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REVIEW **Open Access**

Effect of virtual reality-based upper limb training on activity of daily living and quality of life among stroke survivors: a systematic review and meta-analysis

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Abstract

Background Stroke is a leading cause of disability worldwide, significantly impairing upper limb (UL) function and reducing patients' ability to perform activities of daily living (ADL) and quality of life (QoL). Virtual reality (VR) has emerged as a promising tool for UL rehabilitation, offering immersive and engaging environments for motor recovery. However, the effectiveness of VR, its integration with conventional therapy, and their efficacy across different stroke recovery stages remain unclear. Therefore, this systematic review and meta-analysis aimed to evaluate the effectiveness of VR-based UL interventions in improving ADL and QoL among stroke survivors.

Method This study adhered to PRISMA guidelines and was registered on PROSPERO (CRD42023426256). A systematic search of PubMed, Scopus, and Web of Science identified randomized controlled trials (RCTs) published in English. Inclusion criteria focused on studies using immersive VR (IVR) and non-immersive VR (NIVR) interventions to assess ADL and QoL in stroke survivors. Data extraction and quality assessment were performed independently by two reviewers using the PEDro scale to assess quality. Meta-analyses were conducted to determine the efficacy. Subgroup analyses were performed to compare IVR and NIVR, VR combined with conventional therapy versus standalone VR, and potential differences between stroke recovery stages.

Result Thirty RCTs, representing 1,661 participants, were included. Overall, VR interventions significantly improved ADL (SMD = 0.27, 95% CI [0.11; 0.43], $p < 0.001$) and QoL (SMD = 0.94 [0.09; 1.79], $p = 0.035$) compared to conventional therapy. IVR demonstrated superior outcomes for ADL compared to NIVR (SMD = 0.54 [0.13; 0.95] Vs. 0.17 [0.02; 0.36], $p = 0.03$). Subacute stroke survivors exhibited the most significant gains in ADL (SMD = 0.52 [0.16; 0.88], $p = 0.004$), compared to chronic (SMD = 0.05 [-0.36; 0.46]) or acute patients (SMD = 0.08 [-0.11; 0.27]).

Conclusion VR interventions, particularly IVR and VR combined with conventional therapy, significantly enhance ADL and QoL in stroke survivors with moderate certainty of evidence. These findings underscore the value of VR in rehabilitation, especially during the subacute phase, but highlight the need for further research into long-term effects and implementation in low-resource settings.

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Keywords Stroke, Upper extremity, Exercise, Independent living, psychological wellbeing, Rehabilitation, Immersive technology

Introduction

As the prevalence of chronic diseases is rising globally, there is a great need for acute and long-term rehabilitation services [1, 2]. Stroke, the second most common cause of morbidity worldwide, significantly impairs individuals' lives and poses a rising prevalence. According to the latest Global Burden of Disease report, there were 12.2 million new stroke cases and 101 million existing cases globally, underscoring the urgent need for immediate action to address this multifaceted public health challenge [3, 4]. Stroke survivors commonly experience upper limb (UL) impairment, with 50–80% affected in the acute, 40–60% in the subacute, and 30–50% in the chronic phase [5, 6]. Decreased UL function is a common post-stroke impairment, restricting activities of daily living (ADL), with around 30% requiring assistance, and also negatively impacting quality of life (QoL) for up to two-thirds of stroke patients [7, 8].

Targeting improvement in patients' ability to carry out ADL independently are main objectives of UL rehabilitation programs and a main driver of independence and QoL. One key factor for a successful rehabilitation is the dosage. The total amount of rehabilitation, refers to the cumulative duration of rehabilitation interventions administered to a patient, typically measured in minutes and calculated from the frequency and duration of therapy sessions was the strongest predictors of UL motor function recovery after stroke, with high-intensity having better outcome [9–11]. However it is to note that, currently, the need for rehabilitation is most of the time unmet and the patients do not benefit from enough rehabilitation, especially in Low and Middle-Income Countries (LMICs), leading to suboptimal and poor recovery [12]. Therefore, there is a huge need to develop and implement additional complementary or alternative solutions to the current rehabilitation services provided to people with stroke [4, 5]. Virtual Reality (VR) based interventions have the potential to positively improve ADL and QOL which could be the most promising substitute or addition to the current global stroke rehabilitation programs [13, 14]. VR is a computer-human interface that allows users to interact with computers, generating virtual environments where users can perform different tasks in real time [15].

VR offers numerous benefits, such as simulating real environments for training, enabling 3D visualization and modification of the body (embodiment), and enhancing motivation through fun [16, 17]. Immersive virtual reality (IVR) fully immerses users in a simulated environment using head-mounted displays, minimizing awareness of their physical surroundings. However, non-immersive VR (NIVR) relies on traditional displays like smartphone screens or monitors. Semi-Immersive VR allows interaction with virtual content while informing users of the real world, often utilizing large screens or projection systems [18]. VR therapy has improved compliance by enhancing patient engagement in rehabilitation [19], leading to greater exercise adherence while reducing physical and mental fatigue [20], even though it may cause cybersickness in some patients [21]. Few systematic reviews focused on the effect of game-based VR on upper limb impairment and function without considering ADL or QoL. They did not comprehensively examine VR's effectiveness across stroke recovery stages [22–26]. VR, as an adjunct to conventional therapy, is reported to be safe for stroke since it significantly enhances the quality of life compared to standard rehabilitation, specifically with immersive VR [27]. Current evidence demonstrates the superiority of VR, both with or without conventional therapy, over conventional therapy alone. However, there is currently no evidence regarding the comparative effectiveness of combining conventional treatment compared to solely VR [28–30]. Furthermore, the optimal timing for initiating VR interventions after a stroke, as well as identifying the most effective types of VR interventions for upper limb rehabilitation, remain unclear. Therefore, the primary objective was to examine the effect of upper-limb VR training on ADL and QoL in stroke survivors. Secondary objectives included assessing the impact of total rehabilitation time on ADL and QoL; comparing the effectiveness of IVR and NIVR, and evaluating the added benefit of combining conventional rehabilitation with VR.

Methods

This systematic review reporting was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [31], and the protocol was registered on PROSPERO (CRD42023426256).

Search strategy

The literature search was conducted in PubMed, Web of Science, and Scopus by two independent researchers. Key search terms included "stroke", "virtual reality", "upper limb", "quality of life" and "activity of daily living" using Boolean operators (AND/OR). The search term was ("virtual reality" OR "video game" OR "immersive" OR "non-immersive") AND ("upper limb" OR "upper extremity") AND (exercise OR training OR rehabilitation

OR "quality of life*" OR "activity of daily living") AND (stroke OR " cerebrovascular disorder") for the three databases (the complete search strategy is presented in Supplementary Material 1). The search was completed on February 4, 2025, and was not limited based on the year of publication given the recent development of this technology. Additionally, remaining references were manually retrieved using the snowball method from previous relevant reviews and literatures.

Study selection

The identified articles were imported into Rayyan [32], where duplicates were eliminated. Two reviewers independently reviewed titles and abstracts to select eligible articles for the review. Both reviewers then independently examined the full-text articles. Final decisions on each article were reached through consensus, with a third reviewer consulted in cases of disagreement. The study selection process done by using a predefined inclusion criteria based on the Population Intervention Comparison Outcome Study Design (PICOs) method [33].

- Population: Participants aged 18 years or older with any type of upper limb stroke. Studies involving healthy individuals or non-stroke patients were excluded.
- Intervention: Studies utilized VR for upper limb intervention, either of IVR and NIVR, as well as VR combined with neuromuscular stimulation and robotic assistance.
- Comparison: Conventional rehabilitation without VR intervention. Conventional rehabilitation that utilized any feature of VR as a comparison group were excluded.
- Outcome: Studies measured either activity of daily living (by Barthel Index, BI; Modified Barthel Index, MBI; or Functional Independence Measure, FIM) or quality of life (by EQ VAS, Euro QoL Visual Analogue Scale; SS QoL, Stroke Specific Quality of Life; SIS, Stroke Impact Scale; or SF-36, Short-Form 36 Health Survey). Studies that did not measure at least one of the above outcomes were excluded.
- Study design: Randomized controlled trials (RCTs).

