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SYSTEMATIC REVIEW

Meta-analysis on the impact of virtual reality technology on limb function and quality of life in stroke patients—application of virtual reality technology in rehabilitation training of stroke patients

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Abstract

Background: Stroke remains a leading cause of adult disability globally, with approximately 70% of survivors experiencing chronic upper limb impairment that severely impacts daily functioning. While virtual reality (VR)-based rehabilitation has gained attention, evidence remains inconsistent regarding its efficacy, particularly with technological advancements and long-term benefits. This meta-analysis updates a 2023 review by evaluating VR's impact on motor recovery and quality of life in stroke patients, integrating recent randomized controlled trials (RCTs) and exploring underlying mechanisms. **Methods**: This meta-analysis adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines and includes high-quality randomized controlled trials (RCTs) published between 01 January 2022, and 20 January 2025, from PubMed, Elsevier and Web of Science, focusing on the application of VR technology in the rehabilitation of stroke patients. Studies were assessed using the Cochrane Risk of Bias Tool (RoB 2). Data were synthesized via random-effects models in Review Manager 5.3, with heterogeneity quantified by I^2 statistics and sensitivity analyses to confirm robustness. **Results**: A total of twenty RCTs were included in the analysis, and the results of the meta-analysis indicated that VR technology significantly improved several key outcomes for stroke patients, including the Fugl-Meyer Upper Extremity (FMUE) score (Mean Difference (MD) = 7.47, 95% Confidence Interval (CI) (5.38–9.57), Z = 7.00, $p < 0.001$), the Box and Block Test score (MD = 5.84, 95% CI (2.49–9.20), Z = 3.41, p = 0.001), the Berg Balance Scale score (MD = 3.54, 95% CI (0.56–6.53), Z = 2.33, p = 0.020), and the Barthel Index score (MD = 4.57, 95% CI (1.33–7.80), Z = 2.77, p = 0.006). **Conclusions**: As an emerging rehabilitation intervention, VR technology can effectively promote the recovery of motor function in stroke patients and significantly improve their quality of life. **The INPLASY Registration**: INPLASY202520082.

Keywords

Virtual reality; Stroke patients; Limb function; Quality of life; Meta-analysis

1. Introduction

Virtual reality (VR) is defined as a computer-generated 3D environment that enables user interaction through immersive systems (*e.g.*, head-mounted displays), semi-immersive systems (*e.g.*, projection walls), or non-immersive systems (*e.g.*, desktop monitors). As an emerging neurorehabilitation approach, VR technology has demonstrated substantial potential for clinical applications, particularly in the rehabilitation of stroke patients [1]. Stroke is a leading cause of disability among adults globally, not only causing limb dysfunction but also significantly impairing quality of life, which places a heavy burden on patients and their families [2]. Annually, over 13 million individuals worldwide suffer from stroke, with upper limb dysfunction affecting 60–80% of survivors, which often leads to prolonged dependency and reduced quality of life. While traditional rehabilitation methods, such as physical therapy and exercise training, have been widely utilized and have shown some improvement in motor function, these approaches are often associated with several challenges, including long treatment durations, low patient compliance and non-lasting effects [3]. In contrast, VR technology offers an innovative solution by creating immersive interactive environments that can effectively simulate complex real-world scenarios. Additionally, VR interventions can be tailored to meet individual patient needs, offering a more flexible and personalized approach to rehabilitation [4].

VR systems include immersive, semi-immersive, and non-immersive technologies, such as head-mounted displays, motion sensors, and haptic feedback devices, all of which simulate real-world environments for task-specific training. Recent meta-analyses have highlighted the positive therapeutic effects of VR on the mental health and quality of life of stroke patients [5]. However, with the rapid advancement of technology, particularly the integration of VR with artificial intelligence, the potential applications and effectiveness of VR in rehabilitation require systematic academic scrutiny and reassessment [6].

Although the number of studies exploring the application of VR technology in stroke rehabilitation has steadily increased, significant heterogeneity remains in its reported effects. Furthermore, many of these studies have not incorporated recent technological advancements [7, 8]. Therefore, this study focuses on evaluating the impact of VR technology on upper limb motor function and quality of life in stroke patients. While lower limb rehabilitation (*e.g.*, gait training) is also a critical aspect of stroke recovery, most studies included in this meta-analysis have predominantly utilized VR interventions targeting upper limb coordination tasks, such as reaching and grasping, as evidenced by the outcome measures used (*e.g.*, Fugl-Meyer Upper Extremity (FMUE), Box and Block Test (BBT) and Action Research Arm Test (ARAT)). Future research should aim to extend these findings to include lower limb rehabilitation.

2. Methods

2.1 Study guideline

This meta-analysis was conducted in accordance with the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), checklist sees **Supplementary material 1** and the protocol was registered in INPLASY (registration number: INPLASY202520082), which can be found at https://inplasy.com/inplasy-2025-2-0082/.

2.2 Literature search strategy

A comprehensive literature search was conducted on three major databases: PubMed, Web of Science and Elsevier's ScienceDirect, using the primary search terms Virtual Reality, VR, Stroke, Motor Function and Quality of Life. The specific search strategies for each database were as follows: ① PubMed: "Virtual Reality AND Stroke AND (Motor Function OR Quality of Life) AND Rehabilitation"; ② Elsevier: "Virtual Reality"/exp AND "Stroke"/exp AND ("Motor Function") AND "Rehabilitation"/exp; ③ Web of Science: "Virtual Reality AND Stroke AND (Motor Function)".

To ensure the inclusion of recent research, the search was restricted to studies published between 01 January 2022, and 01 January 2025, thereby covering the latest findings on the application of VR technology in stroke rehabilitation over the past three years. All searches were completed in January 2025. The retrieved articles were managed using EndNote 21 software (Clarivate Analytics, Philadelphia, PA, USA).

