

Effect of Home-based Virtual Reality Training on Upper Extremity Recovery in Patients with Stroke: Systematic Review

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Abstract

Background: Stroke is a leading cause of long-term disability, often resulting in upper extremity dysfunction. Traditional rehabilitation methods often face challenges such as limited patient access to resources and lack of sustained motivation. Home-based virtual reality (VR) training is gaining traction as an innovative, sustainable and interactive alternative. However, the effectiveness of home-based VR, specifically for upper extremity recovery in patients with stroke, remains insufficiently explored.

Objective: This systematic review aims to synthesize existing evidence to evaluate the impact of home-based VR interventions on upper extremity function recovery in patients with stroke.

Methods: A comprehensive literature search was conducted across PubMed, Web of Science, Scopus, and CINAHL Ultimate databases, targeting English-language randomized controlled trials (RCTs) published up to June 30, 2024. Two independent reviewers screened articles based on predefined inclusion criteria, focusing on studies involving patients with stroke with upper extremity dysfunction who received home-based VR training. Data extraction and risk of bias assessment were performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

Results: Eight RCTs with 392 participants were included. This review shows that home-based VR training positively affects upper extremity function recovery in patients with stroke, especially in motor control improvement. Customized VR systems were more effective than commercial VR systems in patients with moderate to severe disorders. Although studies generally showed positive results, differences in intervention protocols, small sample sizes, and the lack of long-term follow-up limited the generalizability of results. The effectiveness of VR therapy also varied based on the VR system type, intervention intensity, and the functional level of patients.

Conclusions: Home-based VR training is a viable and effective way to enhance upper extremity rehabilitation for stroke patients, especially when using customized systems. However, heterogeneity in study design, differences in outcome measures, and limited long-term follow-up data affect the reliability of the current conclusions. Future studies should include larger, standardized RCTs with long-term follow-up to assess their continued effects. In addition, exploring the introduction of immersive VR in home-based rehabilitation and its cost-effectiveness comparison with traditional methods can help optimize its application and patient rehabilitation outcomes. Clinical Trial: PROSPERO CRD42024526650; https://www.crd.york.ac.uk/prospéro/display_record.php?ID=CRD42024526650

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Original Manuscript

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ABSTRACT

Background: Stroke is a leading cause of long-term disability, often resulting in upper extremity dysfunction. Traditional rehabilitation methods often face challenges such as limited patient access to resources and lack of sustained motivation. Home-based virtual reality (VR) training is gaining traction as an innovative, sustainable and interactive alternative. However, the effect of home-based VR, specifically for upper extremity recovery in patients with stroke, remains insufficiently explored.

Objective: This systematic review aims to synthesize existing evidence to evaluate the impact of home-based VR interventions on upper extremity function recovery in patients with stroke.

Methods: This systematic review followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). A comprehensive literature search was conducted across PubMed, Web of Science, Scopus, and CINAHL Ultimate databases, targeting English-language randomized controlled trials (RCTs) published up to June 30, 2024. Eligible studies involved stroke patients with upper extremity dysfunction who received home-based VR interventions. Data extraction was performed by two independent reviewers, and study quality was assessed using the PEDro scale. Due to heterogeneity in study designs and outcome measures, a narrative synthesis was performed instead of a meta-analysis.

Results: Eight RCTs with 392 participants were included. This review shows that home-based VR training positively affects upper extremity function recovery in patients with stroke, especially in motor control improvement. Customized VR systems were more effective than commercial VR systems in patients with moderate to severe disorders. Although studies generally showed positive results, differences in intervention protocols and small sample sizes limited the validity of results. The effect of VR therapy also varied based on the VR system type, intervention intensity, and the functional level of patients.

Conclusions: This systematic review shows that home-based VR training has a positive impact on upper extremity rehabilitation for stroke patients, particularly in those with varying degrees of dysfunction. However, heterogeneity in study design and differences in outcome measures affect the reliability of the current conclusions. Future studies should include larger, standardized RCTs with long-term follow-up to assess their continued effects. Future research should explore how VR technology can be integrated into comprehensive rehabilitation programs, focusing on patient-centered approaches that incorporate sustainable, personalized technology and support services to optimize recovery outcomes.

Trial Registration:

PROSPERO

CRD42024526650;

https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42024526650

Keywords:

Stroke; Upper extremity; Virtual reality; Home-based

INTRODUCTION

Stroke is a leading cause of disability worldwide, frequently resulting in upper extremity impairments that significantly limit daily function [1]. Studies have shown that approximately 80% of stroke survivors experience upper extremity dysfunction, severely limiting their ability to perform daily activities independently and affecting their overall health [2]. Traditional rehabilitation approaches, such as physical therapy and occupational therapy, have been the mainstay of treatment for post-stroke upper extremity recovery. However, these methods often face limitations, including the availability of trained therapists, high costs, and the lack of engaging and motivating exercises for patients [3]. These challenges become even more pronounced in home-based settings, where supervision and resources are often more limited [4].