The analysis focused exclusively on peer-reviewed articles published in English. This language restriction was implemented to maintain consistency in data extraction, analysis, and interpretation, given the researchers' language proficiency. Limiting the scope to English-language publications also mitigated potential bias introduced by language barriers. Protocols, reviews, conference proceedings, theses, letters, unpublished studies, and studies involving nonhuman subjects were excluded.

Methodological quality assessment

The studies' methodological quality was evaluated using the PEDro scale. The strength of the PEDro scale lies in its comprehensive criteria for quality assessment, specifically designed for RCTs only, making it highly suitable to use in this systematic review study. Furthermore, this scale provides a clear structured format that is not complex to apply while it is comprehensive enough. The PEDro scale has 11 items scale, and each satisfied item contributes one point to the total PEDro score. Item one is omitted for score calculation so that the score ranges from zero to ten points. Total PEDro scale scores of zero to three are considered 'poor quality', four to five 'moderate quality', and six to ten 'good quality' for each RCT study, and this category was used in this study [34–36]. Additionally, the Cochrane Risk of Bias tool (RoB 2) was also used to assess the risk of bias that may have been under evaluated using the PEDRo scale [37]. Two researchers conducted the methodological quality assessment. In cases of disagreement, a third researcher was consulted, and a decision was reached upon agreement. PEDRo scale was conducted to assess the methodological quality [36], to further determine the level of evidence associated with these new interventions using the GRADE system. GRADE summary of evidence and recommendation was conducted by using GRADEPro software [38, 39].

Data extraction and synthesis

Two reviewers independently extracted data from the included studies. A third independent reviewer verified the accuracy of the extracted data. Discussions and consultations with the primary author resolved discrepancies and inconsistencies as needed. The extracted information from the included studies encompassed age, gender, authors' names, countries, year of publication, type of intervention, type of stroke, VR type, study design, sample size, type and name of the devices, outcomes on ADL and QoL, and main characteristics of training and interventions. Regarding outcome data, if the single outcome measured by two different tools, we included both outcome in meta-analysis.

Statistical analysis

The potential effect of the VR for UL stroke rehabilitation was examined with meta-analysis. The measure of treatment effect was the standardized mean difference effect size (standardized mean difference (SMD)), defined as the between-group difference in mean values divided by the pooled SD computed using the Hedge's g method. The SMD is categorized as small (0.2), moderate (0.5), or large (0.8), considering the effect size between the two group means in terms of standard deviation units [40]. Change from baseline data was computed for both control and intervention from pre and post-sample size, mean, and standard deviation by using the Wan et al. formula [41]. If several tests were used to evaluate ADL or QoL in the same study, the results of the different tests were combined, using weighted mean, to produce a single SMD according to Cochrane's recommendation [42]. If the median and range were reported instead of the mean and standard deviation, these values were estimated using the methods developed by Luo et al. and Wan et al. [41, 43]. We assessed the heterogeneity in stratified analyses by type of VR and stroke classification using I^2, computed using a restricted maximum likelihood method (REML). We categorized I^2 using 25%, 50%, and 75%, representing low, moderate, and high heterogeneity [44]. To deal with high or moderate heterogeneity, we used random-effect models and presented forest plots [45]. We checked for publication bias using a funnel plot [50] and Egger's test for the intercept was applied to check the asymmetry [51]. Random-effects meta-regression analysis quantified the association of changes in ADL and QoL and the total amount of training (number of sessions multiplied by the duration of one session). Studies were weighted by the inverse of the sum of the within- and between-study variance. Also, we reported stroke classification as acute, subacute, and chronic. Sensitivity analysis was performed using the leave-one-out method to assess the robustness of the meta-analysis results. This approach involved systematically removing one study at a time from the analysis and recalculating the pooled effect estimate. This process helped us to identify whether any single study had a disproportionate influence on the overall results and evaluate the stability of the findings. Finally, a GRADE assessment of the level of evidence and recommendations was performed by systematically identifying the clinical question, population, interventions, and outcomes. The level of evidence for each outcome was based on factors such as risk of bias, imprecision, inconsistency, indirectness, and publication bias. Then, GRADE recommendations were subsequently categorized as high, moderate, or low, considering the balance of benefits and harms, the level of evidence, and other factors [46]. Statistical analyses were performed at an overall significance level of 0.05 in the R program (version 4.4.1).

Results

Search results

A total of 3030 research papers were identified from the three databases with 1294 records were filtered using the titles and abstracts. After, 673 full texts were checked and 30 RCTs were finally included in this analysis. The complete flow chart of study selection is presented in Fig. 1.

Characteristics of the participants

1661 patients were included in this review, with a predominance of male (60%) compared to women. The mean age was 59.8 ± 5.4 years (complete socio-demographic characteristics of the patients are presented in Table 1).

Concerning stroke's stage, the most frequently assessed population was subacute stroke survivor with,10 studies [47–56]. Four studies involved people in the acute stage [57–60], and in the chronic phase [61–64]. In 9 studies, a combination of acute, subacute or chronic stages were involved [58, 65–72], the stage was not clearly specified in 3 studies [73–75]. Seventeen studies reported the ratios of ischemic to hemorrhagic strokes, with ischemic strokes being the majority in all cases [48–50, 54–57, 61, 64, 68–73, 76, 77]. The breakdown of ischemic versus hemorrhagic stroke types was not reported in the other studies.

Twenty studies were undertaken in various Asian countries [47–51, 53, 54, 56, 58, 59, 61, 64–67, 72–75], accounting for the majority of the studies conducted. Europe accounted for the second-highest number of studies with 9 studies [55, 57, 60, 68–71, 76]. Both North [52] and South America [62] each contributed one study. In addition, there were no studies conducted in Africa.

Quality of the study

The quality of the research included in the current review exhibited a range of scores on the PEDro scale, spanning from 5 to 8 out of a maximum of 10 points with mean score of 6.27 ± 0.83, indicating moderate to high quality (individual results are presented in Table 1 and Supplementary Material 2). Figure 2 presents the RoB 2 score of the different individuals studies. Subject blinding, therapist blinding, and intention to treat were commonly unmet in the PEDro scale. Based on Rob2 tool for risk of bias assessment, the main cause of bias is deviation from intended interventions.

Type of intervention

Most of the included studies, 77% (n = 23) [50–54, 57–60, 62–68, 70–72, 74–77] used NIVR, while the 7 others used IVR [47–49, 56, 59, 61, 69]. More recent studies showed a higher prevalence of IVR use (Table 1). Another important aspect is how VR was integrated in the care: VR was either used alone or in combination with conventional therapy. The majority of the studies 66% (n = 20), combined VR with conventional rehabilitation (Table 1).