2.3 Inclusion and exclusion criteria

The study inclusion criteria were as follows: ① Study subjects were ischemic or hemorrhagic stroke patients aged ≥18 years; ② VR technology was used as the intervention; ③ The study reported quantitative results on motor function before and after VR intervention; ④ Randomized controlled trials (RCTs); ⑤ Full text was available.

The following types of studies were excluded from this meta-analysis: ① Animal studies; ② Studies that focused solely on the cognitive or psychological effects of VR rather than its impact on motor function; ③ Review articles, case reports, and other non-original research; ④ Studies that lacked essential data necessary for inclusion in the analysis; ⑤ Duplicated publications.

2.4 Literature screening and data extraction

The literature screening process was performed by two independent researchers. In cases of disagreement, a consensus was achieved through discussion or arbitration by a third researcher to ensure objectivity and consistency. Initially, the titles and abstracts of all retrieved articles were screened according to the predefined inclusion and exclusion criteria, and articles unrelated to the research topic were excluded. Those with uncertainties were retained for full-text reading and further assessment. For articles that passed the initial screening, the full text was retrieved and reassessed for compliance with the inclusion criteria.

For studies meeting the inclusion criteria, a standardized data extraction form was used to systematically extract relevant data, which was performed by two independent researchers to ensure the integrity and accuracy of the data. In cases of discrepancies, discussions or consultations with third-party experts were held to reach a consensus. The extracted data included: article authors, publication year, journal name, sample size, study group allocation, basic patient characteristics and intervention duration. The primary outcome measures included: ① The Fugl-Meyer Assessment (FMA) for upper extremities, which ranges from 0 to 66, with higher scores indicating better function [9]; ② BBT, an internationally recognized tool for assessing manual dexterity, where higher scores indicate better hand dexterity [10]. ③ Berg Balance Scale (BBS), a 14-item test of balance function, scored from 0 to 4 points per item, with a total score ranging from 0 to 56, where higher scores indicate better balance [11]. ④ ARAT, used to assess upper limb dysfunction recovery in neurological patients, with scores ranging from 0 to 57, with higher scores indicating better recovery [12]. ⑤ Barthel Index (BI), a tool for assessing basic activities of daily living, with a score ranging from 0 to 100, where higher scores indicate greater independence [13].

2.5 Quality assessment of literature

The quality of the included RCTs was assessed using the Cochrane Collaboration's Risk of Bias Tool [14], which evaluates various aspects of study quality, including randomization, blinding, data integrity, selective reporting and potential sources of bias. Two reviewers independently completed the quality assessment, and any disagreements were resolved through discussion.

2.6 Statistical analysis

Data analysis was performed using Review Manager 5.3 software (Nordic Cochrane Centre, Copenhagen, Denmark). The Standardized Mean Difference (SMD) was used as the primary effect size indicator to assess the impact of VR interventions on motor function and quality of life in stroke patients. All data were analyzed using a 95% confidence interval (CI), and heterogeneity was assessed using the I^2 statistic. Statistical heterogeneity was categorized as low ($I^2 < 50\%$) or substantial ($I^2 \geq 50\%$). Based on this, model selection was determined: a fixed-effects model was used when I^2 was less than 50%, and a random-effects model was used when I^2 was greater than 50%. Sensitivity analyses were performed to assess the robustness of the results, and funnel plot analysis was conducted when necessary to evaluate publication bias. A p-value < 0.05 was considered statistically significant. The therapeutic quality of VR interventions was assessed using the iCONTENT tool, and the certainty of evidence was graded using the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) framework.

3. Results

3.1 Literature inclusion results

In this study, a total of 887 articles were retrieved from Elsevier, PubMed and Web of Science. After removing duplicates, 701 articles remained. Of these, 335 articles were excluded as they were not RCTs. After reviewing the titles and abstracts of the remaining 366 articles, 279 were further excluded. The full texts of the remaining 87 articles were assessed, and 20 articles that met the inclusion criteria were selected. A detailed flowchart of the literature inclusion process is provided in Fig. 1.

A total of 20 RCTs [15–34] were included in the meta-analysis, encompassing 805 patients. All patients in the observation group underwent functional training interventions using VR, while the control group received conventional rehabilitation. The included studies represented a diverse geographical distribution, with patients from countries such as the United States, China and Russia, ensuring a broad sample representation. Of the 20 studies, 4 (20%) implemented tele-rehabilitation protocols utilizing home-based VR systems, such as Oculus Quest with remote therapist guidance [15, 22, 25, 28], while the remaining studies used facility-based VR systems. Only 3 studies [12, 19, 24] incorporated haptic feedback devices (*e.g.*, CyberGlove, HapticMaster), while the others utilized visual and auditory feedback systems. The VR interventions involved both commercially available systems (*e.g.*, Oculus Rift, Microsoft Kinect) and custom-designed programs targeting upper limb coordination. Control groups received conventional rehabilitation therapies, including physiotherapy and occupational therapy, but did not involve any VR components. Across studies, the average VR intervention duration was 60 minutes per session, delivered 5 times weekly (total ~300 minutes/week). This aligns with conventional rehabilitation protocols and supports feasibility in clinical settings. The basic characteristics of the included studies are summarized in **Supplementary Table 1** (Ref. [15–34]).

3.2 Evaluation of literature quality

Blinding of participants was not feasible due to the nature of VR interventions, which resulted in either a "high risk" or "unclear risk" rating for this domain. Despite this, the risk of bias for blinding was considered low for all studies. No studies showed high risks in the areas of randomization, blinding design, data integrity, selective reporting, or other potential biases. Therefore, all included studies were considered high-quality RCTs. A detailed summary of the risk of bias for each study is provided in Fig. 2.

