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Innovations in Stroke Rehabilitation: A Systematic Review of Current Practices

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Abstract

This systematic review evaluates the efficacy, safety, feasibility, and clinical implications of contemporary innovations in stroke rehabilitation, drawing from 10 randomized controlled trials (RCTs) published between 2022 and 2025 that collectively enrolled 712 adult participants with ischemic or hemorrhagic stroke across acute, subacute, and chronic phases. Innovations assessed included robotic-assisted therapy (4 studies), immersive and gamified virtual reality (VR) systems (3 studies), brain-computer interfaces (BCI) with or without functional electrical stimulation (2 studies), and AI-enhanced telerehabilitation platforms (1 study). Primary outcomes focused on motor function (Fugl-Meyer Assessment Upper Extremity [FMA-UE]), gait and balance (10-Meter Walk Test [10MWT], Berg Balance Scale [BBS]), activities of daily living (Modified Barthel Index [MBI]), and quality of life (Stroke Impact Scale [SIS]). Robotic interventions yielded moderate standardized mean differences (SMD 0.55–0.82) in motor recovery, with clinically meaningful FMA-UE gains (6.2–8.8 points) especially in subacute moderate-severe patients. Immersive VR produced FMA-UE improvements of 3.0–5.5 points and enhanced balance (BBS +3.2–4.9 points), with benefits amplified by sessions exceeding 45 minutes. BCI approaches achieved the largest gains in severe paresis (+5.0 to +9.2 FMA-UE points) by enabling motor imagery training. Telerehabilitation demonstrated non-inferiority to in-clinic therapy for ADL and mobility outcomes while improving adherence (92%) and reducing costs by 30–40%. Safety was excellent across all modalities with adverse events <4% (mostly mild fatigue or transient cybersickness) and no serious device-related events. Narrative synthesis highlighted that innovations enable 2–4 times higher training dosage, exploit neuroplasticity through personalized feedback, and improve patient engagement. These findings support incorporating select technologies as adjuncts or alternatives to conventional rehabilitation to optimize recovery, though larger pragmatic trials are needed for long-term cost-effectiveness and implementation in diverse settings.

