SR, Stratford PW, Lambert CL, Masters LM, Streiner DL. Test-retest reliability, validity, and sensitivity of the Chedoke arm and hand activity inventory: a new measure of upper-limb function for survivors of stroke. Arch Phys Med Rehabil 2005;86(8):1616-1622 [FREE Full text] [doi: 10.1016/j.apmr.2005.03.017] [Medline: 16084816]
46. Jebsen RH, Taylor N, Trieschmann R, Trotter M, Howard L. An objective and standardized test of hand function. Arch phys med Rehabil 1969;50(6):311–319 [PMID:5788487]
47. Uswatte G, Taub E, Morris D, Vignolo M, McCulloch K. Reliability and validity of the upper-extremity motor activity log-14 for measuring real-world arm use. Stroke 2005;36(11):2493-2496 [FREE Full text] [doi: 10.1161/01.STR.0000185928.90848.2e] [Medline: 16224078]
48. Carroll D. A quantitative test of upper extremity function. J Chronic Dis 1965;18(5):479-491 [FREE Full text] [doi: 10.1016/0021-9681(65)90030-5] [Medline: 14293031]
49. Jester A, Harth A, Wind G, Germann G, Sauerbier M. Disabilities of the arm, shoulder and hand (DASH) questionnaire: determining functional activity profiles in patients with upper extremity disorders. J Hand Surg Br 2005;30(1):23-28 [FREE Full text] [doi: 10.1016/J.JHSB.2004.08.008] [Medline: 15620487]
50. Gummesson C, Ward MM, Atroshi I. The shortened disabilities of the arm, shoulder and hand questionnaire (QuickDASH): validity and reliability based on responses within the full-length DASH. BMC Musculoskelet Disord 2006;7(1):1-7 [FREE Full text][doi: 10.1186/1471-2474-7-44] [Medline: 16709254]
51. Dunning, K. Ashworth spasticity scale (and modified version). In: Kreutzer JS, DeLuca J, Caplan B, editors. Encyclopedia of clinical neuropsychology. New York: Springer; 2011. p. 254-255.

52. Roorda LD, Houwink A, Smits W, Molenaar IW, Geurts AC. Measuring upper limb capacity in poststroke patients: development, fit of the monotone homogeneity model, unidimensionality, fit of the double monotonicity model, differential item functioning, internal consistency, and feasibility of the stroke upper limb capacity scale, SULCS. Arch Phys Med Rehabil 2011;92(2):214-227 [FREE Full text] [doi: 10.1016/j.apmr.2010.10.034] [Medline: 21272717]
53. Kellor M, Frost J, Silberberg N, Iversen I, Cummings R. Hand strength and dexterity. Am J Occup Ther 1971 Mar;25(2):77-83 [PMID:5551515]
54. Mahoney FI, Barthel DW. Functional evaluation: the Barthel index: a simple index of independence useful in scoring improvement in the rehabilitation of the chronically ill. Md State Med J 1965 Feb;14:61-65 [PMID:14258950]
55. Merker B, Podell K. Grooved pegboard test. In: Kreutzer JS, DeLuca J, Caplan B, editors. Encyclopedia of clinical neuropsychology. New York: Springer; 2011.