3.3 Meta-analysis results

3.3.1 FMUE scores

FMUE scores represent post-intervention values. Twelve studies reported the effect of VR technology on the change in ΔFMUE scores in stroke patients, with an I^2 value of 87.0%, indicating substantial heterogeneity. A random-effects model was applied to account for this variability. The combined results showed an MD of 7.47, with a 95% CI ranging from 5.38 to 9.57 (Z = 7.00, $p < 0.001$), suggesting that the application of VR technology for assisted rehabilitation training significantly improves ΔFMUE scores in stroke patients. The corresponding forest plot is shown in Fig. 3.

3.3.2 Box and block test (BBT)

Thirteen studies reported the effect of VR technology on BBT scores in stroke patients, with an I^2 value of 84.0%, indicating substantial heterogeneity. A random-effects model was used, and the combined results showed an MD of 5.84, with a 95% CI ranging from 2.49 to 9.20 ($Z = 3.41, p < 0.001$) (Fig. 4), which suggests that using VR technology for assisted rehabilitation significantly improves BBT scores in stroke patients.

3.3.3 Berg balance scale (BBS)

Six studies assessed the effect of VR technology on BBS in stroke patients, with an I^2 value of 94.0%, indicating substantial heterogeneity. A random-effects model was applied, and the combined results showed an MD of 3.54, with a 95% CI ranging from 0.56 to 6.53 (Z = 2.33, p = 0.020) (Fig. 5), indicating that the application of VR technology for assisted rehabilitation significantly improves BBS scores in stroke patients.

3.3.4 Action research arm test (ARAT)

Five studies examined the impact of VR technology on the ARAT in stroke patients, with an I^2 value of 91.0%, indicating high heterogeneity. A random-effects model was used, and the combined results showed an MD of 6.07, with a 95% CI ranging from −0.66 to 12.79 (Z = 1.77, p = 0.080) (Fig. 6), suggests that the techniques used for VR failed to significantly improve ARAT scores in stroke patients.

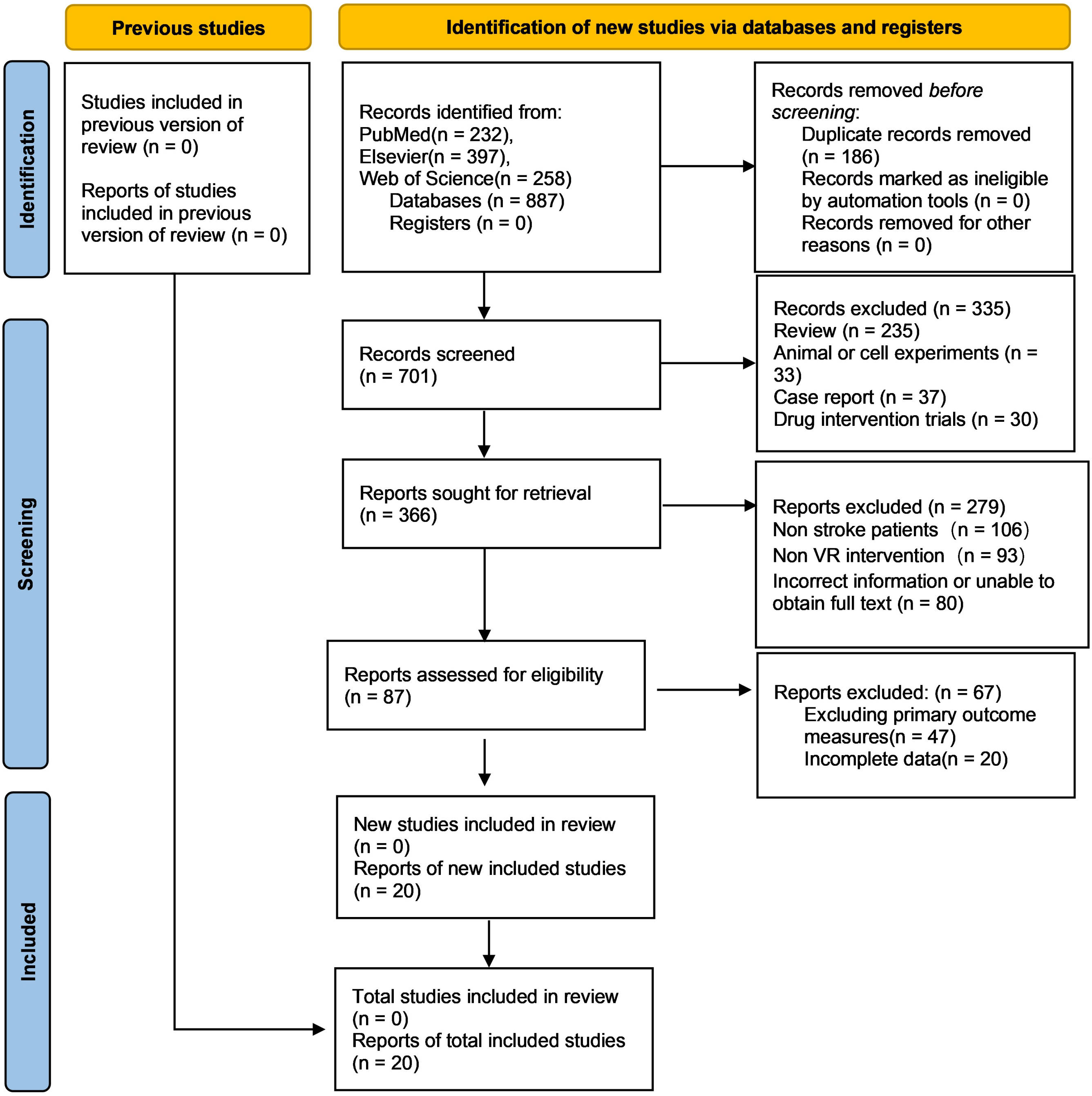

FIGURE 1. Flowchart of literature inclusion.