Immersive vs. non-immersive

The review outlined comprehensive VR exercises and rehabilitation programs for the ULs. Among these were VR video games that allowed patients to reach, grab, and manipulate things in interactive scenarios, such as "Traffic Control [53, 54]," "Mouse Mayhem [54]," and "Balloon

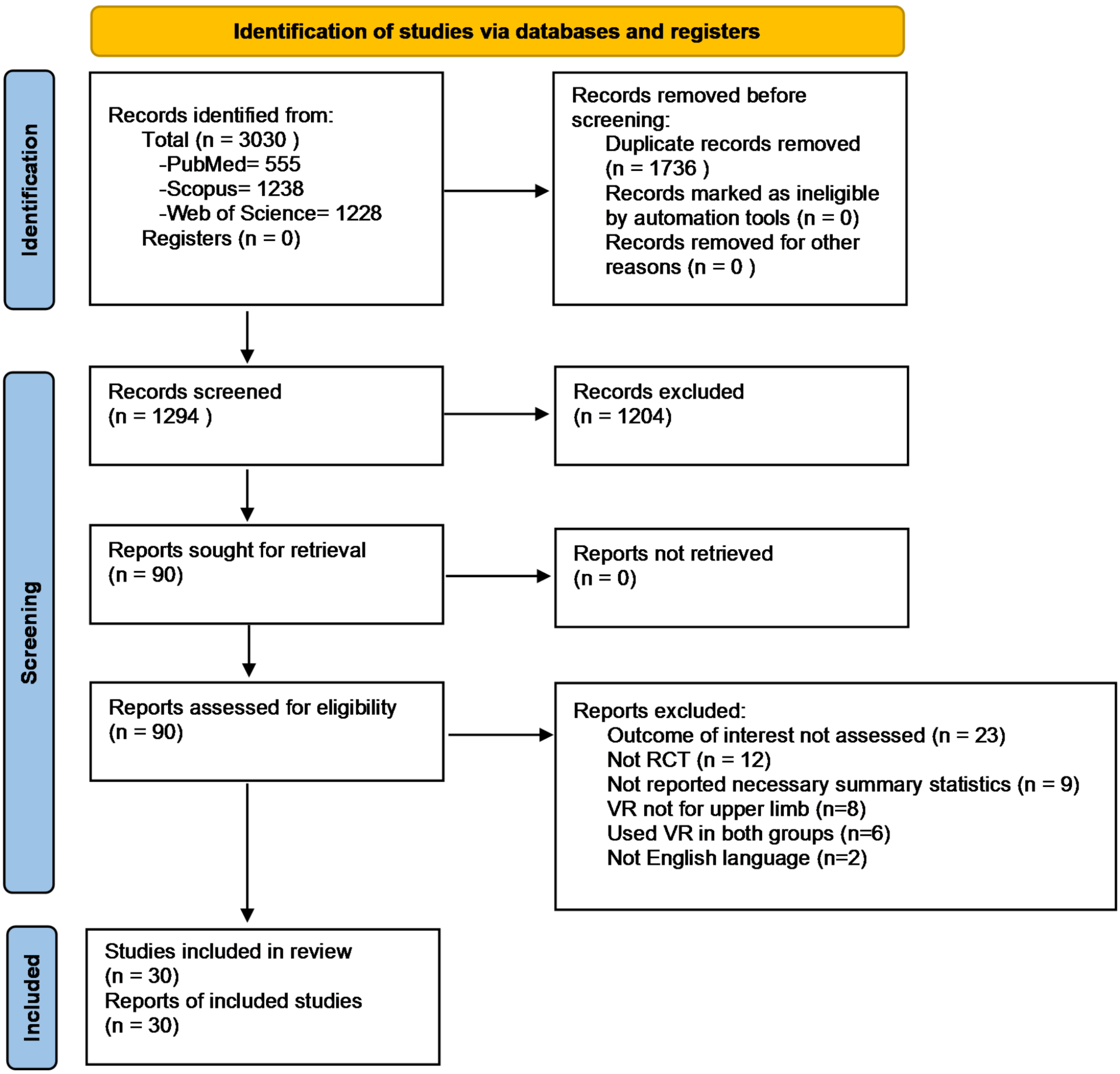

Fig. 1 PRISMA flow diagram of study screening and selection procedures

Buster [53, 54]" Playing games like table tennis [53], bowling [47, 53, 78], bingo [52], reaching [60, 73, 76], gripping [48], moving [47, 78], and releasing balls [56, 65], and other tabletop activities [56, 74, 78]. Patients also practiced specific movement patterns like flexion, extension, and abduction through targeted exercises [64, 69, 72]. IVR games such as "Underwater Fire" [72, 75] and "Bug Hunter" [72, 75] offered engaging landscapes that test one's ability to lift, reach, and coordinate their hands and fingers. Other exercises concentrated on movement speed, duration, and difficulty. Some systems incorporated advanced technology for rehabilitation, such as motion tracking and exoskeletons, to facilitate accurate and personalized instruction in reaching, gripping, and manipulating objects. In general, the data showed various and creative ways of VR being used to provide efficient and engaging UL therapy through interactive tasks, games, and immersive experiences (Table 1).

Virtual reality devices

The studies included a wide range of VR hardware and software platforms in programs for the rehabilitation of ULs. These include VR systems connected to well-known gaming consoles like Xbox Kinect (30%, $n=9$) [53–55, 58, 61, 64, 67, 71, 76] and the Nintendo Wii (10%, $n=3$) [49, 52, 62], enabling patients to participate in interactive,

Table 1 Characteristics of the included studies

Authors	Country of the study	Stroke stages	Stroke types in I /H ratio	Sex in M /F ratio	Mean age in years	Sample Size in C/E ratio	Exercise or training given	Types of VR	VR device used	Total PEDro score out of ten	Cochrane risk of Bias Over all (RoB2)
Laffonte et al.,2020 [55]	France	SA	C = 16/10 E = 22/3	C = 15/11 E = 16/9	C = 55.8 ± 14.0 E = 60.8 ± 14.1	C = 26 E = 25	Passive and active mobilization of limbs	NIVR	VR based video game device	8	Low
Afsar et al., 2018 [54]	Turkey	SA	C = 12/4 E = 15/4	C = 8/8 E = 12/7	C = 63.44 ± 15.73 E = 69.42 ± 8.55	C = 16 E = 19	Mouse Mayhem, traffic control, Balloon Buster and Mather sizing games	NIVR	VR based Xbox Kinect Game system	6	High
Gueye et al.,2021 [60]	Czech Republic	A	NS	C = 15/10 E = 14/11	C = 68.12 ± 11.97 E = 66.56 ± 12.26	C = 25 E = 25	Reach and grasping exercise	NIVR	Armeo spring upper limb exoskeleton	5	High
Leng et al.,2022 [53]	China	SA	NS	C = 8/18 E = 6/25	C = 59.12 ± 11.62 E = 59.25 ± 10.70	C = 26 E = 31	Balloon buster, table tennis, bowling and traffic control games	NIVR	Microsoft Xbox 360 Kinect	6	Low
Keskin et al.,2020 [67]	Turkey	M	NS	C = 6/8 E = 5/7	C = 63.6 ± 7.1 E = 63.6 ± 9.2	C = 12 E = 12	Difficulty, duration and speed exercise	NIVR	VR based with leap motion camera device	7	High
Rong et al.,2021 [74]	China	NS	NS	C = 14/6 E = 17/3	C = 62.30 ± 13.10 E = 56.25 ± 12.29	C = 20 E = 20	Object reaching, grasping and placing	NIVR	Arm rehabilitation robot and a customized camera based MVR	6	High
Saposnik et al.,2016 [80]	Canada	SA	NS	NS	NS	C = 70 E = 71	Playing cards, bingo, Jenga or ball games	NIVR	VR based Nintendo Wii gaming	7	Some concerns
Choi et al.,2014 [49]	South Korea	SA	C = 8/2 E = 6/4	C = 5/5 E = 5/5	C = 64.70 ± 11.3 E = 64.30 ± 10.3	C = 10 E = 10	Stretching and strengthening exercise	NIVR	Nintendo Wii based commercial game with VR	7	High
Shin et al.,2014 [75]	South Korea	M	NS	C = 3/4 E = 5/4	C = 46.6 ± 5.8 E = 52.0 ± 11.9	C = 7 E = 9	Underwater fire, bug hunter, and roller coaster game	NIVR	A task specific interactive game based VR	5	High
Kiper et al.,2013 [71]	Italy	M	C = 11/10 E = 13/10	C = 15/6 E = 14/9		C = 21 E = 23	Grasping ball, disk or glass	NIVR	Virtual reality rehabilitation system	5	High
Lee et al.,2016 [64]	South Korea	Ch	C = 5/8 E = 5/8	C = 10/3 E = 8/5	C = 69.92 ± 7.18 E = 66.46 ± 7.26	C = 13 E = 13	Flexion, diagonal extension and diagonal flexion	NIVR	VR with motion capture sensor (KINECT)	5	Some concerns
Long et al.,2020 [66]	China	M	NS	C = 16/11 E = 18/7	C = 54.11 ± 14.81 E = 53.28 ± 15.30	C = 27 E = 25	Arm flexion, abduction, gold coin picking, and cross and mixed training	NIVR	VR based game system with KINECT	7	Some concerns
Yin et al.,2014 [58]	Singapore	A	NS	C = 10/2 E = 6/5	C = 62(only mean) E = 56(only mean)	C = 12 E = 11	NS	NIVR	Non immersive VR based game	6	High
Park et al.,2019 [73]	South Korea	NS	C = 5/7 E = 8/5	C = 7/5 E = 8/5	C = 51.5 ± 16.7 E = 53.5 ± 13.0	C = 12 E = 13	Point to point reaching, circle drawing, and free exploration	NIVR	VR based planar motion	7	High
Turolla et al.,2013 [76]	Italy	M	C = 82/31 E = 188/75	C = 72/41 E = 157/106	C = 65.4 ± 12.5 E = 60.2 ± 14.3	C = 113 E = 263	Reaching movement, putting glass on shelf, and holding objects	NIVR	VR rehabilitation system with 3D motion tracking	5	High
Piron et al., 2014 [63]	Italy	Ch	NS	C = 12/11 E = 17/10	C = 62.2(9.75) E = 58.8 (8.3)	C = 23 E = 23	Touching, recognizing different arm position, and follow trajectories	NIVR	VR based reinforced feedback (RFVE)	8	High

