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REVIEW ARTICLE **OPEN ACCESS**

EFFECTS OF IMMERSION LEVEL AND INTERVENTION TIMING IN VR-BASED STROKE REHABILITATION: A META-ANALYSIS OF UPPER LIMB RECOVERY

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ABSTRACT

Background: Virtual Reality (VR) has emerged as a contemporary modality in neurorehabilitation, utilizing interactive environments and multisensory feedback to support neuroplasticity and motor learning. However, the influence of stroke phase and VR immersion level on therapeutic effectiveness has not been systematically synthesized.
Objective: To systematically synthesize the effectiveness of VR-based interventions on upper limb motor function after stroke and critically evaluate the moderating effects of stroke phase and VR immersion level on rehabilitation outcomes.
Methods: A systematic review and meta-analysis were conducted in accordance with PRISMA guidelines, with searches across major scientific databases. Experimental studies, including randomized controlled trials (RCTs) and quasi-experimental studies, assessing upper limb motor function using the Fugl-Meyer Assessment–Upper Extremity (FMA-UE) were included. Risk of bias was evaluated using the Cochrane Risk of Bias tool. A random-effects model was applied to calculate pooled Mean Differences (MDs), with subgroup analyses based on stroke phase and VR immersion level.
Results: Eleven studies (10 RCTs and 1 quasi-experimental study) involving 388 participants were included. VR-based interventions demonstrated a statistically significant improvement in upper limb motor function compared with conventional therapy (MD = 8.97; 95% CI 6.11–11.82; $p < 0.00001$). Significant effects were consistently observed in both the chronic phase (MD = 9.96) and the subacute phase (MD = 8.36). Both non-immersive and immersive VR yielded clinically meaningful benefits, with no significant difference between immersion levels ($p = 0.97$).
Conclusion: Virtual Reality based neurorehabilitation significantly enhances post-stroke upper limb motor recovery, with consistent effectiveness regardless of stroke phase or device immersion level. These findings support VR as a flexible and clinically applicable adjunct to standard rehabilitation, although standardized intervention protocols and long-term outcome evaluations remain necessary.

Keywords: immersion, stroke rehabilitation, upper limb motor recovery, virtual reality

Introduction

Stroke is the leading cause of long-term disability in the global adult population, with upper extremity motor recovery often remaining limited despite multimodal rehabilitation. Virtual Reality (VR) technology has demonstrated effectiveness in enhancing post-stroke motor function through neuroplasticity mechanisms; however, previous meta-analyses have reported variations in outcomes influenced by the level of VR immersion (non-immersive, semi-immersive, to fully immersive) and the phase of stroke (acute/subacute versus chronic).[1-4] Several systematic reviews and meta-analyses have demonstrated that VR is superior to conventional therapy, with a tendency toward greater benefits in interventions involving higher levels of immersion and longer exercise durations

(>15 hours).[1-2,5-6] Nevertheless, stratified analyses in these studies often fail to demonstrate significant differences between stroke phases or immersion levels, which is likely influenced by the heterogeneity of intervention protocols and relatively small sample sizes.

Consequently, meta-analytic evidence that comprehensively and quantitatively evaluates the relative contributions and potential interactions between stroke phase and VR immersion levels on upper extremity motor outcomes remains limited.[2,6-7] Therefore, this meta-analysis aims to synthesize evidence from randomized controlled trials regarding VR-based stroke rehabilitation by comparing intervention effectiveness across different stroke phases and immersion levels, as well as identifying the most relevant moderating factors to support evidence-based clinical guidelines.

Methods

The literature search and data collection were conducted through online databases, including PubMed, Scopus, and Google Scholar. This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The PICO framework Population (P), Intervention (I), Comparator (C), and Outcome (O) was employed to formulate the research question. Based on this framework, the research question was defined as: “Is Virtual Reality (VR)-based rehabilitation more effective than conventional rehabilitation in improving upper extremity motor function in post-stroke patients?”. The inclusion criteria comprised randomized controlled trials (RCTs); adult participants (≥18 years) diagnosed with stroke (sub-acute or chronic phase); the use of VR as either a primary or adjunctive intervention for upper extremity rehabilitation; quantitative outcomes measured by the Fugl-Meyer Assessment Upper Extremity (FMA-UE) score; and publications released between 2015 and 2025. Exclusion criteria included non-RCT studies; case reports, reviews, or conference abstracts without complete data; and studies that did not utilize FMA-UE as a primary outcome parameter.