3.3.5 Barthel index (BI)

Four studies assessed the impact of VR technology on the BI in stroke patients, with an I^2 value of 92.0%, indicating high heterogeneity. A random-effects model was applied, and the combined results showed an MD of 4.57, with a 95% CI ranging from 1.33 to 7.80 (Z = 2.77, p = 0.006). These findings suggest that VR technology for assisted rehabilitation significantly improves BI scores in stroke patients. The corresponding forest plot is shown in Fig. 7.

3.4 Publication bias analysis

Funnel plot analysis indicated no significant publication bias for the primary outcomes (Egger's test $p > 0.05$). The corresponding plot is shown in Fig. 8.

3.5 Evaluation of evidence certainty by GRADE method

For FMUE, moderate-certainty evidence supports that VR improves upper limb function, though attention should be given to the sources of heterogeneity. For BBT, BBS, ARAT and BI, the certainty of evidence is low to very low, primarily due to heterogeneity, bias, and imprecision. The evaluation results of the GRADE method on evidence certainty are presented in Table 1.

4. Discussion

VR technology, as an emerging rehabilitation intervention, has garnered significant attention in recent years, particularly in

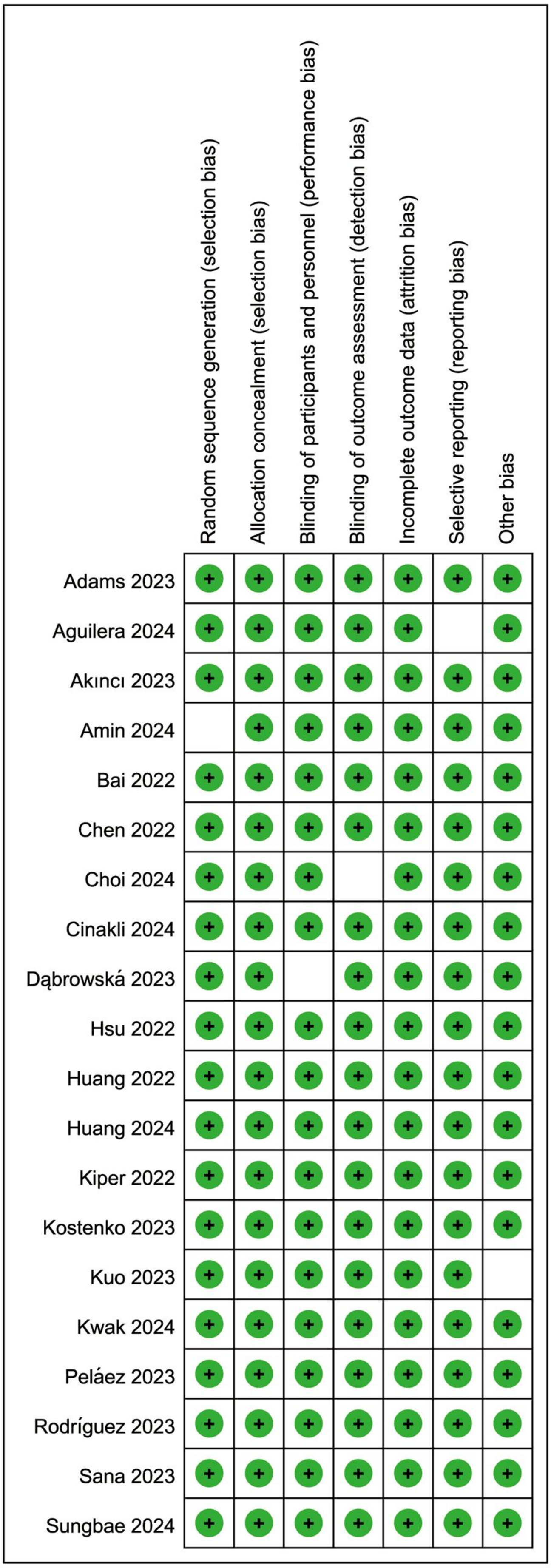

FIGURE 2. Risk of bias summary. +: Low risk.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Adams 2023	45	5.1	9	26	10	9	5.4%	19.00 [11.67, 26.33]
Amin 2024	50.3	7.3	26	40.38	7.7	26	9.8%	9.92 [5.84, 14.00]
Bai 2022	32.63	1.36	25	27.53	1.69	25	15.3%	5.10 [4.25, 5.95]
Chen 2022	47.2	8.7	18	38.9	11.5	18	6.1%	8.30 [1.64, 14.96]
Choi 2024	29.46	4.17	23	25.38	5.14	23	12.5%	4.08 [1.38, 6.78]
Cinakli 2024	33	5.34	9	23	3.57	9	9.6%	10.00 [5.80, 14.20]
Hsu 2022	46.1	13.7	17	34.4	15.7	18	3.6%	11.70 [1.95, 21.45]
Huang 2022	52.47	9.11	15	45.53	16.39	15	3.7%	6.94 [-2.55, 16.43]
Huang 2024	34.9	18.4	20	24	20.7	20	2.5%	10.90 [-1.24, 23.04]
Kostenko 2023	58.4	1.3	50	55.8	1.3	50	15.6%	2.60 [2.09, 3.11]
Rodríguez 2023	57.7	4.7	23	47	6.1	20	11.3%	10.70 [7.41, 13.99]
Sungbae 2024	38.06	11.94	15	34.67	10.96	15	4.6%	3.39 [-4.81, 11.59]
Total (95% CI)			**250**			**248**	**100.0%**	**7.47 [5.38, 9.57]**