56. Tiffin J, Asher EJ. The purdue pegboard: norms and studies of reliability and validity. J Appl Psychol 1948;32(3):234-247 [doi: 10.1037/h0061266]
57. Carswell A, McColl MA, Baptiste S, Law M, Polatajko H, Pollock N. The Canadian occupational performance measure: a research and clinical literature review. Can J Occup Ther 2004 Oct;71(4):210-222 [FREE Full text] [doi: 10.1177/000841740407100406] [Medline: 15586853]
58. Penta M, Thonnard J-L, Tesio L. ABILHAND: a Rasch-built measure of manual ability. Arch Phys Med Rehabil 1998;79(9):1038-1042 [FREE Full text] [doi: 10.1016/S0003-9993(98)90167-8] [Medline: 9749680]
59. Roman NA, Miclaus RS, Nicolau C, Sechel G. Customized manual muscle testing for post-stroke upper extremity assessment. Brain Sci 2022 Mar 28;12(4):457 [FREE Full text] [doi: 10.3390/brainsci12040457] [Medline: 35447988]
60. Huang CY, Lin GH, Huang YJ, Song CY, Lee YC, How MJ, Chen YM, Hsueh IP, Chen MH, Hsieh CL. Improving the utility of the Brunnstrom recovery stages in patients with stroke: validation and quantification. Medicine (Baltimore) 2016 Aug;95(31):e4508 [FREE Full text] [doi: 10.1097/MD.0000000000004508] [Medline: 27495103]
61. Gajdosik RL, Bohannon RW. Clinical measurement of range of motion: review of goniometry emphasizing reliability and validity. Phys Ther 1987;67(12):1867-1872 [FREE Full text] [doi: 10.1093/ptj/67.12.1867] [Medline: 3685114]
62. Norkin CC, White DJ. Measurement of Joint Motion: A Guide to Goniometry. 5th edition. Philadelphia, Pa: FA Davis Company; 2016. ISBN:9780803645660
63. Park J, Xu D. Multi-finger interaction and synergies in finger flexion and extension force production. Front Hum Neurosci 2017 Jun 19;11:318. [FREE Full text] [doi: 10.3389/fnhum.2017.00318] [Medline: 28674489]
64. Demeurisse G, Dermol O, Robaye E. Motor evaluation in vascular hemiplegia. Eur Neurol 1980;19(6):382-389. [doi: 10.1159/000115178] [Medline: 7439211]
65. Dean CM, Mackey FM. Motor assessment scale scores as a measure of rehabilitation outcome following stroke. Aust J Physiother 1992;38(1):31-35 [doi: 10.1016/S0004-9514(14)60548-1] [Medline: 25025514]
66. Collen FM, Wade DT, Robb GF, Bradshaw CM. The Rivermead mobility index: a further development of the Rivermead motor assessment. Int Disabil Stud 1991 Apr-Jun;13(2):50-54 [doi: 10.3109/03790799109166684] [Medline: 1836787]
67. Bohannon RW. Reference values for the timed up and go test: a descriptive meta-analysis. J Geriatr Phys Ther 2006;29(2):64-68 [FREE Full text] [doi: 10.1519/00139143-200608000-00004] [Medline: 16914068]
68. Tutus N, Ozdemir F. The effects of gastrocnemius muscle spasticity on gait symmetry

and trunk control in chronic stroke patients. Gait and Posture 2023;105:45-50 [doi: 10.1016/j.gaitpost.2023.07.004] [Medline: 37480819]
69. Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. Can J Public Health 1992 Jul-Aug:83 Suppl 2:S7-11 [Medline: 1468055]
70. Potter K, Brandfass K. The mini-balance evaluation systems test (mini-BESTest). J Physiother 2015 Oct;61(4):225 [doi: 10.1016/j.jphys.2015.04.002] [Medline: 26044345]
71. Gorman SL, Radtka S, Melnick ME, Abrams GM, Byl NN. Development and validation of the function in sitting test in adults with acute stroke. J Neurol Phys Ther 2010;34(3):150-160 [FREE Full text] [doi: 10.1097/NPT.0b013e3181f0065f] [Medline: 20716989]
72. Verheyden G, Mertin J, Preger R, Kiekens C, Weerdt WD. The trunk impairment scale: a new tool to measure motor impairment of the trunk after stroke. Clin Rehabil 2004;18:326-334 [doi: 10.1191/0269215504cr733oa] [Medline: 15137564]
73. Benaim C, Pérennou DA, Villy J, Rousseaux M, Pelissier JY. Validation of a standardized assessment of postural control in stroke patients: the postural assessment scale for stroke patients (PASS). Stroke 1999 Sep;30(9):1862-1868 [doi: 10.1161/01.str.30.9.1862] [Medline: 10471437]
74. Bushnik T. Brunel balance assessment. In: Kreutzer JS, DeLuca J, Caplan B, editors. Encyclopedia of clinical neuropsychology. New York: Springer; 2011.