In home-based settings, routine care often lacks sufficient intensity and task-specific training, which are critical for motor learning and functional recovery [3]. Similarly, traditional therapies at home may suffer from limited professional supervision, reduced patient motivation, and lower adherence rates compared to hospital-based programs [5, 6]. These limitations hinder the effectiveness of home-based interventions and highlight the need for alternative approaches that can overcome these barriers, such as virtual reality (VR) training [7, 8]. In recent years, home-based VR training has emerged as a potential alternative for rehabilitation in patients with stroke [8, 9]. VR technology enables patients to perform repetitive, task-specific movements in an engaging, interactive environment, potentially enhancing motor recovery and improving adherence to rehabilitation protocols [10].

VR technology has garnered significant attention for its potential to enhance rehabilitation outcomes across various treatment environments. Research indicates that

VR-based therapies, when used as an adjunct to conventional rehabilitation methods, can significantly enhance somatic functional recovery in patients with stroke [11-15]. For instance, Laver et al. (2017) noted in their systematic review that rehabilitation training integrating VR in hospital settings can improve upper extremity function and overall recovery [5]. In community settings, Kim et al. (2015) confirmed that VR training effectively enhances balance in patients with stroke [16]. Furthermore, Hao et al. (2023) explored the impact of home-based VR rehabilitation and found that this method significantly improves upper extremity mobility and walking ability in patients [17]. These studies suggest that incorporating VR technology into traditional therapies can provide targeted and repetitive practice, crucial for promoting neuroplasticity and motor learning. These trials suggest that home-based VR could be a promising and effective method for upper extremity training in stroke rehabilitation.

However, existing research shows varied effect of VR training systems on upper extremity function, with differences particularly evident between Commercial VR systems and Customized VR systems. Commercial VR systems, designed primarily for general consumer use, are often marketed for gaming and entertainment purposes rather than rehabilitation [18]. While these systems can be cost-effective and engaging, they frequently lack the specific therapeutic features needed for rehabilitation, resulting in inconsistent outcomes [19]. In contrast, Customized VR systems are specifically developed for clinical or rehabilitative applications. These systems are tailored to meet individual therapeutic needs, offering features such as personalized exercises, real-time performance feedback, and adaptive difficulty levels [20]. These characteristics make them especially effective for patients with severe impairments [21]. Despite their promise, discrepancies in outcomes between these two VR system types underscore the need for further investigation into how each can be optimally utilized for different patient

populations..

Furthermore, the evidence supporting the effect of home-based VR training for upper extremity recovery in patients with stroke is still limited and remains to be systematically evaluated. A recent review investigated VR as an approach to telerehabilitation, and the results showed that VR played a positive role in promoting upper extremity function [17]. Nevertheless, upper extremity function was not the main focus of their research interests, and upper extremity assessment was not used in some of the included studies. Nor is the home setting the only study setting, which also includes small clinics and community rehabilitation. Consequently, the heterogeneity of the study setting, methods, and assessments limits the strength of the evidence.

Despite the growing interest in home-based VR training for upper extremity recovery in patients with stroke, there is a lack of comprehensive and up-to-date evidence synthesis on this topic. To address these gaps, this systematic review aims to comprehensively evaluate the effect, quality, and intervention characteristics of home-based VR training as reported in existing systematic reviews and randomized controlled trials. By analyzing key factors such as the population studied, the duration and intensity of interventions, and the type of VR technology used, this review seeks to identify elements that influence rehabilitation outcomes and provide a clearer understanding of how home-based VR training can be optimized for stroke rehabilitation.

METHODS

Study design and registration

This systematic review was conducted and reported according to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [22].

Per the PRISMA guidelines, the protocol is registered with the International Prospective Register of Systematic Reviews (PROSPERO) (Registration ID: CRD42024526650).

Search strategy

This systematic review searched the English articles from PubMed, Web of Science, Scopus and CINAHL Ultimate databases from inception to 30 June 2024. Search terms include (virtual reality OR VR OR video game OR telerehabilitation OR gamification OR exergame OR virtual environment) AND stroke AND upper extremity AND (home OR community). The search strategies are presented in the online supplementary.

Eligibility criteria

Study types

This systematic review aims to describe and qualitatively assess the effect of home-based VR training on upper extremity recovery in patients with stroke. To ensure high-quality evidence, we included only randomised controlled trials (RCT), defined as studies that utilized a random allocation process to assign participants to intervention or control groups. Quasi-randomized trials or non-randomized studies were excluded.

Inclusion and exclusion criteria

Studies that met the following criteria were included: (1) All subjects were diagnosed with stroke. (2) All subjects presented upper extremity dysfunction. (3) The interventions were implemented in the home environment. (4) The experimental group utilized VR as the primary intervention method. (5) Upper extremity performance was assessed as the primary outcome measure. Exclusion criteria: (1) The subjects had neurological diseases other than stroke. (2) The study type was a non-randomized controlled trial, such as quasi-randomized or observational studies. (3) Articles published in a non-English journals. (4) Articles without full text or peer-reviewed publication status.