Table 1 (continued)

Authors	Country of the study	Stroke stages	Stroke types in I /H ratio	Sex in M /F ratio	Mean age in years	Sample Size in C/E ratio	Exercise or training given	Types of VR	VR device used	Total PEDro score out of ten	Cochrane risk of Bias Over all (RoB2)
Cameir˜ao et al., 2011 [57]	Spain	A	C=6/2 E=6/2	C=4/4 E=4/4	C=65.22±11.46 E=58.77±11.42	C=8 E=8	Hitting, grasping, and placing	NIVR	VR based rehabilitation gaming	6	Some concerns
Ballester et al., 2016 [70]	Spain	M	C=6/3 E=8/1	C=8/1 E=7/2	C=54.80 (12.00) E=63.40 (9.40)	C=9 E=9	NS	NIVR	Rehabilitation gaming system	7	High
Zheng et al., 2015 [50]	China	SA	C=35/19 E=834/24	C=33/21 E=35/23	C=66.2±13.1 E=65.4±13.5	C=54 E=58	NS	NIVR	Transcranial magnetic stimulation with VR	6	High
Shin et al., 2016 [72]	South Korea	NS	C=14/8 E=15/7	C=17/5 E=19/5	C=54.6713.4 E=53.3711.8	C=22 E=24	Forearm pronation, wrist flexion, and finger flexion	NIVR	VR based RAPEL SMART glove	6	High
Rodríguez-Hernández et al., 2021 [68]	Spain	M	C=21/4 E=18/2	C=18/5 E=17/3	C=63.6±12.2 E=62.6±13.5	C=23 E=20	Resistant with ball, moving objects on table, and elevation	NIVR	VR with 3D Tutor	5	High
Ribeiro et al., 2015 [62]	Brazil	Ch	NS	C=10/5 E=9/6	C=52.8 (8.6) E=53.7 (6.1)	C=15 E=15	Transforming objects	NIVR	VR based Nintendo Wii	7	Low
Ali et al., 2024 [65]	India	M	C=47/9 E=53/11	C=41/15 E=50/14	C=57.7±10.9 E=54.4±11.7	C=56 E=64	Delicious dosa, stride the mosquito, champion cleaner, bouncing ball and fresh fruit catcher	NIVR	VR-based Arm Able TM device	7	Low
Mekbib et al.,2021 [56]	China	SA	C=8/3 E=9/3	C=8/3 E=9/3	C=61.00±7.69 E=52.17±13.26	C=11 E=12	top tabletop ball grasping, transporting, and releasing	IVR	VR based mounted head-mounted display with motion tracking	7	High
Huang et al.,2023 [48]	China	SA	C=18/2 E=19/1	C=11/9 E=13/7	C=65.05±6.14 E=63.3±14.32	C=20 E=20	Gripping and selective finger movement, gross movement, strength, and stretching	IVR	Immersive VR device not specified	7	Some concerns
Ogun et al.,2019 [61]	Turkey	Ch	C=32/0 E=33/0	C=23/9 E=28/5	C=59.75±8.07 E=61.48±10.92	C=32 E=33	A cube handling, decorating the tree with leaves, drumming, and picking up vegetables games	IVR	based VR-based game with leap motion tracking	6	High
Choi et al.,2021 [51]	South Korea	SA	NS	C=6/6 E=5/7	C=61.58±9.99 E=63.00±10.02	C=12 E=12	Visual tracking, writing, drawing, and puzzling	IVR	Ocular rift Dk2 and leap motion	7	Low
Sip et al., 2023 [69]	Poland	M	C=10/0 E=10/0	NS	C=59.2±4.34 E=54.9±9.38	C=10 E=10	Flexion, opening and closing fist, spreading and bringing together	IVR	Oculus Quest VR device	7	High
Amin et al., 2024 [47]	Pakistan	SA	NS	C=18/8 E=16/10	C=49.8±9.9 E=51.8±12.9	C=26 E=26	Hitting rolling balls, grasping balls, and swapping hand position	IVR	Oculus Quest 2 VR device	7	Low
Kwon et al. 2012 [59]	South Korea	A	NS	C=5/8 E=8/5	C=57.92±12.32 E=57.15±15.42	C=13 E=13	Reaching and lifting at different angles	IVR	Immersive VR game with video capture	5	High

A=Acute, SA=Sub-acute, Ch=Chronic, M=Mixed, NS=Not Specified, I=Ischemic, H=Hemorrhagic, C=Control, E=Experimental, M=Male, F=Female, IVR=Immersive Virtual Reality, and NIVR=Non-Immersive Virtual Reality