75. Tinetti ME, Williams TF, Mayewski R. Fall risk index for elderly patients based on number of chronic disabilities. Am J Med 1986 Mar;80(3):429-434 [doi: 10.1016/0002-9343(86)90717-5] [Medline: 3953620]
76. Hill KD, Schwarz JA, Kalogeropoulos AJ, Gibson SJ. Fear of falling revisited. Arch Phys Med Rehabil 1996 Oct;77(10):1025-1029 [doi: 10.1037/t77971-000] [Medline: 8857881]
77. Moore JL, Potter K, Blankshain K, Kaplan SL, O'Dwyer LC, Sullivan JE. A core set of outcome measures for adults with neurologic conditions undergoing rehabilitation: a clinical practice guideline. J Neurol Phys Ther 2018 Jul;42(3):174-220 [doi: 10.1097/NPT.0000000000000229] [Medline: 29901487]
78. Harada N, Chiu V, Stewart AL. Mobility-related function in older adults: assessment with a 6-minute walk test. Arch Phys Med Rehabil 1999;80(7):837-841 [doi: 10.1016/s0003-9993(99)90236-8] [Medline: 10414771]
79. Butland RJ, Pang J, Gross ER, Woodcock AA, Geddes DM. Two-, six-, and 12-minute walking tests in respiratory disease. Br Med J (Clin Res Ed) 1982 May 29;284(6329):1607-1608 [doi: 10.1136/bmj.284.6329.1607] [Medline: 6805625]
80. Mehrholz J, Wagner K, Rutte K, Meiner D, Pohl M. Predictive validity and responsiveness of the functional ambulation category in hemiparetic patients after stroke. Arch Phys Med Rehabil 2007 Oct;88(10):1314-1319 [doi: 10.1016/j.apmr.2007.06.764] [Medline: 17908575]
81. Tsang RCC, Chau RMW, Cheuk THW, Cheung BSP, Fung DMY, Ho EYL, et al. The measurement properties of modified Rivermead mobility index and modified functional ambulation classification as outcome measures for Chinese stroke patients. Physiother Theory Pract 2014 Jul;30(5):353-359 [FREE Full text] [doi: 10.3109/09593985.2013.876563] [Medline: 24400683]
82. Duncan PW, Wallace D, Lai SM, Johnson D, Embretson S, Laster LJ. The stroke impact scale version 2.0: evaluation of reliability, validity, and sensitivity to change. Stroke 1999 Oct;30(10):2131-2140 [FREE Full text] [doi: 10.1161/01.str.30.10.2131] [Medline:

10512918]
83. Sousa P, Gaspar P, Vaz DC, Gonzaga S, Dixe MA. Measuring health-promoting behaviors: cross-cultural validation of the health-promoting lifestyle profile-II. Int J Nurs Knowl 2015 Apr;26(2):54-61 [doi: 10.1111/2047-3095.12065] [Medline: 25389054]
84. Kwah LK, Diong J. National institutes of health stroke scale (NIHSS). J Physiother 2014 Mar;60(1):61 [doi: 10.1016/j.jphys.2013.12.012] [Medline: 24856948]
85. Reitzen SD, Babb JS, Lalwani AK. Significance and reliability of the House-Brackmann grading system for regional facial nerve function. Otolaryngol Head Neck Surg 2009 Feb;140(2):154-158 [doi: 10.1016/j.otohns.2008.11.021] [Medline: 19201280]
86. Wang YC, Chang PF, Chen YM, Lee YC, Huang SL, Chen MH, Hsieh CL. Comparison of responsiveness of the Barthel index and modified Barthel index in patients with stroke. Disabil Rehabil 2023 Mar;45(6):1097-1102 [FREE Full text] [doi: 10.1080/09638288.2022.2055166] [Medline: 35357990]