Participants

This review included patients diagnosed with stroke and presenting upper extremity

dysfunction. Stroke was defined as a neurological deficit resulting from an acute vascular event in the central nervous system (i.e, brain, retina, or spinal cord) by a vascular cause, typically diagnosed through clinical evaluation and neuroimaging, including CT or MRI [23]. Upper extremity dysfunction was defined as any impairment in arm or hand function following a stroke, regardless of severity.

Types of interventions

The experimental group used VR technology for home rehabilitation training for upper extremity function of patients with stroke. VR is a simulation environment created by computer technology so that users can experience and interact with it. VR systems can be immersive, semi-immersive or non-immersive, and both commercial and customized systems are eligible.

Comparisons or control

The review included studies with a comparator, which can be any of the following: traditional treatment, routine care or another form of VR in a hospital, clinic, or home setting.

Outcome measures

This review included changes in patients' upper extremity function as the primary outcome, using a variety of assessment tools to evaluate changes in upper extremity function, including but not limited to Fugl-Meyer Assessment upper extremity section (FMA-UE), Action Research Arm Test (ARAT), Wolf Motor Function Test (WMFT), Box and Block Test (BBT), Nine-Hole Peg Test (NHPT), Purdue Peg Test (PPT) et al. These assessments measured improvements in motor function from baseline to the end of the follow-up period.

Data collection and analysis

Selection of studies

Two reviewers independently collated and uploaded the data to EndNote 21 (Clarivate

Analytics, Pennsylvania, USA), removed duplicate data, and screened all titles and abstracts to determine whether they met the inclusion criteria for this review. Finally, the full text of eligible studies was evaluated in detail according to the inclusion criteria. The two reviewers searched four databases for relevant reviews on similar topics. They performed citation searches and full-text evaluations of the references to these reviews to identify other eligible studies. Any conflicts during this process will be discussed and resolved in team meetings.

Data extraction and management

Two reviewers independently extracted data from included articles, including the following items: (1) author and year of publication; (2) mean age; (3) mean time since stroke; (4) inclusion and exclusion criteria; (5) the number of participants; (6) intervention intensity and frequency; (7) description of intervention measures; (8) measurement time points; (9) upper extremity function baseline; (10) primary outcome measurement; (11) secondary outcome measures; (12) major findings. Two reviewers cross-check the extracted data, and disagreements are discussed and resolved in a team meeting. All data is collated, archived and stored in a secure electronic database.

Qualitative Synthesis

Due to the heterogeneity of the included studies (e.g., differences in VR system types, patient populations, and outcome measures), a meta-analysis was not feasible. Therefore, a qualitative synthesis was performed to summarize and interpret the findings. Given the small number of studies using commercial VR (n=1) and focusing on participants with moderate upper extremity dysfunction (n=1), subgroup analyses were not conducted. The narrative synthesis focused on the following:

Key Findings: We summarized the improvements in upper extremity function, with common trends observed across studies, particularly in motor control and patient engagement.

Variations: Differences in intervention design, outcome measures, and patient characteristics were discussed, noting how these factors may have influenced the results.

Assessment of methodological quality

To determine the validity of the included articles, we used the Physiotherapy Evidence Database scale (PEDro scale) to assess the included randomized controlled trials (RCTs) [24, 25]. The PEDro scale consists of 11 items: (1) eligibility criteria and source of participants; (2) random allocation; (3) concealed allocation; (4) baseline comparability; (5) blinding of participants; (6) blinding of therapists; (7) blinding of assessors; (8) less than 15% dropouts; (9) intention-to-treat analysis; (10) between-group statistical comparisons; and (11) point and variability measures. The researchers considered that scores 9-10 are excellent quality, 6-8 are good quality, 4-5 are fair quality, and <4 are regarded as poor quality. Two independent reviewers assessed the risk of bias for each study, and differences were resolved through discussion with a third reviewer. The results of this assessment were incorporated into the interpretation of findings, with higher-quality studies given greater weight in the synthesis.

RESULTS

Study identification

A total of 675 articles were searched in the electronic database (PubMed=170, Web of Science=231, Scoups=194, CINAHL Ultimate=80). After removing duplicates and two screening phases, eight RCTs qualified for inclusion in this review. The literature retrieval and screening process is shown in Figure 1.