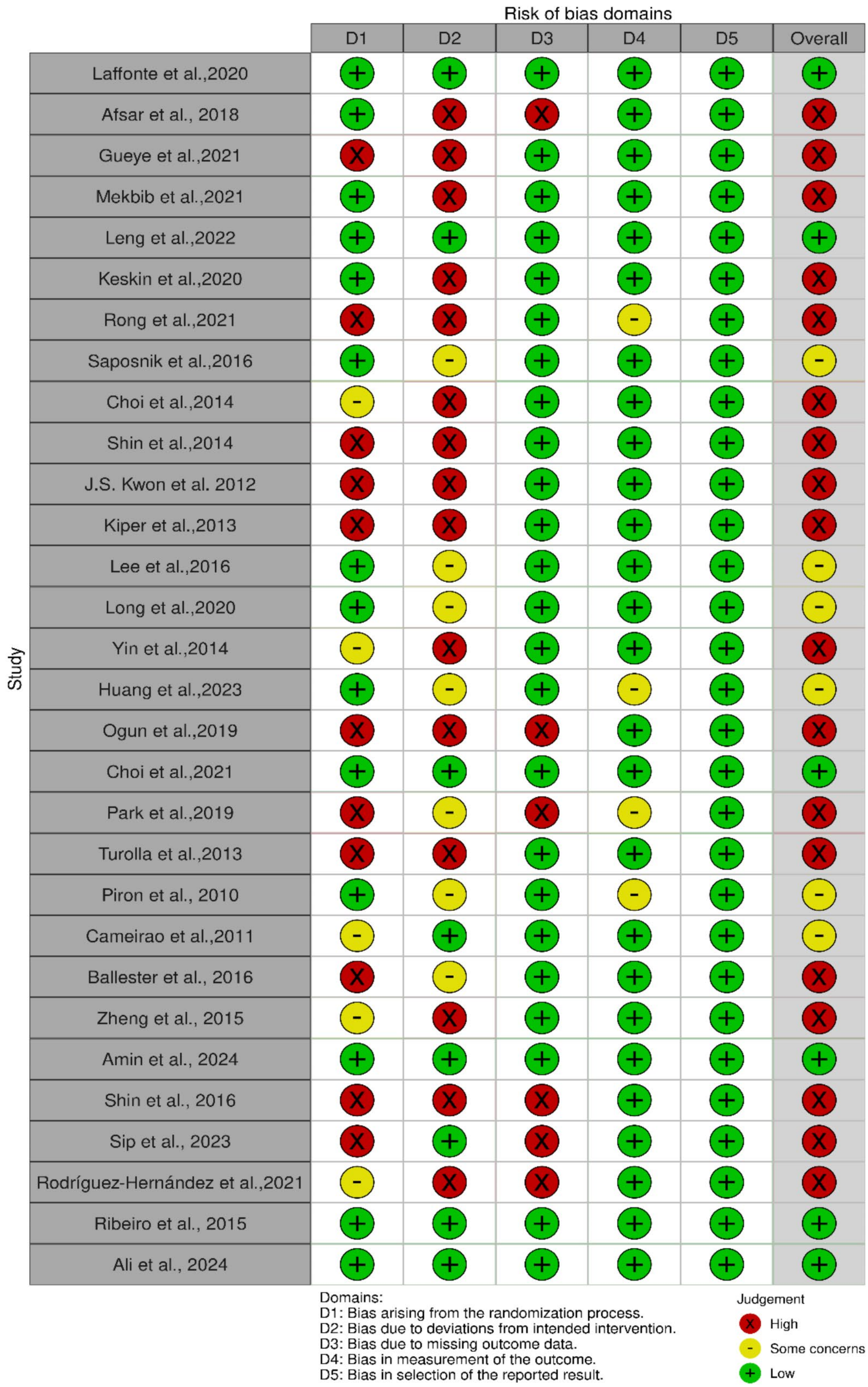

Fig. 2 : Risk of bias assessment (RoB 2) for included study

motion-controlled activities. Other systems combined VR settings with specialist rehabilitation robots, like the Armeo Spring exoskeleton [60], to facilitate passive and active limb motion. Advanced motion tracking-equipped head-mounted VR displays [47, 49, 56, 59, 61, 69], were also used to generate engaging, interactive training experiences. Interactive rehabilitation including task-specific games [75], reinforced feedback systems [63], and unique camera-based motion capture were also used [56, 58, 61, 67]. (Table 1).

Intervention dose

The trials' median duration was 4 weeks, ranging from 2 to 12 weeks. The control groups' average daily exercise session length ranged from 20 to 150 min. Session lengths of 30 to 60 min of conventional therapy per week were included in 70% of the studies [47–52, 54–56, 58, 59, 61, 63, 64, 66, 67, 73]. Although they were less prevalent, longer sessions ranging from 90 to 150 min per day were also used [68, 71, 76, 77], mainly when the overall duration of the intervention was shorter (i.e., 2 to 3 weeks). The intervention lasted a median of 4 weeks (IQR: 3 to 6), with median sessions of 52.5 min (IQR: 30 to 60). (Table 2)

Clinical efficacy

To assess the clinical efficacy of VR for UL stroke rehabilitation on ADL and QoL, different analyses were performed.

The activity of daily living

Twenty-five studies were included in this meta-analysis, in addition to 2 studies using two different measures (FIM, MBI or BI) to assess ADL [52, 66], resulting in 25 outcomes included in this section. ADL was assessed using FIM in 9 studies [52, 54, 58, 60, 61, 63, 71, 74, 76], MBI in 10 studies [47, 50, 51, 59, 64, 66, 73–75], and BI in 8 studies [48, 52, 53, 55–57, 67, 70].

The overall SMD indicates a statistically significant larger effect of VR in comparison with conventional therapy (SMD = 0.27 [95% CI 0.11; 0.43], $p < 0.001$). We then perform subgroup analysis to compare IVR and NIVR. A statistically significant difference was found between the two types of interventions ($p = 0.03$), with larger effect reported for the IVR group (SMD = 0.54 [95% CI 0.13; 0.95], $p < 0.001$) in comparison with NIVR (SMD = 0.19 [95% CI 0.02; 0.36], $p = 0.004$). (Fig. 3).

We then compared the efficacy of VR alone and in combination with conventional therapy. No statistically significant difference was found between the two groups ($p = 0.39$), but a tendency was found for a larger effect in the combined group (SMD: 0.31, [95% CI 0.12; 0.49]) compared to VR only intervention (SMD: 0.15, [95% CI -0.26; 0.56]), see Supplementary Material 3 for complete results.

Lastly, we compared the efficacy according to the stroke stage. Statistically significant differences were found between the different strokes' stages ($p = 0.048$) with larger effect obtained in the subacute phase (SMD = 0.52 [95% CI 0.16; 0.88]), in comparison with acute (SMD = 0.08 [95% CI -0.11; 0.27]) or chronic (SMD = 0.05 [95% CI -0.36; 0.46]). The forest plot is presented in Supplementary Material 4.

Quality of life

Eight studies were included in this meta-analysis using 4 different tools to measure QoL; SF-36 in 3 studies [62, 69, 73], SIS in 3 studies [50, 65, 72], EQ-VAS in one study [78], and SSQoL in one study [47].

When compared to conventional treatment, an overall statistically significant effect was found in favor of VR (SMD = 0.94 (95% CI: [0.09; 1.79], $p = 0.035$). When comparing IVR and NIVR, no statistically significant difference was found ($p = 0.98$), as presented in Fig. 4.

We then compared the efficacy of VR alone or in combination with conventional therapy. A statistically significant difference was found between the two groups ($p = 0.007$) with larger effect observed for the combination group (SMD = 1.39 [95% CI 0.13; 2.64])) compared to VR alone (SMD = 0.08 [95% CI -0.63; 0.80], see complete results in Supplementary Material 5. No significant difference was observed based different stages of stroke see Supplementary Material 6.

According to the GRADE summary of the evidence, we are moderately confident in the effect estimate for both ADL and QoL outcomes, and we can only conditionally recommend the intervention. (Supplementary Materials 7 and 8).

Dose response

We performed meta-regression to determine if the total amount of rehabilitation influences the outcome. We did not find a statistically significant association between the total duration of rehabilitation and the clinical outcome for neither ADL (β = -0.0000, Standard Error [SE] = 0.0001, $p = 0.88$), nor for QoL (β = 0.001, SE = 0.0006, $p = 0.17$) (Fig. 5). Note that for QoL this analysis may be underpowered due to the low number of included studies ($n = 8$).