Study selection was conducted in three stages. First, two independent reviewers searched the databases using keywords such as “virtual reality,” “stroke,” “upper limb,” “rehabilitation,” and “Fugl-Meyer Assessment,” with search strategies formulated using Boolean operators “AND” and “OR.” Retrieved articles were exported to reference management software to remove duplicates. Second, a calibration between the two researchers was performed to test inter-rater reliability using Cohen’s Kappa. The reviewers applied the criteria to a selected set of articles until a Kappa value of > 0.80 (almost perfect agreement) was achieved. Third, both reviewers screened all primary studies through abstract screening, followed by full-text review for eligible studies. Risk of bias assessment was performed using the Cochrane Risk of Bias 2 (RoB 2) tool, which evaluates five domains of potential bias: (1) randomization process, (2) deviations from intended interventions, (3) missing outcome data, (4) measurement of the outcome, and (5) selection of the reported result. Each domain was categorized as having a “low risk,” “some concerns,” or “high risk” of bias. The assessment was conducted independently by two reviewers.

Extracted data included study identification (author, year), sample size, stroke phase (sub-acute/chronic), VR type (immersive/non-immersive), intervention duration, and FMA-UE scores (mean and standard deviation). The pooled mean difference (MD) was analyzed using meta-analysis software with a random-effects model, with statistical significance set at $p < 0.05$. Subgroup analyses were performed based on stroke phase and VR immersion level to identify sources of heterogeneity. A forest plot was utilized to summarize the effect size estimates from all included studies.

Results

The literature search identified a total of 455 articles: 241 from PubMed, 119 from Google Scholar, and 95 from Scopus. After removing duplicates, 250 articles proceeded to the screening stage, resulting in the exclusion of 196 articles. In the subsequent phase, full-text retrieval was attempted for 54 reports, of which 24 articles were successfully obtained for eligibility assessment. A total of 13 articles were excluded due to inadequate reporting. Ultimately, 11 articles were included in the systematic review and meta-analysis. The PRISMA flow diagram is presented in Figure 1. The risk of bias assessment using RoB 2 indicated low-to-moderate risk of bias across the included studies.

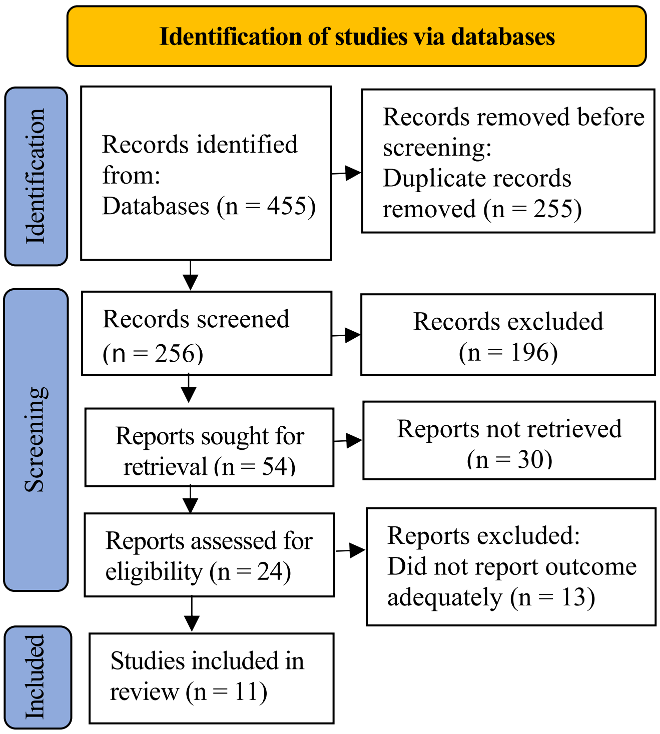

Figure 1. PRISMA Flow Chart Diagram

A summary of the extracted data is presented in Table 1, and the meta-analysis results are shown in Figures 2–3 using a random-effects model.