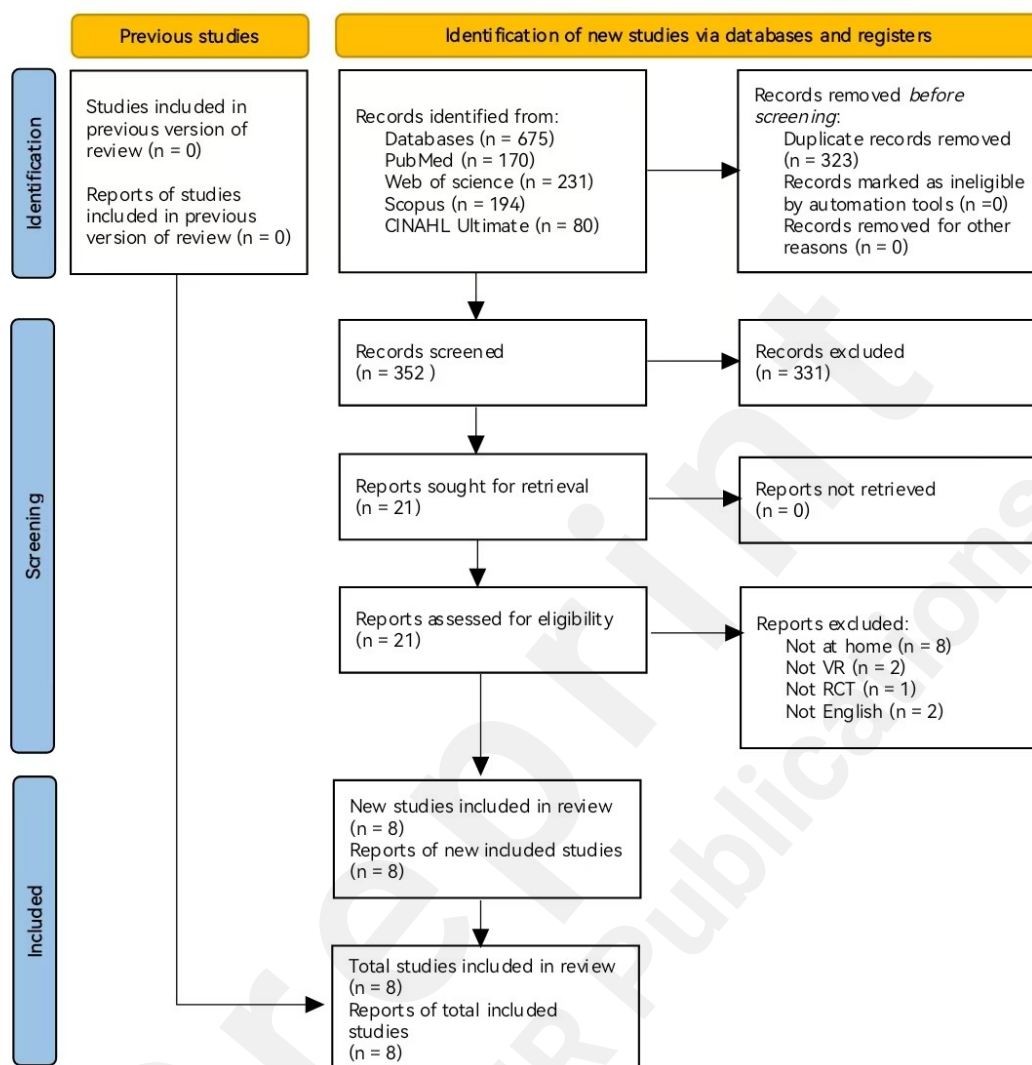


Figure 1 PRISMA 2020 flow diagram for this systematic review.

Study characteristics

Eight randomized controlled trials were published from 2017 to 2023 and included 392 participants, with one study having a big sample size of 235 and the rest ranging from 11 to 39 (Table 1). In eight of the included studies, participants were diagnosed with stroke and upper extremity dysfunction. The studies varied in terms of participant characteristics, with most focusing on patients with mild to moderate upper extremity dysfunction. Based on the baseline data from various assessment tools, we found that four studies (FMA-UE, ARAT) reported moderate impairment, with baseline scores

ranging from 40 to 45 points [26-29]. Two studies using the WMFT and BBT tests indicated mild functional impairment, with baseline scores generally around 2-3 seconds for WMFT [30, 31]. Additionally, one study (Hernandez et al., 2022) indicated that some participants in the experimental group had severe impairment, with baseline FMA-UE scores below 30 [32]. Although one study did not conduct baseline assessments, based on the Chedoke-McMaster scoring (with a 2-6 range for inclusion criteria), it can be inferred that the participants in this study had moderate functional impairment at baseline [33].

The duration and frequency of home-based VR interventions varied across the studies, typically lasting between 4 to 8 weeks, with longer durations showing more sustained improvements in upper extremity function. Thielbar et al. (2020) found that a 2-week, high-intensity, daily 1-hour intervention with a multimodal approach improved function significantly more than a single-modality intervention, highlighting the importance of adaptable interventions for maintaining patient engagement [27]. Similarly, Allegue et al. (2022) found that moderate-intensity interventions (30 minutes, 5 times a week) for 3 months led to significant improvements in FMA-UE and MAL, underscoring the value of structured, long-term interventions [33]. Wilson et al. (2021) showed that a flexible 8-week intervention with the EDNA system (3 to 4 sessions per week) significantly improved upper extremity function, emphasizing the role of consistent engagement [30]. Lastly, Standen et al. (2017) demonstrated that even lower-intensity training (20 minutes, 3 times a week) for 8 weeks effectively improved function, supporting the importance of adaptable intervention strategies [31]. Overall, the studies suggest that structured yet adaptable interventions can maintain patient engagement and maximize functional gains in upper extremity rehabilitation.