87. Saver JL, Chaisinanunkul N, Campbell BC, Grotta JC, Hill MD, Khatri P, et al. Standardized nomenclature for modified Rankin scale global disability outcomes: consensus recommendations from stroke therapy academic industry roundtable XI. Stroke 2021 Aug;52(9):3054-3062 [FREE Full text] [doi: 10.1161/STROKEAHA.121.034480] [Medline: 34320814]
88. Maritz R, Tennant A, Fellinghauer C, Stucki G, Prodinger B. The functional independence measure 18-item version can be reported as a unidimensional interval-scaled metric: internal construct validity revisited. J Rehabil Med 2019 Mar 13;51(3):193-200 [FREE Full text] [doi: 10.2340/16501977-2525] [Medline: 30843597]
89. Nouri FM, Lincoln NB. An extended activities of daily living scale for stroke patients. Clin Rehabil 1987;1(4):301-305 [doi: 10.1177/026921558700100409]
90. Goffredo M, Mazzoleni S, Gison A, Infarinato F, Pournajaf S, Galafate D, et al. Kinematic parameters for tracking patient progress during upper limb robot-assisted rehabilitation: an observational study on subacute stroke subjects. Appl Bionics Biomech 2019 Oct 21;2019:4251089 [FREE Full text] [doi: 10.1155/2019/4251089] [Medline: 31772604]
91. Williams LS, Weinberger M, Harris LE, Clark DO, Biller J. Development of a stroke-specific quality of life scale. Stroke 1999 Jul;30(7):1362-1369 [FREE Full text] [doi: 10.1161/01.str.30.7.1362] [Medline: 10390308]
92. EuroQol Group. EuroQol-a new facility for the measurement of health-related quality of life. Health Policy 1990 Dec;16(3):199-208 [doi: 10.1016/0168-8510(90)90421-9] [Medline: 10109801]
93. Morisky DE, Green LW, Levine DM. Concurrent and predictive validity of a self-reported measure of medication adherence. Med Care 1986 Jan;24(1):67-74 [doi: 10.1097/00005650-198601000-00007] [Medline: 3945130]
94. Huang KL, Liu TY, Huang YC, Leong CP, Lin WC, Pong YP. Functional outcome in acute stroke patients with oropharyngeal dysphagia after swallowing therapy. J Stroke Cerebrovasc Dis 2014 Nov-Dec;23(10):2547-2553 [doi: 10.1016/j.jstrokecerebrovasdis.2014.05.031] [Medline: 25245482]
95. Everton LF, Benfield JK, Michou E, Hamdy S, Bath PM. Reliability of the penetration-aspiration scale and temporal and clearance measures in poststroke dysphagia: videofluoroscopic analysis from the swallowing treatment using electrical pharyngeal stimulation trial. J Speech Lang Hear Res 2022 Mar 8;65(3):858-868 [doi: 10.1044/2021_JSLHR-21-00083] [Medline: 35114799]
96. Zigmond AS, Snaith RP. The hospital anxiety and depression scale. Acta Psychiatr Scand 1983 Jun;67(6):361-370 [doi: 10.1111/j.1600-0447.1983.tb09716.x] [Medline:

6880820]
97. Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, et al. The Montreal cognitive assessment, MoCA: a brief screening tool for mild cognitive impairment. J Am Geriatr Soc 2005 Apr;53(4):695-699 [FREE Full text] [doi: 10.1111/j.1532-5415.2005.53221.x] [Medline: 15817019]
98. Wilson BA, Greenfield E, Clare L, et al. The Rivermead Behavioural Memory Test – Third Edition (RBMT-3). London, UK: Pearson Clinical Assessment; 2008.