Table 1. Literature Search Results

Author Year (References)	Study Design	Subject (n)	BCI Type	Stroke Phase	Duration	Outcome (FMA-UE)*	Key Finding
Adams 2022[8]	RCT	VR Group (n = 9); Control Group (n = 9)	Non-Immersive (SaeboVR + Kinect)	Chronic (10-25 months)	45 min/session, 4x/weeks, 8 weeks	VR group : 52.3 ± 5.1 Control group : 44 ± 10	The VR-based home exercise program supported by telehealth provided significant clinical and statistical improvements in upper motor function ($p = 0.002$)
Alves 2018[9]	RCT	VR Group (n = 17; Control Group (n = 10)	Non-immersive (Nintendo Wii)	Chronic (≥ 6 months)	75 min/session, 5x/weeks, 2 weeks	VR group: 122 ± 13.89 Control group: 100.5 ± 17.85	VR is effective in improving motor function and is more efficient than conventional therapy ($p = 0.031$)
Ase 2025[10]	RCT	VR Group (n = 7); Control Group (n = 7)	Non-immersive (RAPAEL Smart Glove™)	Chronic (> 6 months)	30 min/day, 5 day/week, 4 weeks	VR group: 59.1 ± 4.4 Control group: 44.7 ± 15.8	Self-managed VR-based home programs are more effective in improving motor function compared to conventional home programs ($p = 0.027$)
Yu Bai 2022[11]	RCT	VR Group (n = 25); Control Group (n = 25)	Immersive (VR Digital System)	Sub-Acute (Mean time since onset 132-141 days)	40-60 min/day, 5 day/week, 10 weeks	VR group: 47.46 ± 0.48 Control group: 41.82 ± 0.79	VR-based AI rehabilitation systems are significantly more effective in restoring physical function compared to traditional therapy ($p < 0.05$)
Ogun 2019[12]	RCT	VR Group (n = 33); Control Group (n = 32)	Immersive (Oculus Rift + Leap Motion	Chronic (6-24 months)	60 min/session, 3x/weeks, 6 weeks	VR group: 46.54 ± 7.91 Control group: 40.06 ± 8.33	Immersive VR is effective in improving upper extremity function and self-care skills ($p < 0.05$)
Pradana 2025[13]	Quasi - Experi mental	VR Group (n = 10); Control Group (n = 10)	Non-immersive (3D Environment)	Sub-Acute	Administered over 3 months	VR group: 30.9 ± 4.86 Control group: 23 ± 4.02	VRUMT is effective in enhancing upper motor function recovery in stroke patients ($p < 0.05$)
Sip 2023[14]	RCT	VR Group (n = 10); Control Group (n = 10)	Immersive (Oculus Quest 2)	Sub-Acute (Mean time since onset 3,4 months)	30 min/day, 18 days (3 weeks)	VR group: 75.3 ± 22.1 Control group: 55 ± 11.6	Immersive VR is effective in improving upper sensorimotor function and provides advantages in subjective sensation and pain reduction