In the included studies, VR technology types cover commercial and custom systems, each

with unique advantages and application scenarios. Commercial systems such as the Nintendo Wii are inexpensive, easy to use, and stimulating for patients, but have limitations regarding rehabilitation design and personalized training [28]. Customized systems such as Jintronix, EDNA-22 and Glove Rehabilitation Application for Stroke Patients (GRASP) provide personalized training tasks and detailed feedback that can be adjusted to the patient's functional needs, significantly improving training results [26, 30-32]. Additionally, some studies incorporated telehealth technology into VR systems (e.g. GRASP and VirTele), improving the feasibility and adherence of home-based rehabilitation [26, 33]. Multiuser VR systems, such as Virtual Environment for Rehabilitative Gaming Exercises (VERGE), introduced interactive and social components that increased participation and user motivation [27]. These diverse VR technologies provide effective rehabilitation options for patients with different levels of impairment, showcasing their potential for remote and personalized rehabilitation.

Effect of Home-Based VR Training

Numerous studies have demonstrated the positive impact of home-based VR training on improving upper extremity function in stroke patients. For instance, Adams et al. (2023) found that the GRASP HEP system significantly improved FMUE by 10.1 points ($p < 0.001$) [26]. Similarly, Allegue et al. (2022) showed significant improvements in FMA-UE using the VirTele system in comparison to the GRASP system in the control group [33]. Additionally, Wilson et al. (2021) demonstrated that the EDNA-22 system also outperformed traditional rehabilitation methods in improving upper extremity function, with a mean improvement of 1.53 points ($p = 0.05$) on the BBT [30]. These findings collectively underscore the effectiveness of customized VR systems in promoting upper extremity rehabilitation.

Several studies revealed significant differences between intervention and control groups

in terms of upper extremity function. In Adams et al. (2023), the GRASP HEP group demonstrated a significant 8.6-point improvement in FMUE compared to the UCT group ($p = 0.002$) [26]. Moreover, In Thielbar et al. (2020), participants in the MU VR mode had a significantly higher arm displacement (414.6 meters, $p = 0.019$) than those in the SU VR mode (327.0 meters), showing the greater benefits of interactive VR systems [27]. On the other hand, Adie et al. (2017) reported no significant difference between the Wii™ system (commercial VR) and the control group in ARAT ($p > 0.05$) [28]. These results suggest that while home-based VR training is generally effective, tailored VR systems tend to produce more significant improvements compared to traditional methods or commercial VR systems.

Table 1. Characteristics of included studies

Author Year	Characteristics of participants	Number of particip ants	Intervention intensity	Intervention Grouping	Measurement time points	Primary outcome measures	Secondary outcome measures	Major findings
Adams et al 2023	Shoulder joint flexion, abduction, adduction ≥30° Shoulder joint rotation ≥15° Elbow joint flexion ≥45°	21	45 min 4 d/wk 8 wk	EG: GRASP HEP	T0: 0 T1: 8 weeks	FMA-UE	WMFT BBT MAL	Both groups improved significant on the FMUE and MAL. Significant difference between groups only in the FMUA and MAL, EG better performance
				CG:UCT				

Allegue et al 2022	CAHAI scores 2-6 No longer receiving rehabilitation services and were able to use the exergame system	11	30 min 5 d/wk 3mos	EG: VirTele program Jintronix exergames CG: GRASP	T0: 0 T1: 3 months Follow-up: 1 month after T1 Follow-up: 2 months after T1	FMA-UE	MAL SIS-16 TSRQ-15	than CG. Both groups showed improvement in all outcome measures. No significant difference on all outcomes between groups. Both groups maintained improved outcomes only on FMUE and MAL at follow- up.

Hernandez et al 2022	First-time stroke having occurred >6 months earlier CAHAI scores 2-6 No longer receiving rehabilitation services	19	20min 5 d/ wk 4 wk	EG: Jintronix system CG: GRASP	T0: 0 T1: 4 weeks Follow-up: 4 weeks after T1	FMA-UE	SIS MAL	Both groups improved significantly on the FMA-UE, but most disappeared during follow-up. No significant differences on all outcomes between groups.
Wilson et al 2021	Age ≥18 years old Shoulder joint flexion ≥20° Elbow joint flexion ≥90° The ability to	19	30min 3~4 d/ wk 8 wk	EG: EDNA + Treatment As Usual—TAU CG: GRASP + TAU	T0: 0 T1: 8 weeks Follow-up: 3 months after T1	BBT MoCa	9-HPT SIS NFI	EG groups improved significantly on the BBT, and moderate (but

	maintain the wrist in a neutral position while holding an object used by the EDNA system							non-significant) improvement on the 9HPT, SIS and NFI. Significant difference
Thielba r et al 2020	Stroke □ 6 months CAHAI scores 3-5	21	1 h/ d 4 d/ wk 2 wk MU 2 wk SU	EG: VERGE system MU mode CG: SU mode	T0: 0 T1: 2 weeks T3: 4 weeks	The VERGE system records the time of each	FMA-UE	Both groups improved in arm displacement and tranning time, but EG improved