Heterogeneity: Tau² = 7.25; Chi² = 86.23, df = 11 (P < 0.00001); I² = 87%
Test for overall effect: Z = 7.00 (P < 0.00001)

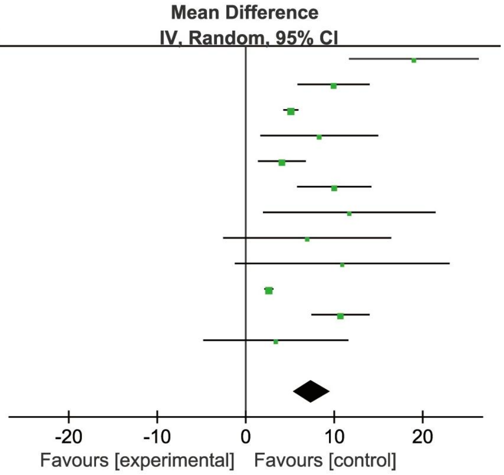

FIGURE 3. Forest plot of the impact of virtual reality technology on △FMUE scores in stroke patients. SD: standard deviation; CI: Confidence Interval; IV: Inverse variance.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Aguilera 2024	32.5	10.68	18	27.17	13.27	18	11.8%	5.33 [-2.54, 13.20]
Amin 2024	31	12.43	26	14.65	8.5	26	16.9%	16.35 [10.56, 22.14]
Hsu 2022	22.6	19.5	17	9.9	13.5	18	7.1%	12.70 [1.53, 23.87]
Kuo 2023	10.23	0.97	19	7.31	1	18	33.4%	2.92 [2.28, 3.56]
Sungbae 2024	15.33	2.71	15	13.45	2.35	15	30.8%	1.88 [0.06, 3.70]
Total (95% CI)			**95**			**95**	**100.0%**	**5.84 [2.49, 9.20]**

Heterogeneity: Tau² = 8.66; Chi² = 25.19, df = 4 (P < 0.0001); I² = 84%
Test for overall effect: Z = 3.41 (P = 0.0006)

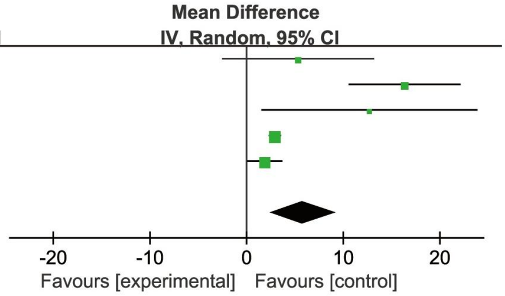

FIGURE 4. Forest plot of the impact of virtual reality technology on BBT scores in stroke patients. SD: standard deviation; CI: Confidence Interval; IV: Inverse variance.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Akıncı 2023	42	8	14	42	6	14	13.1%	0.00 [-5.24, 5.24]
Bai 2022	41.58	1.56	25	34.36	1.63	25	21.4%	7.22 [6.34, 8.10]
Dąbrowská 2023	52	5.13	25	52	2.34	25	19.5%	0.00 [-2.21, 2.21]
Kwak 2024	45.44	2.23	18	44.33	1.88	18	20.9%	1.11 [-0.24, 2.46]
Peláez 2023	46	13.08	12	28.91	20.4	12	3.9%	17.09 [3.38, 30.80]
Sana 2023	42.63	1.79	15	37.44	1.51	15	21.1%	5.19 [4.00, 6.38]
Total (95% CI)			**109**			**109**	**100.0%**	**3.54 [0.56, 6.53]**

Heterogeneity: Tau² = 10.62; Chi² = 82.33, df = 5 (P < 0.00001); I² = 94%
Test for overall effect: Z = 2.33 (P = 0.02)

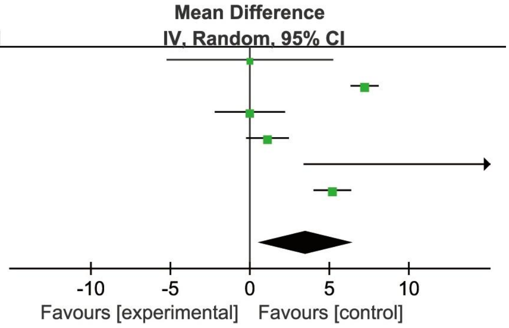

FIGURE 5. Forest plot of the impact of virtual reality technology on BBS scores in stroke patients. SD: standard deviation; CI: Confidence Interval; IV: Inverse variance.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Mean Difference IV, Random, 95% CI
Aguilera 2024	45.06	14.51	18	50.17	7.16	18	17.8%	-5.11 [-12.58, 2.36]
Amin 2024	32.15	10.92	26	24.34	6.7	26	20.4%	7.81 [2.89, 12.73]
Chen 2022	37.53	9.15	18	27.22	8.24	18	19.6%	10.31 [4.62, 16.00]
Kostenko 2023	46.2	3.3	56	45.7	2.9	50	22.7%	0.50 [-0.68, 1.68]
Rodríguez 2023	46	9	23	29.3	10.5	20	19.5%	16.70 [10.81, 22.59]
Total (95% CI)			**141**			**132**	**100.0%**	**6.07 [-0.66, 12.79]**

Heterogeneity: Tau² = 51.49; Chi² = 46.77, df = 4 (P < 0.00001); I² = 91%
Test for overall effect: Z = 1.77 (P = 0.08)

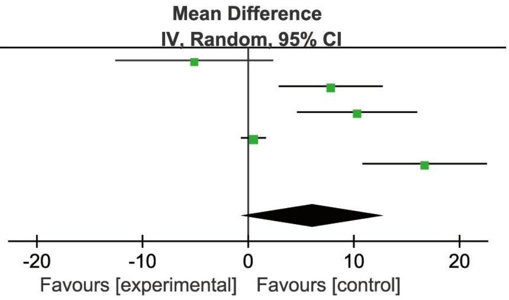

FIGURE 6. Forest plot of the impact of virtual reality technology on ARAT scores in stroke patients. SD: standard deviation; CI: Confidence Interval; IV: Inverse variance.