Table 1. Literature Search Results

Author Year (References)	Study Design	Subject (n)	BCI Type	Stroke Phase	Duration	Outcome (FMA-UE)*	Key Finding
Hsu 2022[15]	RCT	VR Group (n = 18); Control Group (n = 17)	Immersive (Oculus Rift + Leap Motion)	Chronic (> 6 months post-stroke)	50 min/session, 2x/weeks, for 9 weeks	VR group: 46.1 ± 13.7 Control group: 35.1 ± 18.6	VR-MT has the potential to restore upper motor function, although the interaction effect for the total FMA-UE score was not significant (p = 0.075)
Huang 2022[16]	RCT	VR Group (n = 15); Control Group (n = 15)	Immersive (HTC VIVE HMD)	Sub-Acute (> 3 months post-stroke)	60 min/day, 2-3x/weeks, 16 total sesion	VR group: 52.47 ± 9.11 Control group: 45.53 ± 16.39	There was a significant interaction (p = 0.008) demonstrating the superiority of immersive VR over conventional occupational therapy in improving total FMA-UE scores
Leng 2022[17]	RCT	VR Group (n = 31); Control Group (n = 26)	Non-immersive (Microsoft Xbox 360 Kinect)	Sub-Acute (< 6 months post-stroke)	30 min VR, 5 day/week, for 3 weeks	VR group: 31.87 ± 19.42 Control group: 31.54 ± 19.95	VR intervention is as effective as conventional therapy in improving upper extremity motor function
Amin 2025[18]	RCT	VR Group (n = 26); Control Group (n = 26)	Immersive (Headset Oculus Quest 2)	Sub-Acute (2 weeks – 6 months post-stroke)	4 day/week for 6 weeks (24 total session)	VR group: 55.92 ± 7.3 Control group: 42.23 ± 7.9	Immersive VR gaming with enhanced visual feedback significantly improves hand motor function compared to conventional therapy alone

*Data are presented as mean ± standard deviation
RCT: randomized controlled trial; FMA-UE: Fugl-Meyer Assessment Upper Extremity; VR: Virtual Reality

A total of 11 studies were included in both qualitative and quantitative analyses. The pooled sample comprised 388 participants, including 201 patients in the VR intervention group and 187 in the control group. The largest sample size was reported in 2019,[12] whereas the smallest was observed in 2025. The included studies comprised randomized controlled trials (RCTs) and one quasi-experimental study.[10] Most studies involved patients with ischemic stroke. All studies employed the Fugl-Meyer Assessment of Upper Extremity (FMA-UE) as the outcome measure for motor function improvement. Overall, the findings consistently indicated that VR-based stroke rehabilitation had a significant positive effect on upper limb motor recovery.

