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Impact of the combination of virtual reality and noninvasive brain stimulation on the upper limb motor function of stroke patients: a systematic review and meta-analysis

Nuo Zhang^{1†}, Hujun Wang^{1†}, Hanming Wang¹ and Shuyan Qie^{1*}

Abstract

Background Stroke frequently results in upper limb motor dysfunction, with traditional therapies often failing to yield sufficient improvements. Emerging technologies such as virtual reality (VR) and noninvasive brain stimulation (NIBS) present promising new rehabilitation possibilities.

Objectives This study systematically reviews and meta-analyses the efectiveness of VR and NIBS in improving upper limb motor function in stroke patients.

Methods Registered with PROSPERO (CRD42023494220) and adhering to the PRISMA guidelines, this study conducted a thorough search of databases including PubMed, MEDLINE, PEDro, REHABDATA, EMBASE, Web of Science, Cochrane, CNKI, Wanfang, and VIP from 2000 to December 1, 2023, to identify relevant studies. The inclusion criterion was stroke patients receiving combined VR and NIBS treatment, while exclusion criteria were studies with incomplete articles and data. The risk of bias was assessed using the Cochrane Collaboration tool. Statistical analysis was performed using Stata SE 15.0, employing either a fixed-effects model or a random-effects model based on the level of heterogeneity.

Results A total of 11 studies involving 493 participants were included, showing a signifcant improvement in Fugl-Meyer Assessment Upper Extremity (FMA-UE) scores in the combined treatment group compared to the control group (SMD=0.85, 95% CI [0.40, 1.31], p=0.017). The Modifed Ashworth Scale (MAS) scores signifcantly decreased (SMD=− 0.51, 95% CI [− 0.83, − 0.20], p=0.032), the Modifed Barthel Index (MBI) scores signifcantly increased (SMD=0.97, 95% CI [0.76, 1.17], p=0.004), and the Wolf Motor Function Test (WMFT) scores also signifcantly increased (SMD=0.36, 95% CI [0.08, 0.64], p=0.021). Subgroup analysis indicated that the duration of treatment infuenced the outcomes in daily living activities.

Conclusions The combination of VR and NIBS demonstrates signifcant improvements in upper limb motor function in stroke patients. The duration of treatment plays a critical role in infuencing the outcomes, particularly in activities of daily living. This systematic review has limitations, including language bias, unclear randomization descriptions, potential study omissions, and insufficient follow-up periods. Future studies should focus on exploring long-term efects and optimizing treatment duration to maximize the benefts of combined VR and NIBS therapy.

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Keywords Stroke rehabilitation, Virtual reality, Noninvasive brain stimulation, Upper limb motor function, Systematic review, Meta-analysis

Introduction

Motor dysfunction is a common post-stroke complication with recovery of the afected upper limb typically being more limited than that of the lower limb due to its inherent fexibility [[1\]](#page-14-0). Approximately 50–60% of stroke patients experience residual upper limb impairment after traditional physical therapy, which signifcantly impacts their daily life [\[2](#page-14-1)]. Since hand function is closely related to activities such as using a mobile phone, eating, and writing, its rehabilitation is crucial for overall well-being $[3]$ $[3]$. The motor relearning program after stroke is affected by various factors, including training intensity, task specifcity, motivation, and feedback [[4](#page-14-3)]. However, traditional rehabilitation approaches that focus primarily on repetition and intensity may not optimally restore neural plasticity and address the diverse needs of stroke patients [\[5\]](#page-14-4).

Emerging technologies have shown promise in overcoming these limitations and enhancing physical function recovery. Among these, noninvasive brain stimulation (NIBS) has proven efective in enhancing neuroplasticity and facilitating stroke recovery [[6\]](#page-14-5). Techniques like transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) use electrical and magnetic energy to modulate cortical excitability noninvasively, inducing sustained neuroplasticity changes $[7]$ $[7]$. The application of repetitive transcranial magnetic stimulation (rTMS) triggers neuronal growth in the brain, leading to the initiation of novel action potentials [\[8](#page-14-7)]. Studies have demonstrated the benefts of rTMS for upper limb rehabilitation in stroke patients across different stages of recovery [\[9](#page-14-8)], while tDCS has been shown to improve upper limb motor function in chronic stroke patients [[10\]](#page-14-9).