						exercise, and the total arm displacement.		significantly. All groups improved significant on the FMA-UE, Both groups showed greater
Adie et al 2017	Stroke 6 months MRC 5	235	45 min/ d 6wk	EG: Wii™	T0: 0	ARAT	COPM SIS mRS EQ-5D 3L	Both groups improved significant on
				CG: GRASP	T1: 6 weeks T2: 6months after T0			

								the ARAT. No significant difference on all
Ballest er et al 2017	First-ever stroke >12 months MRC□2 Age between 45-85 years old Previous experience with RGS in the clinic	39	20 min 5 d/ wk 3 wk	EG: RGS	T0: 0 T1: 15 days T3: 12 weeks after T0	FMA-UE CAHAI	BI ASp MRC	EG groups improved significant on the CAHAI..
				CG: OT task				
Stande n et al 2017	Age□18 years old No longer receiving rehabilitation services Patients were	27	20 min 3 times/ d 8 wk	EG: Virtual glove CG: Usual care	T0: 0 T1: 4weeks after T0 T2: 8 weeks after T0	WMFT	9-HPT MAL NEADL	EG groups improved significant on the WMFT and MAL at

	excluded if they had							midpoint.
	no detectable							
ARAT: Action Research Arm Test; ASp□Ashworth Scale Proximal limb; BBT: Box and Blocks Test; BI: Barthel Index; CAHAI: Chedoke Arm and Hand Activity Inventory (version CAHAI-13); COPM: Canadian Occupational Performance Measure; FMA-UE: Fugl-Meyer Assessment upper extremity section; MAL: Motor Activity Log; MoCa: Montreal Cognitive Assessment; MRS: Modified Rankin Scale; NEADL: Nottingham Extended Activities of Daily Living Scale; NFI: Neurobehavioural Function Inventory; SIS-16: Stroke Impact Scale-16; TSRQ-15: Treatment Self-Regulation Questionnaire-15; WMFT: Wolf Motor Function Test; 9-HPT: Nine-Hole Peg Test								

Risk of bias in included studies

PEDro scale showed 4 studies scored 7; three studies scored 6, indicating these studies were of good quality methodologically. Only one study showed relatively low quality, but it reached fair (PEDro scale=5). Common limitations across the studies included the lack of blinding of participants and therapists. Detailed information on the risk of bias is presented in Table 2.

Table 2. Physiotherapy Evidence Database scores of Included studies.

Studies	Items											Score (0-10)
	1	2	3	4	5	6	7	8	9	10	11	
Adams et al [26]	√	√	√	√			√	√		√	√	7
Allegue et al [33]	√	√	√	√							√	4
Hernandez et al [32]	√	√	√	√			√	√		√	√	7
Wilson et al [30]	√	√	√	√			√	√		√	√	7
K.O. Thielbar et al [27]	√	√	√	√				√		√	√	6
Adie et al [28]	√	√	√	√			√	√		√	√	7
Ballester et al [29]	√	√	√	√				√		√	√	6
Standen et al [31]	√	√	√	√			√			√	√	6
Rating items: 1—eligibility criteria and source of participants; 2—random allocation; 3—concealed allocation; 4—baseline comparability; 5—blinded participants; 6—blinded therapists; 7—blind assessors; 8—adequate follow-up; 9—intention-to-treat analysis; 10—between-group comparisons; 11—point estimates and variability. Item 1 evaluates external validity and does not contribute to the total score.												

DISCUSSION

This systematic review aimed to evaluate the impact of home-based VR training on upper extremity function recovery after stroke. The results generally suggest that home-based VR interventions have a positive role in promoting upper extremity function recovery. However, several factors such as patient characteristics, VR system types, intervention

intensity, and study heterogeneity need to be considered to fully understand the treatment effects.

Participant Population

This study involved 392 participants with upper extremity dysfunction following stroke, who exhibited significant heterogeneity in their baseline functional status. Although all participants had upper extremity dysfunction, their baseline severity varied considerably, which may influence the interpretation of the study's findings. Most studies included participants with mild to moderate impairment, who typically demonstrated some loss of motor function but still retained significant recovery potential, likely making them more responsive to interventions [26, 30]. In contrast, participants with severe impairment, particularly those with baseline FMA-UE scores below 30, tend to have more complex rehabilitation needs [32]. For these individuals, the recovery process is generally slower, and intervention effects may be less pronounced.

This variation suggests that when assessing treatment outcomes, it is crucial to consider the functional status of participants at baseline, as treatment responses may differ across severity levels. Future research could refine participant stratification by standardizing baseline assessments and tailoring interventions based on varying degrees of impairment, thus more accurately evaluating treatment outcomes for different subgroups. Additionally, interventions for those with severe functional impairments may need to be more intensive and personalized to accommodate their more complex rehabilitation requirements. Overall, the heterogeneity of the population in this study not only reflects diverse responses to rehabilitation but also provides important insights for future research design, particularly in terms of stratified approaches and standardized evaluations.