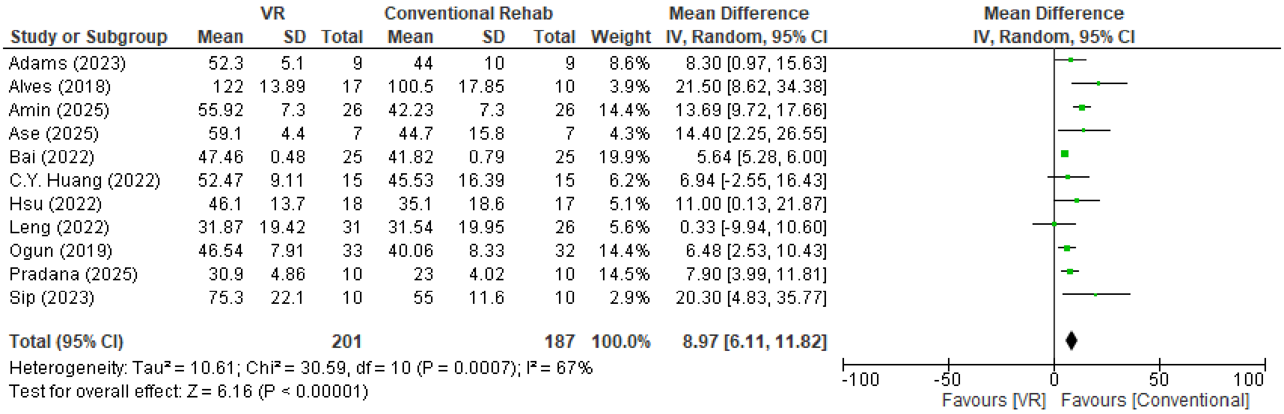

Figure 2. VR vs. Control in FMA-UE Improvement

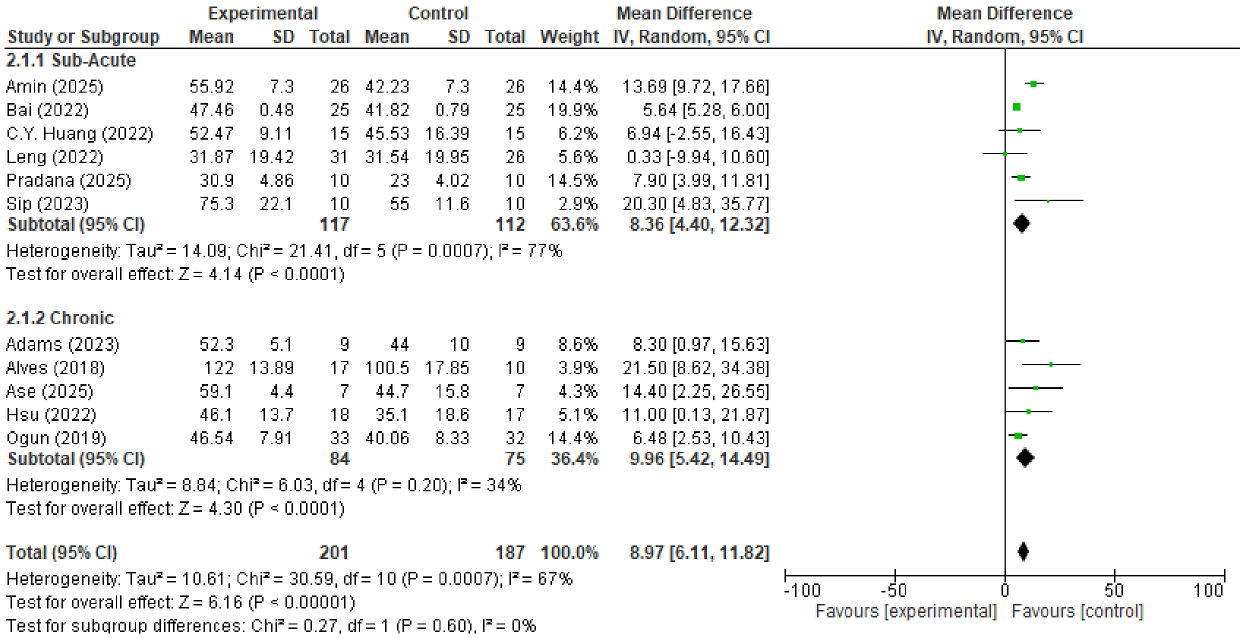

Figure 3. Stroke Phase in VR vs. Control for FMA-UE Improvement

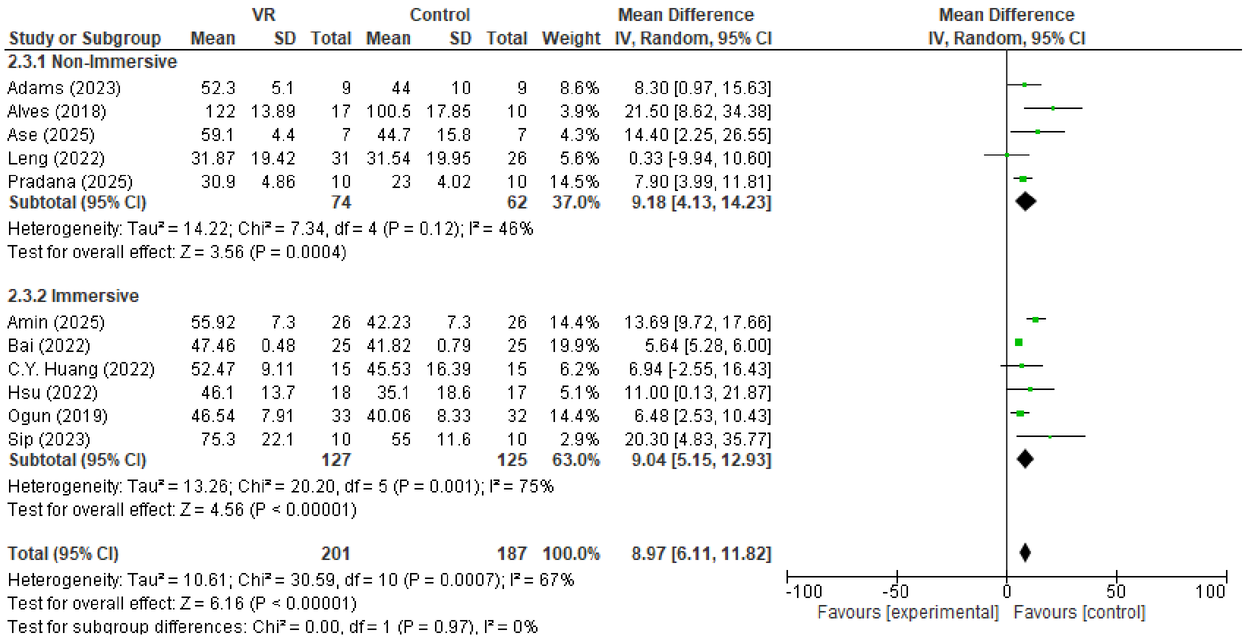

Figure 4. Immersive Levels of VR vs. Control in FMA-UE Improvement

Based on Figures 2, 3, and 4, the cumulative data across all studies indicate that VR interventions are statistically superior to conventional rehabilitation in improving motor outcomes. The pooled analysis yielded an overall MD of 8.97 [95% CI: 6.11, 11.82] with a significance level of $p < 0.00001$. Subgroup analysis further revealed that VR interventions in the Chronic phase produced significant results, with an MD of 9.96 [95% CI: 5.42, 14.49] and $p < 0.0001$, while the Sub-Acute phase also showed significant improvement with an MD of 8.36 [95% CI: 4.40, 12.32] and $p < 0.0001$. Regarding the level of immersion, the non-immersive approach demonstrated a significant difference with an MD of 9.18 [95% CI: 4.13, 14.23] and $p = 0.0004$, whereas the Immersive approach also yielded significant outcomes with an MD of 9.04 [95% CI: 5.15, 12.93] and $p < 0.00001$.

Out of a total of 455 articles identified during the initial search, 11 studies met the eligibility criteria and were included in the systematic review and meta-analysis. The inter-rater reliability between the two independent reviewers was very high, with a Cohen's kappa (K) value of 0.865. This indicates 'almost perfect agreement' according to the Landis and Koch interpretation.