99. Daly JJ, McCabe JP, Holcomb J, Monkiewicz M, Gansen J, Pundik S. Long-dose intensive therapy is necessary for strong, clinically significant, upper limb functional gains and retained gains in severe/moderate chronic stroke. Neurorehabil Neural Repair 2019 Jul;33(7):523-537 [FREE Full text] [doi: 10.1177/1545968319846120] [Medline: 31131743]
100. Guggisberg AG, Koch PJ, Hummel FC, Buetefisch CM. Brain networks and their relevance for stroke rehabilitation. Clin Neurophysiol 2019 Jul;130(7):1098-1124 [doi: 10.1016/j.clinph.2019.04.004] [Medline: 31082786]
101. Coscia M, Wessel MJ, Chaudary U, Millán JDR, Micera S, Guggisberg A, et al. Neurotechnology-aided interventions for upper limb motor rehabilitation in severe chronic stroke. Brain 2019;142(8):2182-2197 [FREE Full text] [doi: 10.1093/brain/awz181] [Medline: 31257411]
102. Rubio Ballester B, Nirme J, Camacho I, Duarte E, Rodríguez S, Cuxart A, et al. Domiciliary VR-based therapy for functional recovery and cortical reorganization: randomized controlled trial in participants at the chronic stage post stroke. JMIR Serious Games 2017 Aug 7;5(3):e15 [FREE Full text] [doi: 10.2196/games.6773] [Medline: 28784593]
103. Nijenhuis SM, Prange-Lasonder GB, Stienen AH, Rietman JS, Buurke JH. Effects of training with a passive hand orthosis and games at home in chronic stroke: a pilot randomised controlled trial. Clin Rehabil 2016;31:207-216 [FREE Full text] [doi: 10.1177/0269215516629722] [Medline: 26869596]
104. Assis GA, Correa AG, Martins MB, Pedrozo WG, de Deus Lopes R. An augmented reality system for upper-limb post stroke motor rehabilitation: a feasibility study. Disabil Rehabil Assist Technol 2016 Aug;11(6):521-528 [doi: 10.3109/17483107.2014.979330] [Medline: 25367103]
105. Bank PJM, Cidota MA, Ouwehand PEW, Lukosch SG. Patient-tailored augmented reality games for assessing upper extremity motor impairments in Parkinson's disease and stroke. J Med Syst 2018 Oct 30;42(12):246. [FREE Full text] [doi: 10.1007/s10916-018-1100-9] [Medline: 30374695]
106. Lloréns R, Noé E, Colomer C, Alcañiz M. Effectiveness, usability, and cost-benefit of a virtual reality–based telerehabilitation program for balance recovery after stroke: a randomized controlled trial. Arch Phys Med Rehabil 2015;96(3):418-425 [FREE Full text] [doi: 10.1016/j.apmr.2014.10.019] [Medline: 25448245]
107. Keser Z, Ikramuddin S, Shekhar S, Feng W. Neuromodulation for post-stroke motor recovery: a narrative review of invasive of invasive and non-invasive tools. Curr Neurol Neurosci Rep 2023 Dec;23(12):893-906 [doi: 10.1007/s11910-023-01319-6] [Medline: 38015351]
108. Adeyemo BO, Simis M, Macea DD, Fregni F. Systematic review of parameters of stimulation, clinical trial design characteristics, and motor outcomes in non-invasive brain stimulation in stroke. Front Psychiatry 2012 Nov 12;3:88 [FREE Full text] [doi: 10.3389/fpsyt.2012.00088] [Medline: 23162477]

Supplementary Files

Multimedia Appendixes

Methodological quality of 7 studies based on AMSTAR2 criteria.
URL: http://asset.jmir.pub/assets/403cb0a680f6e50aad02596424e0a765.docx

Characteristics of the reviewed studies .
URL: http://asset.jmir.pub/assets/9ca1ab23c952d7d966c798d1f4a0bd2e.docx