Similarly, virtual reality (VR) is increasingly efective in motor function recovery and neuroexcitation. VR training robustly engages key brain regions, including the prefrontal lobe and motor networks, driving signifcant improvements in motor function and spatial awareness [[11\]](#page-14-10).VR can be immersive or non-immersive, depending on the user's isolation from the physical environment during interaction [\[12\]](#page-14-11). Recent studies indicate that VR is benefcial for post-stroke rehabilitation, with positive effects comparable to traditional treatments $[13, 14]$ $[13, 14]$ $[13, 14]$ $[13, 14]$ $[13, 14]$. Karamians et al. highlighted VR-based rehabilitation as potentially more efective than traditional training methods for upper limb recovery in stroke patients [\[15](#page-14-14)].

When combined, noninvasive brain stimulation [[16\]](#page-14-15) and virtual reality [\[17\]](#page-14-16) can synergistically provide personalized training programs that encourage upper limb movement post-stroke. This integrated approach ofers a more engaging and personalized rehabilitation experience, potentially overcoming the limitations of conventional therapeutic methods. Previous studies have confrmed the efectiveness of combined VR and NIBS therapy for upper limb rehabilitation in stroke patients [[18–](#page-14-17)[20\]](#page-14-18). Moreover, a meta-analysis showed that adding tDCS to VR-mediated movement observation and performance tasks enhances movement improvement after stroke [\[20](#page-14-18)].

Considering the limitations of previous meta-analysis, which included a limited number of studies and lacked quality assessment, this study aimed to analyze the current scientifc evidence on combined VR and NIBS therapy for restoring upper limb motor function post-stroke. By expanding the range of databases and incorporating quality assessments, this research aims to provide a more comprehensive and reliable evaluation of the combined therapy's efficacy.

Methods

Literature review design

This study is registered with PROSPERO (CRD42023494220) and was conducted in accordance with the 2020 version of the PRISMA statement.

Search strategy and data sources

A comprehensive systematic search was conducted from 2000 to December 1, 2023, in the following databases: PubMed, MEDLINE, PEDro, REHABDATA, EMBASE, Web of Science, CNKI, Wanfang, and VIP. The search strategy included terms related to virtual reality, stroke, and non-invasive brain stimulation. Specifically, we used combinations of medical subject headings (MeSH) terms and keywords such as "virtual reality," "stroke," "cerebrovascular accident," "noninvasive brain stimulation," "transcranial direct current stimulation," and "transcranial magnetic stimulation." The detailed search strategy and full list of search terms are provided in Table [1.](#page-2-0) Searches were not restricted by language, publication date, or publication status. The search will be updated before the final analysis to ensure inclusion of the most recent studies. We used the PICOS principle proposed by Cochrane: population (stroke); intervention (VR combined with NIBS); comparison (combined or conventional

AND"current"[All Fields] AND"stimulation"[All Fields]) OR "transcranial direct current stimulation"[All Fields] OR "tdcs"[All Fields]) OR ("transcranial magnetic stimulation"[MeSH Terms] OR ("transcranial"[All Fields] AND"magnetic"[All Fields] AND"stimulation"[All Fields]) OR "transcranial magnetic stimulation"[All Fields] OR "rtms"[All Fields]) OR "iTBS"[All Fields]

#4 #1 AND #2 AND #3

treatment); outcome [for the intervention and control groups, the study reported values for the change in upper limb functional score before and after treatment, including Fugl-Meyer Assessment Upper Extremity (FMA-UE), Modified Barthel Index (MBI), Modified Ashworth Scale (MAS), and the Wolf Motor Function Test (WFMT)]; and study design (RCT or non-RCT, irrespective of publication date, status, or language).

Inclusion criteria

Two authors (Nuo Zhang and Hujun Wang) independently screened the titles and abstracts of all the studies to determine eligibility. Any disagreements were resolved by consulting a third author (Hanming Wang). The inclusion criteria were as follows: (1) participants had a stroke; (2) received VR combined with NIBS treatment; (3) aimed to evaluate the efect of combined treatment on upper limb function; (4) included FMA-UE as an indicator; (5) RCT or non-RCT studies. The exclusion criteria were as follows: (1) duplicated studies; (2) studies not available in full text; (3) studies with incomplete data; (4) studies without quantitative data.