Table 2. Inter-reviewer Reliability Using Cohen's Kappa

	Symmetric Measures			
	Value	**Asymp. Std. Error[a]**	**Approx. T[b]**	**Approx. Sig.**
Measure of Agreement Kappa	0.865	0.129	3.381	0.001
N of Valid Cases	15			

a. Not assuming the null hypothesis
b. Using the asymptotic standard error assuming the null hypothesis

Discussion

The results of this meta-analysis confirm that VR interventions are significantly superior to conventional rehabilitation in improving upper extremity motor function in stroke patients, with a MD of 8.97 [95% CI: 6.11, 11.82; $p < 0.00001$]. These findings are consistent with the accumulated data from 11 RCTs and one quasi-experimental study involving 388 patients, all of which utilized the FMA-UE as the primary outcome measure. The superiority of VR is clearly demonstrated in Figures 2, 3, and 4, which show a positive cumulative effect without excessive heterogeneity, indicating the overall robustness of the results.

Further subgroup analysis strengthens these findings. In the chronic stroke phase, VR yielded an MD of 9.96 [95% CI: 5.42, 14.49; $p < 0.0001$], while in the sub-acute phase, it achieved an MD of 8.36 [95% CI: 4.40, 12.32; $p < 0.0001$]. These results demonstrate that VR is effective across various stages of recovery, likely due to its ability to provide repetitive, task-based training and real-time feedback that simulates real-world environments.