Risk of publication bias and sensitivity analysis

Lastly, to test the robustness of our results, we performed sensitivity analysis to detect any potential study with extreme large effect and assessed the risk of publication bias. The analysis of the funnel plot did not reveal significant asymmetry (Supplementary Materials 9 and 10 for ADL and QoL respectively). Furthermore, the statistical

Table 2 Intervention characteristics for the comparative effectiveness of virtual reality-based upper limb rehabilitation versus conventional therapy on ADL and QoL in stroke patients

Authors	Characteristics of exercise in control	Characteristics of exercise in experimental	Primary outcome	Is the VR intervention combined with conventional?	Duration of interventions (weeks)	Duration and frequency	
						Control	Intervention
Laffonte et al.,2020 [55]	CT	CT plus VR	BI	Yes	6	45 Min/session, 5 days /week	45 Min/session, 5 days /week
Afsar et al., 2018 [54]	CT	CT Plus Xbox Kinect game system	FIM	Yes	4	60 Min /session, 6 days/week	60 Min /session, 6 days/week
Gueye et al.,2021 [60]	CT	CT plus VR Armeo Spring	FIM	Yes	3	40 Min/session, 4 days/week	40 Min/session, 4 days/week
Mekbib et al.,2021 [56]	CT	CT for plus IVR	BI	Yes	2	60 Min/session, 4 days/week	60 Min/session, 4 days/week
Leng et al.,2022 [53]	CT	CT plus VR-based game	BI	Yes	3	30 Min/session, 5 days a week	30 Min /session, 5 days a week
Shin et al.,2014 [75]	CT	CT plus VR-based training	MBI	Yes	6	60 Min/session, 3days/week	60 Min/session, five 3days/week
Rong et al.,2021 [74]	CT with Mirror visual feedback	CT plus Robot-assisted training combination with base camera-based Mirror-Visual feedback	FIM and MBI	Yes	4	90 Min/session, 5 days/week	90 Min/session, 5 days/week
Kwon et al. 2012 [59]	CT	CT combined with an intensive VR program	MBI	Yes	4	70 Min/session, 5 days/week	30 Min/session, 5 days/week
Long et al.,2020 [66]	CT	CT plus VR program	MBI	Yes	3	45 Min/session, 5 days/week	45 Min/session, 5 days/ week
Yin et al.,2014 (58)	Ct	CT plus VR therapy	FIM	Yes	2	30Min/session, 5days/week	30Min/session, 5days/week
Huang et al.,2023 [48]	CT	CT plus VR	BI	Yes	3	60Min/session, 5days/week	30Min/session,5days/week
Park et al.,2019 [73]	CT	CT plus based VR-based therapy	MBI and SF-36	Yes	4	30 min/session, 5 days/week	30 min/session, 5 days/week
Turolla et al.,2013 [76]	CT	CT plus VR	FIM	Yes	4	120Min/session, 5 days /week	120Min/session, 5 days /week
Cameir˜ao et al., 2011 [57]	CT	CT plus VR-based games	BI	Yes	12	20 Min/session, 3days/ week	20 Min/session, 3days/ week
Zheng et al., 2015 [50]	CT	CT plus VR	MBI and SIS	Yes	4	30 Min/ session, 6 days/week	30 Min/ session, 6 days/week
Amin et al., 2024 [47]	CT	CT plus VR	MBI and SS QOL	Yes	6	48 Min/session for 2 weeks then 80 Min/session for 4 weeks, 4 days/week	24 Min/per session for 2, then 40 Min/per session for 4 weeks, 4 days/per week
Shin et al., 2016 [75]	CT	CT plus VR	SIS	Yes	4	30 Min /session, 5 days/week	30 Min /session, 5 days/week
Sip et al., 2023 [69]	CT	CT plus VR	SF-36	Yes	3	30 Min/session, 6days/week, 18days only	30 Min/session, 6days/week, 18days only
Rodríguez-Hernández et al., 2021 [68]	CT	CT plus VR	EQ-VAS	Yes	3	150 Min/session, 5days week	150 Min/session, 5days week
Ribeiro et al., 2015 [62]	CT	CT plus VR based therapy	SF-36	Yes	8	60 Min/session, 2 days/week	60 Min/session, 2 days/week
Ali et al., 2024 [65]	CT	CT plus VR-based gamified therapy	SIS	Yes	6	120 Min/session, 6 days /week	120 Min/session, 6 days /week
Keskin et al.,2020 [67]	CT	VR-based therapy	BI	No	6	60 Min/session, 5 days/weekdays/week	60 Min/session, 5 days/week
Saposnik et al.,2016 [80]	CT	VR-based Nintendo Wii	BI and FIM	No	2	60 Min/session, 5 days/week	60 Min/session, 5 days/week

Table 2 (continued)

Authors	Characteristics of exercise in control	Characteristics of exercise in experimental	Primary outcome	Is the VR intervention combined with conventional?	Duration of interventions (weeks)	Duration and frequency	
						Control	Intervention
Choi et al.,2014 [49]	CT	Commercial gaming-based VR therapy using Wii (Nintendo, Tokyo, Japan)	MBI	No	4	30 Min/session, 5 days/4 week	30 Min/session, 5 days/4 week
Kiper et al.,2013 [71]	CT	VR-based therapy	FIM	No	5	120/session, 5 days/week	120/session, 5 days/week
Lee et al.,2016 [64]	CT	Individual-based VR-based therapy	MBI	No	8	30 Min/session, 3 days/week	30 Min/session, 3 days/week
Ogun et al.,2019 [61]	CT	VR based therapy	FIM	No	6	60 Min/session, 3 days/week	60 Min/session, 3 days/week
Choi et al.,2021 [51]	CT	VR based therapy	MBI	No	4	30 Min/session, 3 days/ week	30 Min/session, 3 days/ week
Piron et al., 2010 [63]	CT	VR based therapy	FIM	No	4	60 Min/session, 5 days /week	60 Min/session, 5 days /week
Ballester et al., 2016 [70]	CT	VR-based therapy	BI	No	6	30 Min/session, 5 days /week	30 Min/session, 5 days /week

CT = Conventional Therapy, BI = Barthel Index, MBI = Modified Barthel Index, FIM = Functional Independence Measure, Min = Minute/s, EQ VAS = Euro QoL Visual Analogue Scale; SS QoL = Stroke Specific Quality of Life, SIS = Stroke Impact Scale, and SF-36 = Short-Form 36 Health Survey

assessment using Egger's intercept yielded a value of 0.21 (SE = 0.68), with a corresponding *p*-value of 0.76 for ADL and 2.63 (3.55), $p = 0.48$ for QoL. Furthermore, the sensitivity analysis (Supplementary Materials 11 and 12 for ADL and QoL respectively) did not identify any study that had an extreme influence on the overall results.

Discussion

The main goal of this research was to evaluate the effectiveness of VR therapies designed for UL rehabilitation in comparison to conventional rehabilitation. The presented systematic review and meta-analysis thoroughly analyzed data from 30 RCTs, which included a cohort of 1661 stroke survivors. The review identified a diverse, versatile range of immersion ideal for upper limb rehabilitation. In general, VR-based technology illustrates an innovative approach to providing UL rehabilitation. In current review, 77% of the studies used NIVR systems, the average duration of session length was 30 to 60 min, and the median duration of the intervention programs was 4 weeks.