Influence of System Type

The findings of this systematic review highlight that the effectiveness of home-based VR training in upper extremity rehabilitation after stroke is influenced by the type of VR

system used. Customized VR systems, specifically designed for patients, offer advantages in treating both mild and severe impairments by adjusting the intensity and complexity of exercises to individual needs [34, 35]. These systems have been shown to be more versatile and effective for a wider range of functional levels, including those with moderate to severe dysfunction, as they provide more tailored and adaptable interventions [34, 36]. On the other hand, commercial VR systems, designed primarily for healthy individuals, tend to be more suitable for patients with mild functional impairments, as they are often not flexible enough to accommodate the specific needs of more severely impaired patients [37]. This discrepancy highlights the importance of customizing VR interventions to fit patient characteristics, particularly in clinical settings where maximizing the therapeutic effect is essential.

While commercial VR systems offer benefits in terms of accessibility and cost, their application in more severely impaired populations may be limited due to their higher functional demands [38, 39]. Future studies should explore how to optimize commercial VR systems to expand their scope of application and validate the long-term efficacy of these interventions in patients with different levels of function. How to further enhance the personalization and sustainability of VR training in the home environment should be studied to improve its broad application in various rehabilitation scenarios.

Influence of Intervention Intensity and Frequency

Training intensity and duration are important factors affecting the effect of VR intervention. Most studies have set the duration of the intervention between 20 and 60 minutes, and the effect varies depending on the type of human-computer interaction. Some studies have shown that intensive VR exercises, such as rapid continuous extension and contraction of the arm training, can improve the training intensity in a short period, but too long a period may cause patient fatigue and reduce participation and effect [40]. In contrast, decentralized exercises, such as VR training that simulates activities of daily

living, are generally more acceptable to patients due to the familiarity of the task and can maintain a longer training time and higher compliance [26]. VR interventions with different forms of exercise significantly affected the duration of the intervention and patient acceptance. Daily activity simulation VR training can keep patients engaged for a longer period because such tasks are close to the needs of real-life [41]. However, when high-intensity and monotonous intensive VR training is too long, the enthusiasm of patients may be reduced due to fatigue and repeatability [31, 33]. Therefore, it is important to choose the right form of exercise and duration of intervention to balance the training intensity with the patient's acceptance and maximize the intervention effect.

Statistical Power and Study Heterogeneity

The small sample sizes in most studies may limit the statistical power and precision of effect estimates. The heterogeneity in study design, patient population, intervention protocols, and VR system types likely influences the observed treatment effects, making it difficult to generalize the findings. Despite this, positive trends across studies suggest that VR interventions hold promise, particularly when tailored to individual patient needs. Future research should aim to improve statistical power by increasing sample sizes and focusing on more homogeneous populations. Refining study designs to account for these variables and incorporating stratified analyses will help better assess the true impact of VR interventions across different subgroups.

Limitations

However, there are some limitations to this study. First, heterogeneity in study design, patient population, and VR intervention protocols makes it difficult to draw consistent conclusions about the optimal characteristics of home VR training. Second, most studies had small sample sizes, inconsistent outcome measures, and lacked long-term follow-up, which reduced the reliability of conclusions and the assessment of the sustainability of intervention effects. In addition, no meta-analysis was performed due to the qualitative nature of this review, limiting insights into effect sizes and intervention efficacy.

Furthermore, while the PEDro scale was used for quality assessment, the inability to blind patients and therapists in the included studies may have introduced bias and reduced the reliability of the findings. Finally, the search was limited to English-language publications, which may have introduced language bias and excluded relevant studies in other languages.

Future Work

Future research should focus on increasing sample sizes and improving statistical power to enhance the precision and generalizability of findings. Studies should include more homogeneous participant populations to minimize baseline variability and improve the accuracy of treatment effect assessments. Additionally, exploring the impact of different VR system types, intervention protocols, and their long-term effects on recovery will be crucial. Finally, Standardizing outcome measures, incorporating stratified analyses, and conducting large-scale, multi-center trials with robust designs will further strengthen the evidence base.

Conclusions

This systematic review shows that home-based VR training has a certain effect on upper extremity rehabilitation of stroke patients, especially in patients with different degrees of dysfunction. However, challenges such as study heterogeneity, small sample sizes, inconsistent outcome measures, and limited long-term follow-up data have affected the reliability and comparability of the current findings. With the development of the technology and the popularity of applications, larger randomized controlled studies should be conducted in the future, extending follow-up time and exploring how VR technology can be integrated to support comprehensive rehabilitation programs. Home VR rehabilitation has great prospects, but its application needs to be centered on the needs of patients, combined with sustainable, personalized technology and support services to achieve the best recovery results.

Contributors

JH and XW designed the review. JH and PZ screened the studies. JH, PZ and XW rated the quality of the studies and extracted the data. JH analysed the data. JH, YW, PZ, XH, and HL drafted and revised the manuscript. All the authors listed in the manuscript acknowledged and agreed with the format and content of the paper before submission for publication. XW is the corresponding author of this study.

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Conflicts of interest

None declared.