Risk of bias and quality assessment

Two authors (Nuo Zhang and Hujun Wang) independently assessed the risk of bias in each included study using the Cochrane Collaboration tool. The quality was evaluated based on six aspects: random sequence generation (selection bias), allocation concealment (selection bias), blinding (performance bias and detection bias), incomplete outcome data (attrition bias), selective reporting (reporting bias), and other potential sources of bias. The overall risk of bias across studies was assessed, and any discrepancies were discussed with a third author to reach a consensus. The methodological quality of the randomized controlled trials was evaluated using the Physiotherapy Evidence Database Research Organization (PEDro) scale, which contains 11 items (yes or no) with a total score of ten. One item related to external validity was not used in calculating the PEDro score. Studies with PEDro scores between 6 and 10 points were considered "high" quality, those with scores of 4–5 points were considered "moderate" quality, and those with scores of 0–3 points were considered "low" quality $[21]$ $[21]$. The two authors independently evaluated the risk of bias and methodological quality of each article by discussing the results with the third author to reach a consensus when the evaluations difered.

Data extraction and statistical analysis

Two authors independently extracted data from the included studies using a standardized data extraction form, and discrepancies were resolved through discussion to reach a consensus. Extracted data included: (1) basic information of the study (title, author, year of publication, country, study information); (2) PICO information (demographic characteristics, intervention implementation methods, outcome indicators); (3) methodology section (study design, intervention time, stimulation site, parameters) and other information (funding source, potential conficts of interest, conclusions). Data were managed using Excel, and statistical analyses were performed using Stata SE 15.0 (Stata Corp LLC, College Station, TX). The fixed-effects model was used to calculate the overall efect size and 95% confdence interval (CI). The random-effects model was used for significant heterogeneity (p<0.05, $I^2 \ge 50\%$). A p value <0.05 was used to indicate a signifcant diference between the experimental and control groups in the meta-analysis. To analyze the potential factors contributing to heterogeneity among studies, we used meta-regression analysis with robust variance estimation. By adding covariates to the regression model, we analyzed whether diferent covariates afected the efect of combined therapy. Subgroup analyses were performed based on the duration of combined therapy, dividing studies into<4 weeks and>4 weeks. Sensitivity analysis was carried out using the one-by-one exclusion method. Egger's test was used to assess publication bias, with $p < 0.05$ indicating the presence of publication bias. Missing data were addressed by contacting study authors where necessary.

Results

Study characteristics

A total of 527 articles were retrieved from the database search, 21 of which were retained after removing duplicates and irrelevant records. During the detailed full-text screening, 10 studies were excluded for not meeting the inclusion criteria. Overall, the fnal quantitative analysis included 11 studies with a total of 493 participants. The detailed search and selection process are presented in the flow diagram (Fig. [1\)](#page-4-0). The included studies were conducted between 2014 and 2022. In these studies, the mean age of the patients in the combined treatment group ranged from 43.6 to 73.4 years, and the average time from stroke onset ranged from 10 days to 4 years. The treatment frequency varied from 3 to 6 times per week, with one study not reporting the treatment duration. Positive treatment efects were reported in 8 studies, 2 studies showed unclear treatment efects, and 1 study showed no effects. The studies employed different combinations of NIBS and VR: 2 used rTMS combined with VR, 8 used tDCS combined with VR, and 1 used iTBS combined with VR. The characteristics of all included studies are summarized in Table [2](#page-5-0).

Risk of bias and study quality

Figure [2](#page-8-0) presents the overall risk of bias assessment. One study did not report the method of generating the random sequence, one study did not implement allocation concealment, and fve studies did not report on allocation concealment. Eight studies did not involve blinding of participants or personnel, and three studies did not report on blinding. Four studies did not use blinding for outcome assessment, and three studies did

Fig. 1 Flow diagram of the literature screening process

not report on this aspect. Four studies did not report on selective reporting. No studies had attrition bias or other biases. It is inferred that the main risk of bias in the selected articles was due to the difficulty of blinding subjects and therapists.

According to the PEDro scores of all 11 articles in Table [3,](#page-8-1) seven were high-quality studies, three were moderate-quality studies, and one was a low-quality study. All studies achieved random allocation of subjects, obtained similar baselines among groups, reported intergroup statistical results, and provided point measures and measures of variability. However, most articles did not score on items 5, 6, or 9, indicating challenges in subject and therapist blinding (Fig. [3](#page-9-0)).