Our meta-analysis revealed that VR therapy demonstrated statistically significant superiority over conventional therapy. VR therapy showed a moderate improvement in ADL (SMD = 0.27 [0.11; 0.43] and a large effect on QoL (SMD = 0.94 [0.09; 1.79]. Notably, the QoL results were derived from aggregating data from only eight individual studies. The VR therapy has the ability to improve patients' motivation and enjoyment [19], improve their compliance with rehabilitation, and reduce fatigue [79]. In addition, numerous advantages of VR-based programs have been suggested, such as their affordability, ability to improve treatment outcomes, and ability to immerse stroke survivors in a world that closely resembles real objects and events - by integrating multiple sensory stimuli, such as tactile, visual, auditory, and somatosensory systems [62, 80–83]. From this review, it was also shown that VR was effective in improving both ADL and QoL when combined with conventional therapy. This could be explained by the fact that VR enhances movement quality through motor learning and repetitive practice, which can be effectively transferred to ADL [84–86]. The immersive environment that IVR creates contributes to realistic and engaging rehabilitation tasks, which could facilitate greater neuroplasticity and recovery [87, 88]. Immersive VR improves motor learning principles by providing realistic sensory feedback, enhancing task specificity through engaging environments, and facilitating error augmentation that allows users to identify and correct mistakes in a controlled setting, leading to improved skill acquisition compared to non-immersive VR [89]. In addition, IVR may enhance motor learning outcomes through VR-induced sensory integration, which encourages a more cohesive

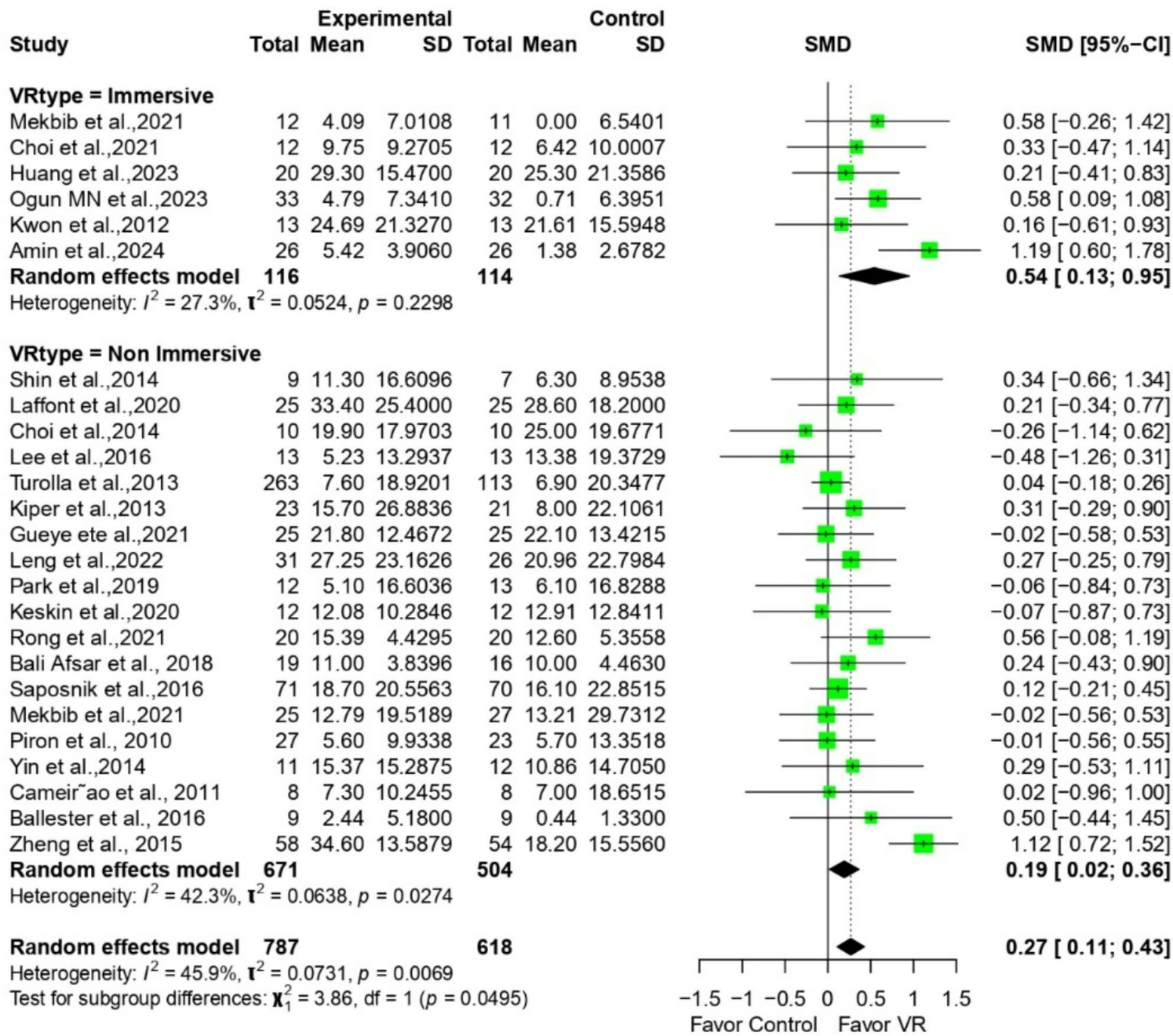

Fig. 3 Forest plot result for the comparative effectiveness of virtual reality-based upper limb rehabilitation versus conventional therapy on ADL in stroke survivors -based VR type

perception of body movements and environment; activation of the mirror neuron system, which improves the simulation of observed actions, and enhanced embodiment creates a sense of presence that strengthens the connection between mental imagery; and physical execution, collectively leading to improved neural pathways for skill acquisition and retention [90]. This approach focuses on improving movement efficiency, particularly within rehabilitation settings. Additionally, VR based rehabilitation promotes movement efficiency by allowing for tailored and repetitive practice, which is especially beneficial for individuals with motor impairments, ultimately improving balance and motor function and enhancing overall quality of life [84, 91].

Similarly, prior research indicates that conventional rehabilitation combined with a particular VR technology may be more beneficial than conventional programs alone in enhancing motor recovery and activity among stroke survivors [78, 92, 93]. Particularly in people with subacute stroke, who showed the most significant improvements with high effect in ADL based on our finding, VR offers a promising tool to accelerate recovery during this critical rehabilitation window [94, 95]. Given the relative difficulty in engaging chronic-phase patients in conventional therapies, VR's gamified and immersive nature offers an innovative alternative that sustains motivation and participation, which may otherwise decline over time. Clinicians can leverage VR to provide a more dynamic, individualized rehabilitation experience. For

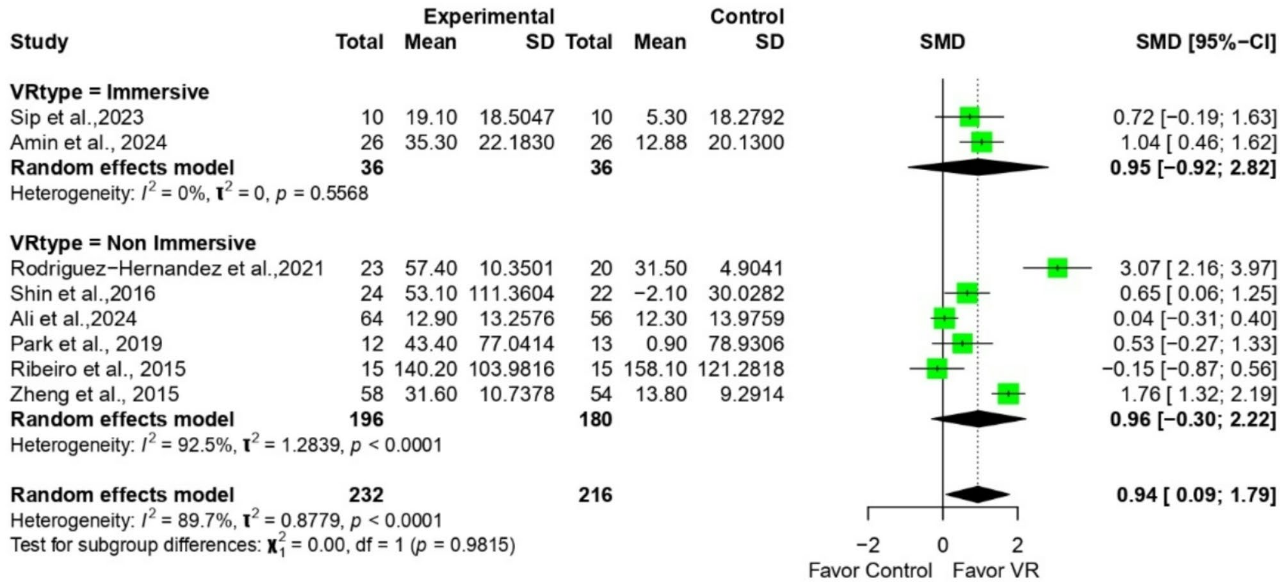

Fig. 4 Forest plot result for the comparative effectiveness of virtual reality-based upper limb rehabilitation versus conventional therapy on QoL in stroke-based VR type subgroup