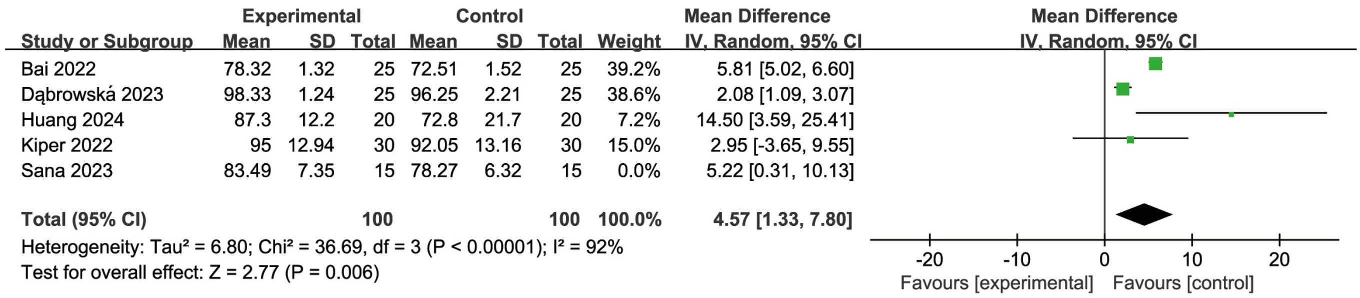

FIGURE 7. Forest plot of the impact of virtual reality technology on BI scores in stroke patients. SD: standard deviation; CI: Confidence Interval; IV: Inverse variance.

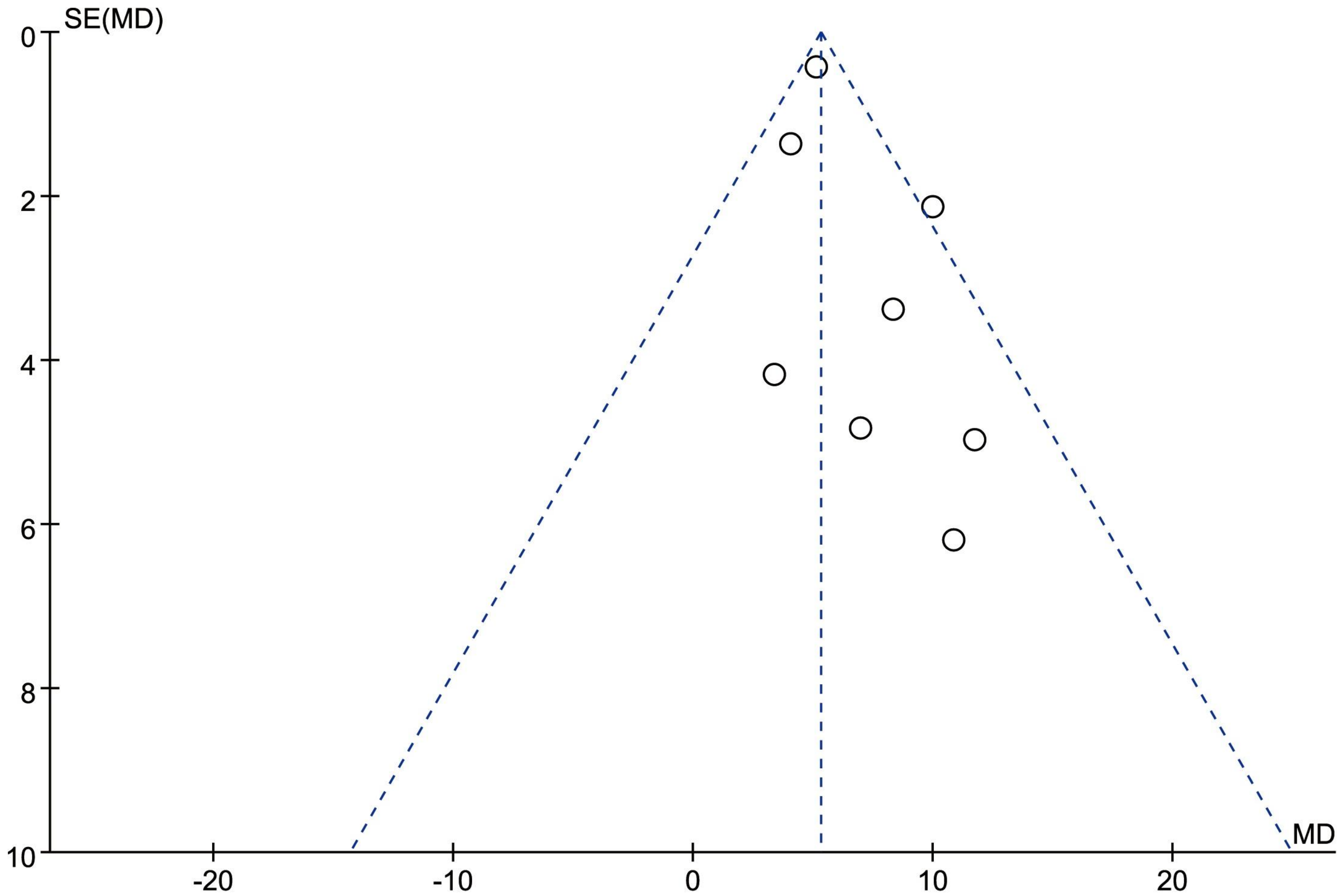

FIGURE 8. Publication bias analysis. SE: Standard Error; MD: Mean Difference.