Outcome measures

Fugl‑Meyer assessment upper extremity

In this study, the FMA scores exclusively pertained to the upper extremities, which have a maximum score of 66, aligning with the research focus on upper limb motor function. All 11 included studies reported FMA-UE results. The meta-analysis showed that despite the intervention group's FMA-UE scores being lower than those of the control group, the combined treatment group exhibited a signifcantly larger efect size (SMD=0.85, 95% CI [0.4–1.31], p=0.017; Fig. [4\)](#page-10-0). However, signifcant heterogeneity was found $(I^2=80.9\%)$. Meta-regression analysis for publication year, study type, age, trial duration, disease course, and treatment duration indicated

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Fig. 2 Risk of bias graph

 $H =$ high quality; M = moderate quality; L = low quality

that disease duration was a signifcant factor afecting heterogeneity ($p=0.047$; Table [4\)](#page-10-1). Egger's test for publication bias had an intercept of 1.78 and a p value of 0.348, suggesting that there was no publication bias. The bottom row of Fig. [4](#page-10-0) describes the overall efect size of the treatment estimated using a random-efects model.

Modifed Ashworth scale

Four studies reported the efect of combined treatment on muscle spasticity in stroke patients. The meta-analysis showed that the combined treatment group had signifcantly lower MAS scores compared to the control group (SMD=− 0.51, 95% CI [− 0.83, − 0.20], p=0.032; Fig. [5](#page-10-2)). The heterogeneity test showed I^2 =0%, indicating no heterogeneity among the studies.

Modifed Barthel index

Seven studies reported MBI results. The meta-analysis showed that the combined treatment signifcantly improved the daily living abilities of stroke patients compared to traditional treatment $(SMD = 0.97, 95\%)$ CI $[0.76-1.17]$, P = 0.004; Fig. [6\)](#page-11-0). The heterogeneity test indicated significant heterogeneity $(I^2=66.2\%)$. Subgroup analysis based on treatment duration (< 4 weeks or > 4 weeks) reduced heterogeneity within subgroups but showed no signifcant diferences, suggesting that treatment duration is a potential factor afecting daily living abilities.

Wolf motor function test

Five studies reported WMFT results. The heterogeneity test indicated $I^2 = 0$ %, indicating no heterogeneity among the studies. The meta-analysis showed that the combined treatment group had signifcantly higher WMFT scores compared to the control group $(SMD = 0.36, 95\% \text{ CI } [0.08 - 0.64], p = 0.021; \text{Figs. } 7, 8).$ $(SMD = 0.36, 95\% \text{ CI } [0.08 - 0.64], p = 0.021; \text{Figs. } 7, 8).$ $(SMD = 0.36, 95\% \text{ CI } [0.08 - 0.64], p = 0.021; \text{Figs. } 7, 8).$ $(SMD = 0.36, 95\% \text{ CI } [0.08 - 0.64], p = 0.021; \text{Figs. } 7, 8).$ $(SMD = 0.36, 95\% \text{ CI } [0.08 - 0.64], p = 0.021; \text{Figs. } 7, 8).$

Fig. 3 Risk of bias summary

Sensitivity results

Based on the leave-one-out sensitivity analysis, the results showed that excluding any of the 11 studies did not exceed the 95% confdence interval and was consistent with the main results, indicating that the fndings were robust.

Discussion

In this study, a meta-analysis was performed to analyze the efectiveness of NIBS combined with VR training to improve upper limb motor function in stroke patients.

Outcome measures

The Fugl-Meyer Assessment Upper Extremity is the most frequently utilized metric across all the studies included in this meta-analysis, providing a standard measure of

upper limb motor function. Additionally, other functional assessments such as the Wolf Motor Function Test, the Modifed Ashworth Scale, and the Modifed Barthel Index were widely employed in these studies to evaluate various aspects of motor impairment and functional independence. Furthermore, it's important to note that some outcome measures not included in the metaanalysis can also assess upper limb function comprehensively. For example, Chen [\[19](#page-14-20)] implemented the Action Research Arm Test, Nine Hole Peg Test, Box and Block Test, and Motor Activity Log to conduct an extensive assessment of upper extremity motor function and fne motor skills. On the other hand, Zhao [[22\]](#page-15-0) focused on the neurophysiological level by utilizing changes in sensorymotor evoked potential latency and peak amplitude to assess the function of sensory and motor nerval conduction systems. This array of assessment tools underscores the multidimensional nature of upper limb rehabilitation and the need for both broad and specifc metrics to fully understand recovery dynamics.