Based on the level of immersion, both non-immersive (MD 9.18 [95% CI: 4.13, 14.23; $p = 0.0004$]) and immersive approaches (MD 9.04 [95% CI: 5.15, 12.93; $p < 0.00001$]) demonstrated statistical significance. Non-immersive VR may be more practical for low-cost clinical settings and high accessibility, whereas immersive VR has the potential to enhance patient motivation through deeply engaging sensory experiences.

These findings are strongly supported by the theory of neuroplasticity, in which VR stimulates the reorganization of post-stroke neural pathways through challenging virtual environments, strengthening existing synaptic connections and forming new ones via multisensory real-time feedback (visual, auditory, and proprioceptive). Motor learning principles are also highly relevant, as repetitive and task-specific training in VR facilitates motor skill acquisition by activating the contralateral sensorimotor cortex, as evidenced by the increase in EEG alpha/beta power in chronic stroke patients. Furthermore, ecological systems theory supports the transfer of skills to the real world through personalized contextual experiences in VR.[19-22]

However, theoretical evidence does not always fully support the absolute superiority of VR. Some studies highlight the limitations of VR-induced neuroplasticity, which still relies on indirect measures such as EEG/fMRI, without robust evidence of long-term reorganization or clear superiority over conventional therapy in high-severity cases. This emphasizes the need for validation through longitudinal neuroimaging to confirm the causal relationship between plastic changes and FMA-UE outcomes.[20,23]

These findings align with a recent meta-analysis reporting significant improvements in FMA-UE scores following VR-based mirror therapy for post-stroke upper extremity rehabilitation (large effect size).[24] Similarly, another meta-analysis found VR to be effective in enhancing upper limb motor function and activities of daily living (ADL) in stroke patients.[23] However, our results appear more robust compared to the Cochrane Review, which concluded that VR was not superior to conventional therapy for upper limb function, although it was beneficial as an adjunct intervention (small effect size).[25] Another meta-analysis also identified significant improvements in chronic stroke patients using VR, albeit without clear statistical superiority over conventional methods. These discrepancies may be attributed to the inclusion of more recent studies in our meta-analysis, particularly those focusing on ischemic stroke and FMA-UE outcomes, as well as the updated Cochrane Review, which now reports slight benefits of VR for upper limb recovery with moderate-to-low certainty.[24-28]

VR can be integrated into standard rehabilitation protocols to accelerate motor recovery, particularly in resource-limited settings like Indonesia. This approach is suitable for both sub-acute and chronic phases, with non-immersive VR serving as a cost-effective entry point. Despite its robustness, this review is limited by RCT dominance, potential publication bias, and variations in VR duration and intensity. The lack of long-term data (>6 months) and secondary outcomes like ADL limits full generalizability. Furthermore, the sample heterogeneity (predominantly ischemic stroke) may not fully represent hemorrhagic stroke. Future research should utilize Individual Participant Data meta-analysis to control variables such as stroke severity and VR duration. Exploring VR combined with other therapies (e.g., mirror therapy) and functional outcomes like ADL and quality of life are essential. Multi-center RCTs with long-term follow-up in Southeast Asian populations would enhance local relevance. Overall, this high-level evidence supports adopting VR as a stroke rehabilitation adjuvant, with the potential to transform clinical practice.

Conclusion

This meta-analysis demonstrates that VR-based rehabilitation significantly improves post-stroke upper extremity motor function compared to conventional therapy, with consistent effects across sub-acute and chronic phases, as well as various immersion levels. These findings bridge the knowledge gap regarding the moderating roles of stroke phase and immersion type, confirming VR as a flexible and adaptive modality for motor recovery. However, these results should be interpreted cautiously due to limitations such as heterogeneous intervention protocols, varying treatment intensities, and a lack of long-term follow-up data. Future large-scale multicenter clinical trials with standardized protocols, stratification by stroke severity, and long-term outcome evaluations are necessary to optimize the clinical implementation of VR, particularly in developing countries like Indonesia.

Research Ethics

This study received no external funding. Ethical approval was not required as this was a systematic review and meta-analysis of published data. All authors approved the final manuscript.

Declaration of Interests

The authors declare no conflicts of interest.

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