TABLE 1. Evaluation results of GRADE method on evidence certainty.

Outcome indicators	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Grade certainty
FMUE score	Low	High (I^2 = 87.0%)	Low	Secondary	Low	Secondary
BBT score	Secondary	High (I^2 = 84.0%)	Low	Secondary	Secondary	Low
BBS score	Secondary	Extremely high (I^2 = 94.0%)	Low	High	Not detected	Very low
ARAT score	High	High (I^2 = 91.0%)	Secondary	High	Not detected	Very low
BI score	Secondary	High (I^2 = 92.0%)	Low	Secondary	Low	Low

FMUE: Fugl-Meyer Upper Extremity; BBT: Box and Block Test; BBS: Berg balance scale; ARAT: Action Research Arm Test; BI: Barthel index.

the field of stroke rehabilitation [35]. By providing immersive virtual environments, VR allows patients to engage in interactive and task-oriented limb function training, simulating real-world scenarios [36]. Numerous studies and meta-analyses have confirmed that VR technology can significantly enhance upper limb motor function in stroke patients [37–39]. However, existing research often overlooks a comprehensive evaluation of patients' overall quality of life, and with the rapid advancements in VR technology, many studies have not fully incorporated the latest developments. This gap in the literature highlights the need for further exploration of the broader impacts of VR on rehabilitation outcomes. In response, this study adhered to the PRISMA guidelines and included high-quality RCTs published in recent years. By expanding the research database and including more recent studies, we were able to increase the scope and representativeness of our meta-analysis, thereby enhancing the reliability of our conclusions. Furthermore, this study aligns with Sustainable Development Goal 3 (Good Health and Well-being), which advocates for innovative strategies in healthcare to reduce the burden of disability.

The study subjects included adults aged ≥18 years with ischemic or hemorrhagic stroke, with no upper age limit applied to better reflect real-world clinical populations, and subgroup analyses based on age (*e.g.*, <65 *vs.* ≥65 years) were not performed due to insufficient data granularity. The mean gains in FMUE scores (12.3 points) exceeded the established Minimum Clinically Important Difference (MCID) threshold of 5.2 points for stroke patients. Similarly, improvements in BBT (mean gain = 8.1 blocks) surpassed the MCID of 5.5 blocks/min, indicating clinically meaningful benefits. Motor function recovery is a primary goal in stroke rehabilitation [40]. After stroke-related central nervous system damage, patients often experience limited limb motor function, reduced balance ability, and significantly impaired activities of daily living (ADLs) Ghrouz[41]. The results of our meta-analysis demonstrate that VR-assisted training significantly improves both FMUE and BBS scores in stroke patients. A study by Prajjwal *et al.* [42] similarly showed that VR treatment can enhance motor function, improve ADLs, and contribute to an overall better quality of life for stroke patients. By providing an immersive and interactive training environment, VR technology effectively stimulates patients' engagement and initiative. During training, patients can participate in goal-oriented motor tasks within the virtual environment, leading to more efficient activation of brain neural circuits and promoting neuroplasticity [26]. Research has shown that VR-based Swiss ball simulation training for 50 minutes a day, five times a week, for a total of 4 weeks can significantly improve patients' balance and mobility [43]. Furthermore, VR technology can design personalized training tasks tailored to each patient's motor function level and rehabilitation needs, ensuring that training intensity and difficulty gradually increase in line with the patient's progress. Real-time feedback further enables patients to adjust their motor strategies promptly, improving the precision and efficiency of their training. Through multi-sensory stimulation, including visual, auditory and tactile feedback, VR enhances the brain's integration of motor control. Multimodal neuroimaging studies have demonstrated that VR training can improve neuroplasticity, affect brain activation, and ultimately enhance motor function [44]. Therefore, the multi-sensory integration mechanism may be one of the key factors contributing to VR's significantly superior efficacy compared to conventional rehabilitation methods.

The central nervous system damage caused by stroke often leads to motor dysfunction in patients, particularly a decline in fine motor skills of the upper limbs. As a result, improving limb function has become an essential area of research in stroke rehabilitation [45]. The results of this meta-analysis demonstrate that VR-assisted training significantly enhances patients' BBT scores. By creating realistic virtual environments, VR provides patients with immediate feedback and reinforcement during task completion, greatly enhancing their engagement and adherence to rehabilitation. The highly interactive nature of VR training encourages active participation from patients, thereby accelerating functional recovery [46]. In a study by Tieri *et al.* [47], VR art therapy based on the "Michelangelo Effect" showed effective improvement in upper limb muscle strength and tone in patients. Functional recovery after stroke primarily relies on neuroplasticity mechanisms. Through task-oriented training and multi-sensory stimulation, VR can activate residual neural pathways in stroke patients, promote functional reorganization in the cerebral cortex, and accelerate motor function recovery [48]. VR technology also enables personalized training programs tailored to patients' functional status and rehabilitation goals. During training, complex tasks are broken down into simpler steps, with gradual increases in difficulty, which not only supports step-by-step recovery of limb function but also reduces the fatigue and frustration that often result from overtraining. By providing multi-modal feedback, such as visual, tactile and auditory, VR can assess patients' motor performance in real-time and make necessary adjustments, thereby helping optimize motor strategies and improve the precision of motor control, especially in fine motor training [49]. Compared to traditional rehabilitation methods, VR offers greater flexibility in training location and scheduling, providing patients with a more convenient and adaptable rehabilitation path. The rapid development of tele-rehabilitation using VR also introduces new opportunities for long-term rehabilitation management, further enhancing accessibility and patient engagement in their recovery process [50].