Fugl‑Meyer assessment upper extremity

This meta-analysis highlights significant improvements in FMA-UE scores with combined NIBS and VR treatment compared to traditional or single training methods $(SMD=0.85, 95\% \text{ CI} [0.40, 1.31], p=0.017)$. This result aligns with previous fndings by Subramanian et al. [\[20](#page-14-18)], emphasizing the potential of combined interventions in enhancing motor recovery. The substantial improvement in FMA-UE scores suggests that integrating NIBS with VR can efectively target and enhance motor learning and neuroplasticity, crucial for upper limb rehabilitation. Notably, the baseline FMA-UE scores for the intervention group were lower than those of the control group, elucidating the initially lower post-intervention scores observed in Fig. [4](#page-10-0). This discrepancy likely reflects the inclusion of patients with more severe motor impairments in the intervention group. Nevertheless, the signifcant improvement in FMA-UE scores in the intervention group highlights the efficacy of the combined VR and NIBS intervention, even in patients with more pronounced deficits at baseline. However, the high heterogeneity (I^2 =80.9%) observed across studies necessitates further analysis to identify contributing factors.

One notable source of heterogeneity is the duration of stroke before intervention. Meta-regression analysis indicated that longer durations since stroke onset were associated with reduced efficacy ($p=0.047$). This finding is consistent with Viana et al. [[23\]](#page-15-1) and Llorens et al. [\[24](#page-15-2)], who reported that stroke patients with a history of more than one year showed limited training effects. These results suggest that early intervention post-stroke may be critical for maximizing therapeutic outcomes. This

		Control		Exp. Mean		$\%$
auther (year)	N	Mean (SD)	N	(SD)	Effect (95% CI)	Weight
Sook Joung Lee (2014)	20	47.70 (21.30)	19	42.90 (23.60)	0.21 (-0.42, 0.84)	9.51
R.T. Viana (2014)	10	50.60 (13.40)	10	46.90 (12.40)	0.29 (-0.59 , 1.17)	8.10
Chan-juan ZHENG (2015)	55	51.70 (9.10)	53	40.00 (11.00)	1.16(0.75, 1.57)	10.64
Roberto Llorens (2017)	$\overline{7}$	18.00 (5.35)	$\overline{7}$	17.60 (5.10)	0.08 (-0.97 , 1.12)	7.19
Haichao Cui (2017)	21	51.10 (8.24)	21	37.14 (7.88)	1.73 (1.02, 2.45)	9.04
Xiaoling Yao (2020)	20	34.40 (17.80)	20	32.40 (16.40)	0.12 (-0.50, 0.74)	9.56
Yuanwen Liu (2020)	15	45.93 (5.48)	15	41.33 (5.60)	0.83(0.08, 1.58)	8.85
Yu-Hsin Chen (2021)	12	47.17 (16.30)	11	40.64 (16.83)	0.39 (-0.43 , 1.22)	8.40
Roberto Llorens (2021)	14	14.79 (7.37)	15	10.13 (4.60)	0.76(0.01, 1.52)	8.80
Fei Zhao (2021)	39	29.26 (4.58)	39	18.63 (3.64)	2.57 (1.97, 3.17)	9.66
Jiahang Zhu (2022)	35	35.91 (4.82)	35	31.86 (4.21)	0.89(0.40, 1.39)	10.24
Overall, DL	248		245		0.85(0.40, 1.31)	100.00
$(I^2 = 80.9\%, p = 0.000)$						
					-2 \overline{c} $\mathbf 0$	

Fig. 4 Meta-analysis of the effect of VR combined with NIBS training on FMA-UE

Table 4 Results of meta-regression analysis

Fig. 5 Meta-analysis of the effect of VR combined with NIBS training on MAS

underscores the importance of timely rehabilitation and possibly revising clinical guidelines to prioritize earlystage interventions.

Modifed Ashworth scale

The analysis of MAS scores revealed a significant reduction in muscle spasticity in the combined treatment group compared to the control group (SMD=− 0.51, 95%

Fig. 6 Meta-analysis of the effect of VR combined with NIBS training on MBI

Fig. 7 Meta-analysis of the effect of combined VR and NIBS training on WMFT

CI $[- 0.83, -0.20]$, p=0.032). The lack of heterogeneity $(I^2=0\%)$ suggests a consistent effect across studies, reinforcing the reliability of these results. These outcomes align with the mechanisms of NIBS, which involve altering cortical excitability, reduce spasticity, and promoting motor recovery through neuromodulation.