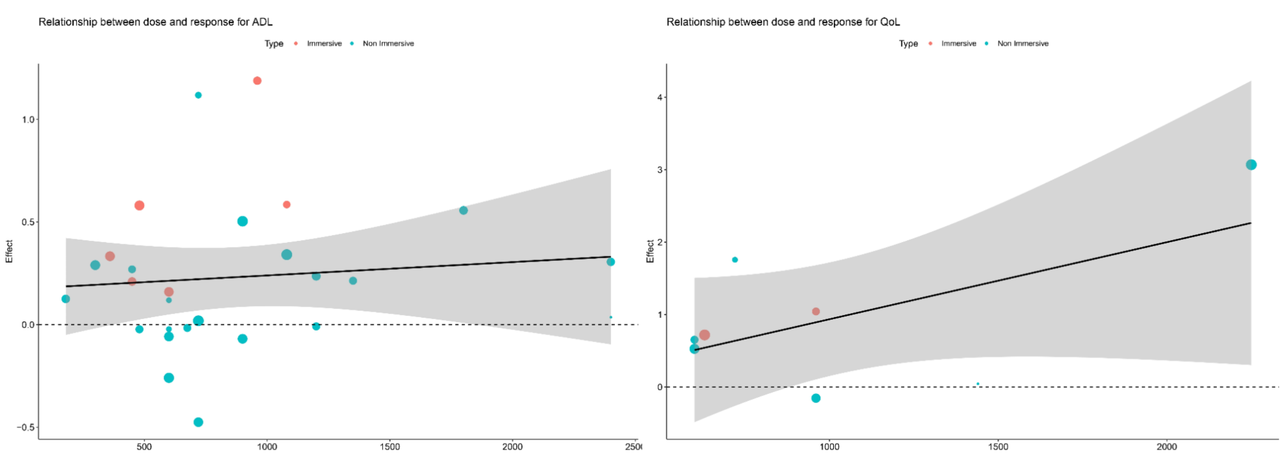

Fig. 5 Bubble plot showing the relationship between the total number of rehabilitation (minutes) and the effect on ADL and QoL (meta-regression). The size is proportional to the study weight

example, VR systems that simulate real-life tasks, such as grasping and manipulating objects, can offer functional and relevant training that directly transfers to improved ADL performance in patients' daily lives [96, 97]. Moreover, the accessibility of non-immersive VR systems (e.g., those using devices such as Microsoft Kinect or Nintendo Wii) makes them suitable for home-based rehabilitation programs [98, 99]. This opens new avenues for post-discharge rehabilitation, which can help maintain gains achieved during inpatient therapy and potentially reduce hospital readmissions. This is particularly critical in regions where access to rehabilitation services is limited or where healthcare resources are strained [100, 101].

The broad spectrum of VR-based options in this review highlights the creative ways that are being investigated to provide efficient, engaging upper limb rehabilitation through immersive, motion-driven experiences as supported by another review [102]. Numerous VR-based hardware and software technologies that have been included into UL rehabilitation programs as highlighted in the review. Training situations that are immersive and engaging are frequently created using head-mounted virtual reality displays that have motion tracking capabilities. IVR demonstrated superior outcomes compared to NIVR for ADL improvements, suggesting that IVR should be prioritized in clinical settings where possible, to maximize the rehabilitation outcomes for UL function so that it will add sensitive measures to current clinically available ones [103]. IVR provides considerable benefits for therapy targeting upper limb recovery after a stroke by increasing patient involvement, mimicking everyday tasks, fostering improved neuroplasticity, enabling real-time treatment monitoring, and enhancing gross motor skills [104, 105].

There was no significant association between the total amount of rehabilitation, ADL, and QoL. This may be due to differences in individuals responsive to VR interventions, the possibility that the amount of rehabilitation is not solely adequate, and the influence of other psychosocial factors that affect recovery beyond the rehabilitation process. Additionally, it maybe because the duration of rehabilitation was not long enough [106, 107]. The actual effect is likely to be close to the effect estimate as per our GRADE summary of the evidence, and we are moderately confident in the effect estimate for both ADL and QoL outcomes; however, there is still a possibility that it is substantially different. Further research could have a substantial impact, which may change the effect estimates. Moreover, we can only conditionally recommend the intervention, and the desirable effects probably outweigh the undesirable effects, but still, we need more confidence.

Strengths and limitations

The results of this study have to be analyzed in light of some limitations. First, even though most of the studies that were included had high methodological quality, most of them lacked blinded allocation and an intention-to-treat analysis, this may have contributed to bias in the included trials. Lack of blinding is one of the most important potential source of bias in rehabilitation research [108–111]. Other limitations including that the results of the study may be difficult to apply to stroke survivors due to high heterogeneity between the studies with important variations in the age and gender of the participants, both ischemic and hemorrhagic strokes survivors were included while their recovery path and rehabilitation process may differ. Additionally, the training parameters, and the treatment durations allocated in the different individual studies, still concerning the intervention, as we also included a few research that combined NIVR with robotic exoskeletons [50, 74, 112, 113], which makes it challenging to conclude the observed difference was solely due to NIVR. Furthermore, beside this high heterogeneity in term of patients and intervention, most of the studies included a relatively low number of participants. There is also a lack of long-term follow-up, many studies had relatively short follow-up periods, limiting the understanding of the long-term effects of VR-based rehabilitation. Thirdly, due to the low number of included studies assessing QoL, these results should be interpreted cautiously, especially for the risk of bias assessment and the meta-regression since less than 10 studies were included [114]. Fourthly, we only included studies assessed activities of daily living using specific tools like BI, MBI, and FIM and did not consider other more general activity measuring tools such as the Chedoke Arm and Hand Activity Inventory. Finally, geographical limitations with LMICs account for about 90% of all stroke-related deaths and disabilities, with sub-Saharan Africa bearing a disproportionately large burden [3]. Thus, research on the feasibility and efficacy of VR-based therapy must be carried out in LMICs, particularly in Africa, to fill the gap.

Despite these limitations, this study demonstrates several strengths. First, it provides a comprehensive analysis of the current literature on the use of VR in upper limb rehabilitation for stroke survivors, clearly articulating the differential impacts of IVR and NIVR. Furthermore, the detailed subgroup analyses offer valuable insights into how the integration of VR and conventional therapy can enhance rehabilitation outcomes. Lastly, the inclusion of both ADL and QoL as outcome measures provides a holistic assessment of the impact of VR interventions.

Conclusion

This systematic review and meta-analysis found that VR upper limb interventions combined with conventional therapy significantly improve ADL and QoL in stroke survivors compared to conventional rehabilitation methods with moderate certainty of evidence. The findings highlight the potential of VR as a beneficial tool in stroke rehabilitation, particularly in enhancing patient motivation and engagement through immersive and interactive environments even though the total amount of VR rehabilitation does not seem to have a statistically significant impact on the clinical outcomes. However, the review also identified several limitations, including high heterogeneity among studies, short follow-up periods, and a lack of research from LMICs. To address these gaps, future research should focus on conducting large-scale studies with diverse populations and extended follow-up durations. Despite the promising results, further research is necessary to establish the long-term benefits of VR-based rehabilitation, particularly in the chronic phase of stroke recovery. More large-scale, high-quality RCTs are needed to assess the durability of VR's effects on ADL and QoL over time, and to determine the optimal dose and intensity of VR interventions. Additionally, studies should explore the integration of more advanced technologies, such as VR combined with robotic devices or neurostimulation, to further enhance motor recovery outcomes.

Supplementary Information

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Supplementary Material 1

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Declarations

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Competing interests
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