Abbreviations

ARAT: Action Research Arm Test

ASp $\square$ Ashworth Scale Proximal limb

BBT: Box and Block Test

CAHAI: Chedoke Arm and Hand Activity Inventory

COPM: Canadian Occupational Performance Measure

FMA-UE: Fugl-Meyer Assessment upper extremity section

GRASP: Glove Rehabilitation Application for Stroke Patients

MAL: Motor Activity Log

MRS: Modified Rankin Scale

MoCa: Montreal Cognitive Assessment

NEADL: Nottingham Extended Activities of Daily Living Scale

NFI: Neurobehavioural Function Inventory

NHPT: Nine-Hole Peg Test

PEDro: Physiotherapy Evidence Database

PPT: Purdue Peg Test

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analysis

PROSPERO: International Prospective Register of Systematic Reviews

RCT: Randomised controlled trial

SIS-16: Stroke Impact Scale-16

TSRQ-15: Treatment Self-Regulation Questionnaire-15

USA: United States of American

VERGE: Virtual Environment for Rehabilitative Gaming Exercises

VR: Virtual reality

WMFT: Wolf Motor Function Test

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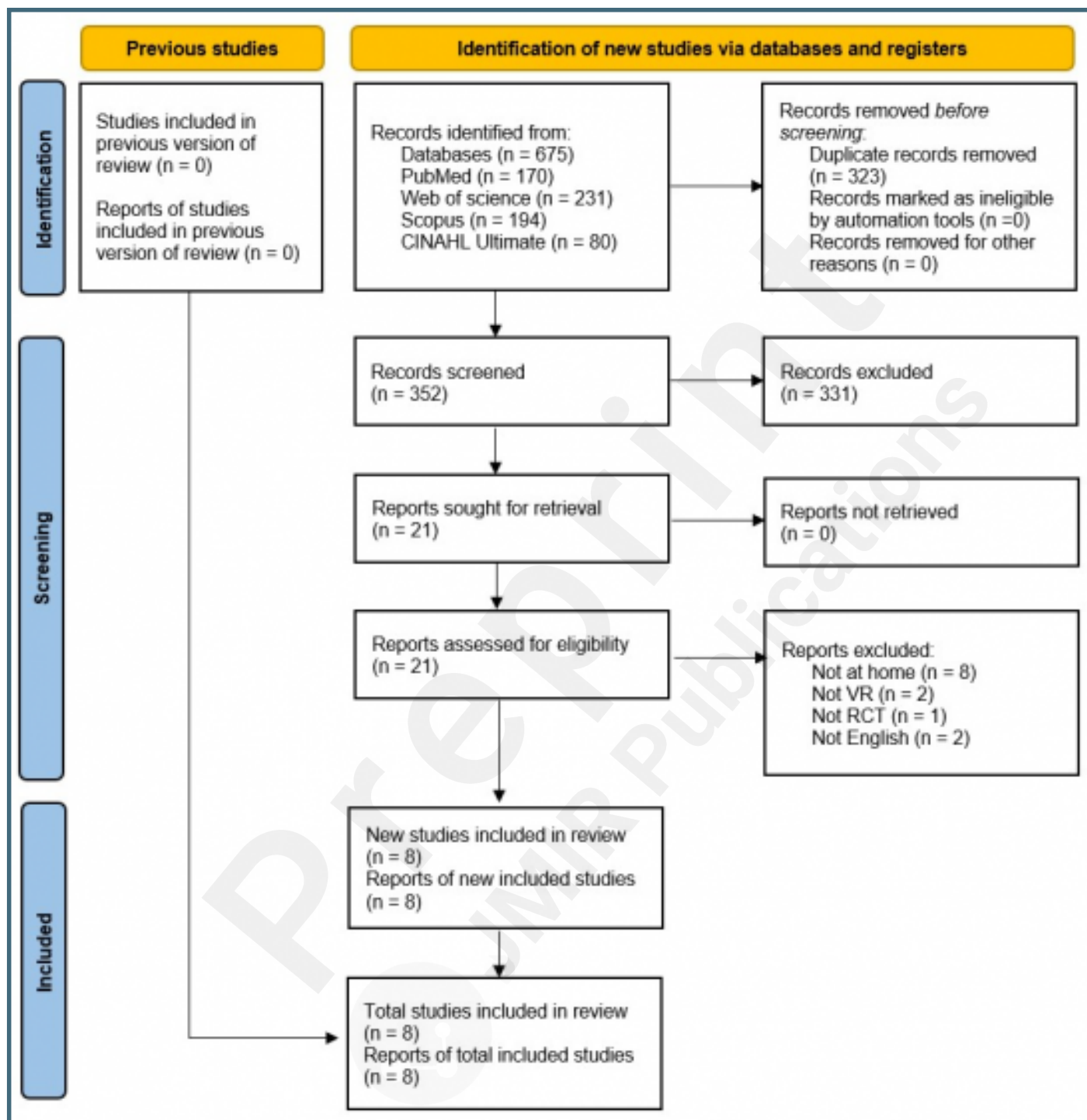
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Supplementary Files

Figures

PRISMA 2020 flow diagram for this systematic review.



Multimedia Appendixes

Supplementary_Search strategy.

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CONSORT (or other) checklists

PRISMA checklist.

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TOC/Feature image for homepages

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