Modifed Barthel index

The meta-analysis showed significant improvements in MBI scores, indicating enhanced daily living abilities in stroke patients receiving combined therapy (SMD=0.97, 95% CI [0.76, 1.17], p=0.004). However, substantial heterogeneity was observed $(I^2=66.2\%)$. Subgroup analysis

based on treatment duration (<4 weeks vs.>4 weeks) revealed that treatment duration is a signifcant factor infuencing ADL outcomes. While the overall improvement in MBI underscores the functional benefts of combined therapy, the variability in results suggests that longer treatment durations may be necessary to achieve consistent improvements in ADLs. This finding highlights the need for personalized treatment plans that consider the duration and intensity of interventions to optimize patient outcomes.

Wolf motor function test

The WMFT results indicated significant improvements in motor function with combined therapy $(SMD=0.36,$ 95% CI $[0.08, 0.64]$, $p=0.021$). The absence of heterogeneity $(I^2=0\%)$ in WMFT scores across studies suggests a uniform beneft of combined therapy in enhancing upper limb motor function. This consistency aligns with the established role of VR in providing engaging and task-specifc training environments, which are essential for motor learning and recovery. The positive effects on WMFT scores reinforce the potential of VR combined with NIBS to facilitate functional motor recovery.

Intensity and duration of virtual reality interventions

The studies reviewed varied in VR intervention durations, ranging from 2 to 8 weeks, with a primary

duration of 4 weeks and an intervention frequency of 5 times per week. Session durations ranged from 13 to 60 min [[19,](#page-14-20) [23\]](#page-15-1), with 20 [\[24](#page-15-2), [25\]](#page-15-3) and 30 min [[26](#page-15-4), [27](#page-15-5)] being the most common. This variability could contribute to the observed heterogeneity in treatment efects. Standardizing VR protocols, including session duration and frequency, could help clarify the optimal parameters for efective intervention. Future research should aim to determine the most efective dose–response relationship to maximize therapeutic benefts.

NIBS location and protocol

This meta-analysis included studies employing different NIBS protocols: tDCS in 7 studies, rTMS in 3 studies, and iTBS in 1 study. The variability in NIBS protocols, such as the use of cathodal versus anodal stimulation and targeting of the afected versus unafected primary motor cortex (M1), adds complexity to interpreting the results. For instance, cathodal and anodal stimulation of the unafected M1 [\[24,](#page-15-2) [25,](#page-15-3) [27–](#page-15-5)[29\]](#page-15-6) showed signifcant intervention efects, whereas anodal stimulation of the affected M1 $[23]$ $[23]$ $[23]$ did not. These findings suggest that the site and type of stimulation are crucial factors infuencing the efficacy of NIBS. The results indicate that targeting the unafected hemisphere may enhance the compensatory mechanisms, facilitating recovery in the afected hemisphere [\[30](#page-15-7)].

NIBS stimulation intensity and duration

In the 7 studies using tDCS, most used a stimulation intensity of 2 mA $[22]$. The duration of each tDCS and rTMS session ranged from 13 to 60 min, with the most common duration being between 20 and 30 min. Additionally, the stimulation frequency was generally 5 times per week. For rTMS, the parameters included 1 Hz stimulation with 800 or 1800 pulses at 80% or 90% of the resting motor threshold (rMT) [[26,](#page-15-4) [31](#page-15-8)], while iTBS was set at 50 Hz with 1200 pulses at 80% of the rMT $[19]$ $[19]$. The diferences in stimulation intensity and duration likely contribute to the variability in outcomes. Standardizing these parameters in future studies could help determine the optimal settings for maximizing therapeutic efects.

Study quality and heterogeneity

The effectiveness of NIBS may be influenced by the duration of stroke, with early-stage intervention showing more promise. Viana's study [\[23\]](#page-15-1), with a high PEDro score, did not show signifcant improvements with tDCS in patients one year post-stroke, whereas Yao et al.'s study [[25\]](#page-15-3) (PEDro score 7) with a larger sample size of subacute or chronic stroke patients demonstrated signifcant benefits. The quality of the included studies varied, with PEDro scores ranging from 2 to 9, indicating a mix of high, moderate, and low-quality studies. The primary sources of bias included lack of blinding and unclear randomization methods, particularly in Chinese studies. Ensuring rigorous methodological standards in future studies will be crucial for obtaining more reliable and generalizable results.