Improving the quality of life is a central objective in stroke rehabilitation. Stroke patients typically face a wide range of challenges, including motor dysfunction, limitations in ADLs, and difficulties with psychological and social participation, which not only affect their physical health but also have a profound impact on their overall life satisfaction and well-being [51]. As a result, improving motor function is not the only focus of rehabilitation, and enhancing patients' quality of life has become an important outcome measure when evaluating the success of rehabilitation interventions. In this context, the results of this meta-analysis show that VR-assisted training significantly enhances patients' ADLs, as demonstrated by a meaningful increase in the BI score (MD = 4.57, 95% CI (1.33–7.80), $Z = 2.77$, $p = 0.006$). VR technology can achieve this by simulating real-life scenarios, such as cooking, shopping and dressing, thereby allowing patients to engage in functional training within a controlled virtual environment. This task-oriented approach is not only highly targeted to specific rehabilitation goals but also facilitates faster recovery of essential independent living skills, which directly improves the quality of life [52].

Furthermore, VR enables patients to interact with virtual characters or peers, increasing enjoyment and engagement during training. This interaction helps overcome the psychological barriers often associated with stroke recovery, such as feelings of loneliness and social isolation. These psychological and social improvements are crucial in enhancing overall quality of life. Shannon *et al.* [53] highlighted that VR technology can be used to allow patients to rate virtual ward environments based on their emotional responses and preferences, thereby personalizing the rehabilitation environment. This personalization not only improves patient compliance with rehabilitation training but also enhances overall rehabilitation outcomes. Additionally, VR technology enables the creation of individualized training programs aligned with patients' rehabilitation stages and functional levels. By gradually increasing the difficulty of tasks, VR helps patients build confidence and experience a sense of accomplishment as they overcome challenges. Furthermore, VR provides real-time visual, auditory and tactile feedback, enabling patients to assess their training performance and make necessary adjustments, which improves the accuracy of movement control. This immediate feedback mechanism accelerates functional recovery, allowing patients to make significant progress in a relatively short period, ultimately improving their ability to live independently [54]. The current meta-analysis primarily focused on upper limb rehabilitation outcomes, as most VR interventions are designed to improve hand-arm coordination. However, lower limb dysfunction, including gait impairment, remains a critical challenge in stroke rehabilitation. Although emerging studies suggest that VR has potential in lower limb training, particularly through treadmill-based simulations, these interventions were not included in this meta-analysis due to the limited number of RCTs that met the inclusion criteria. VR-based tele-rehabilitation enables early intervention initiation and high-frequency training—critical factors during the acute recovery phase. This approach is particularly valuable in resource-limited regions, where healthcare systems struggle to provide timely in-person care. By reducing travel dependence, VR empowers patients to engage in intensive, home-based rehabilitation.

The GRADE assessment highlights the "fragmentation" of evidence in VR rehabilitation, emphasizing the need to enhance the value of evidence through methodological optimization and technical standardization. Moderate to low-certainty evidence supports the short-term improvement of upper limb function and ADL through VR, indicating that VR can serve as a valuable supplement to traditional rehabilitation. However, individualized intervention plans, such as avoiding exercise-induced vertigo, are essential for maximizing effectiveness. For BBS, very low-certainty evidence suggests that the current data are insufficient to support the universal efficacy of VR in improving balance and fine motor function, which underlines the need for further research through standardized, large-sample RCTs, such as those following Consolidated Standards of Reporting Trials (CONSORT)-VR guidelines. This study FMUE scores represent post-intervention values. However, due to heterogeneity in reporting across studies, we recommend future analyses prioritize gain scores (post − pre) adjusted via Analysis of Covariance for enhanced comparability. Future studies should provide detailed descriptions of VR intervention parameters (refer to the tidier list), incorporate adaptive algorithms to dynamically adjust training difficulty, and extend follow-up periods to at least six months to assess the long-term benefits of VR. It is also important to note that, despite its advantages, VR technology may present challenges, including motion sickness in susceptible patients, high initial costs, and limited accessibility in low-resource settings.

5. Conclusions

The results of this meta-analysis demonstrate that VR technology offers significant advantages in improving upper limb motor function, balance and ADLs in stroke patients. Through its immersive, interactive and task-oriented nature, VR technology effectively promotes neuroplasticity, enhances patient engagement, and provides personalized training programs, thereby accelerating functional recovery and improving quality of life. However, there were several limitations that should be considered. First, although we included multiple high-quality RCTs, the sample size was relatively small, and some studies exhibited considerable heterogeneity, which may limit the generalizability of the results. Second, despite observing significant improvements in quality of life with VR, there is still insufficient consistent evidence regarding the impact of different VR training modes, frequencies and durations on rehabilitation outcomes. Third, while the included studies encompassed a broad age range (34–86 years), age-specific responses to VR training remain largely unexplored, as younger patients may experience faster motor adaptation due to greater neuroplasticity, whereas older adults might prioritize compensatory strategies. Thus, future trials could stratify outcomes by age and stroke type (ischemic *vs.* hemorrhagic) to better optimize personalized rehabilitation approaches. Additionally, further research should focus on refining VR training programs and examining their long-term effects, integrating individualized intervention strategies to promote broader and more effective use of VR in stroke rehabilitation.

AVAILABILITY OF DATA AND MATERIALS

The authors declare that all data supporting the findings of this study are available within the paper and any raw data can be obtained from the corresponding author upon request.

AUTHOR CONTRIBUTIONS

XPW, WYP—designed the study and carried them out; supervised the data collection; prepare the manuscript for publication and reviewed the draft of the manuscript. XPW—analyzed the data; interpreted the data. Both authors have read and approved the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This article does not contain any studies with human participants or animals performed by any of the authors.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found, in the online version, at https://oss.signavitae.com/mre-signavitae/article/1942464726230286336/attachment/Supplementary%20material.zip.

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