Limitations

This systematic review has several limitations. Language bias may exist as only English and Chinese articles were included. Additionally, randomization, allocation concealment, and blinding descriptions were unclear in several studies, leading to potential biases. Although the search strategy was comprehensive, some eligible studies may have been missed. The variability in sample sizes and insufficient follow-up periods limit the ability to observe long-term efects. Future research should use a broader range of outcome measures and extend follow-up periods to better understand the intervention's impact on functionality and quality of life.

Future research considerations

To address the limitations identifed in this study, future research should focus on several key areas. Firstly, standardizing protocols for VR and NIBS interventions is crucial to reduce heterogeneity and improve comparability across studies. Establishing consistent parameters such as duration, intensity, and frequency will enable more reliable and reproducible results. Secondly, a broader range of outcome measures should be included to capture the multifaceted impact of these interventions. In addition to motor function, assessments of cognitive function, fne motor skills, sensory processing, and quality of life are essential for a comprehensive understanding of the treatment effects. Thirdly, extending follow-up periods is necessary to evaluate the sustainability and long-term benefts of the interventions, determining whether initial improvements are maintained over time. Additionally, expanding the inclusion criteria to encompass studies published in multiple languages will minimize language bias and enhance the generalizability of fndings. Lastly, future studies should emphasize methodological rigor by providing clear and detailed descriptions of randomization procedures, allocation concealment, and blinding techniques. By addressing these considerations, future research can strengthen the evidence base for VR and NIBS in stroke rehabilitation, leading to more efective and personalized treatment protocols for improving upper limb motor function in stroke patients.

Conclusion

The integration of NIBS and VR has shown promising results in enhancing the recovery of fundamental upper limb motor function in stroke patients within a year postonset. However, this combined approach did not signifcantly improve muscle tone, daily living activities, or advanced functional abilities.

Although most experimental interventions lasted for 4 weeks, analysis suggests that longer durations result in better effects. The frequency of intervention is typically 5 times a week, with VR training sessions lasting 20–25 min and NIBS stimulation sessions lasting 20–30 min. For the intensity and stimulation area of NIBS, when using tDCS, cathodal or anodal stimulation is applied to the unafected primary motor cortex (M1) with a stimulation intensity of 2 mA. When using rTMS, the unafected M1 can be targeted with an intensity of 1 Hz, 800–1800 pulses, or 80–90% of the resting motor threshold (rMT) to enhance the stimulation efect.

In addition to the commonly used evaluation indicators for upper limb motor function in hemiplegic patients, future research should incorporate additional assessment tools, such as cognitive and fne motor skill evaluations, based on changes in stimulation areas and the degree of training. Researchers should also consider using advanced indicators, such as motor and sensory evoked potentials, functional magnetic resonance imaging (fMRI), and biomechanical analysis of movement patterns, to gain a more comprehensive understanding of the intervention's impact.

To fully understand the long-term benefts and persistence of intervention efects, it is recommended that future studies include long-term follow-up periods. This approach will help in assessing the sustainability of the improvements and provide more robust evidence for the efectiveness of combining NIBS and VR in stroke rehabilitation. By addressing these aspects, future research can build on the current fndings to optimize treatment protocols and ultimately improve the quality of life for stroke patients.

Author contributions

In accordance with our authorship policy for BMC, which offers guidance and sets criteria for authorship, the specifc contributions of each author to this manuscript are detailed as follows: Nuo Zhang (N.Z.) and Hujun Wang (H.W.), contributed equally to this work. They were both heavily involved in the conception and design of the study, data collection, and analysis. Hanming Wang (H.W.) contributed signifcantly to the methodology development and played a key role in interpreting the data. Shuyan Qie (S.Q.), as the corresponding author, was responsible for drafting the manuscript and revising it critically for important intellectual content. Additionally, S.Q. provided supervision and guidance throughout the research process. All the authors are afliated with the Department of Rehabilitation, Beijing Rehabilitation Hospital, Capital Medical University, Beijing, 100144, China. Each author has read and approved the fnal version of the manuscript. They have agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This statement supersedes any previous authorship information in the manuscript and is the one that will be published.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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