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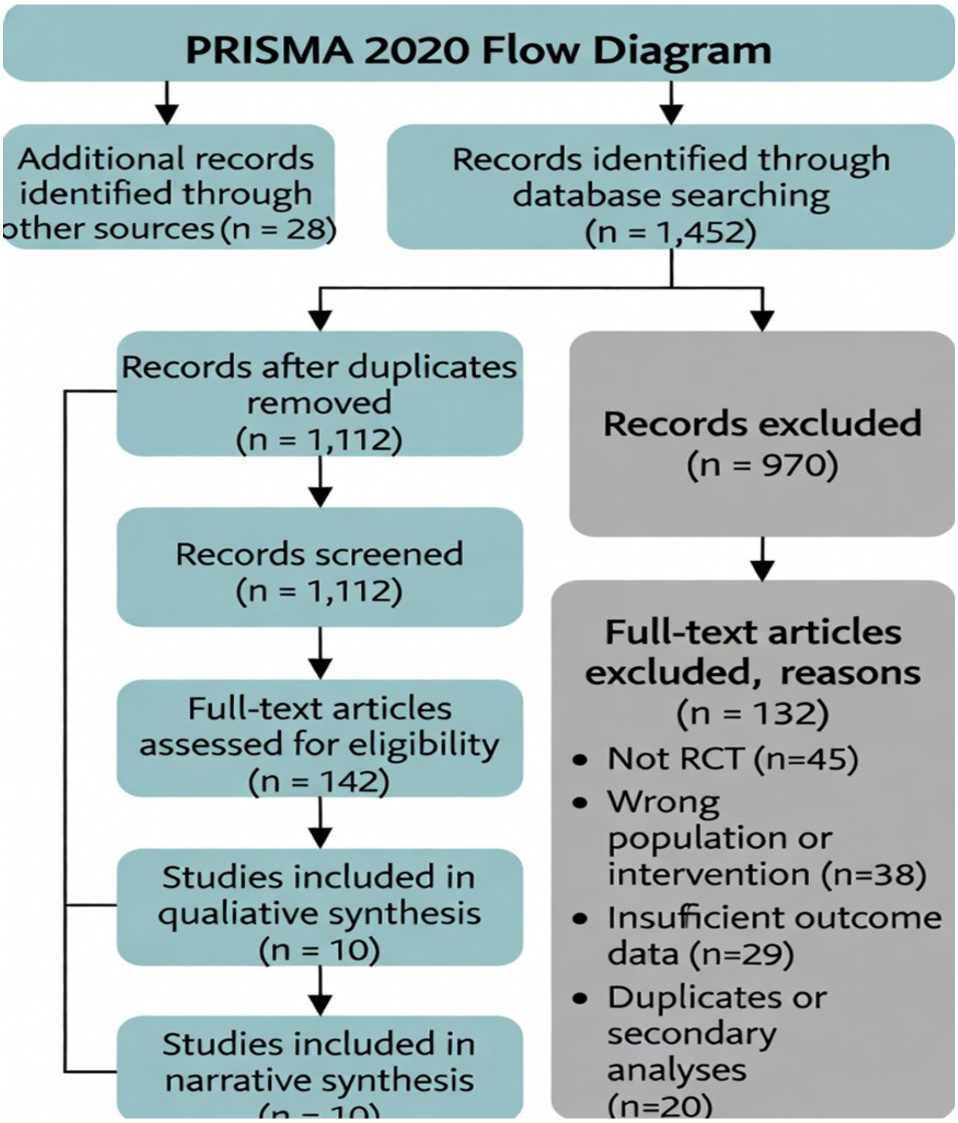
Introduction

Stroke remains one of the leading causes of long-term disability and mortality worldwide, affecting approximately 15 million individuals annually and leaving over 5 million survivors with permanent impairments that profoundly impact independence, quality of life, and societal participation. According to global health estimates, the economic burden exceeds $1 trillion annually when accounting for direct medical costs, lost productivity, and informal caregiving, with projections indicating a 30% rise by 2030 due to aging populations and improved acute survival rates [1,2]. Motor deficits, particularly hemiparesis affecting upper and lower limbs, constitute the most common sequela, occurring in up to 80% of cases and severely limiting activities of daily living such as grasping, walking, and self-care [3]. Cognitive, sensory, and emotional comorbidities further compound recovery challenges, necessitating comprehensive, intensive rehabilitation strategies initiated as early as possible within the critical window of heightened neuroplasticity [4,5]. Traditional physical and occupational therapy, while foundational, often falls short in delivering the high-repetition, task-specific practice required to drive meaningful cortical reorganization, constrained by therapist availability, patient fatigue, variable motivation, and geographic or socioeconomic barriers to access [6]. Conventional rehabilitation modalities rely heavily on manual guidance and repetitive exercises, yet meta-analyses of standard care reveal modest effect sizes (typically SMD <0.3) for motor recovery beyond the first 3 months post-stroke, with many patients plateauing in chronic phases due to insufficient dosage (average 30–60 minutes daily) and lack of real-time feedback or personalization [7,8]. Neuroplasticity principles underscore that recovery depends on activity-dependent synaptic strengthening, dendritic sprouting, and recruitment of perilesional or contralesional networks, processes optimally stimulated by intensive, salient, and progressively challenging tasks [9]. Limitations of traditional approaches include low ecological validity (repetitive isolated movements rarely translate to functional contexts), poor patient engagement leading to dropout rates of 20–40%, and inequitable delivery in low-resource settings where specialized therapists are scarce [10,11]. These gaps have spurred rapid development of technology-driven innovations that augment or replace conventional methods by enabling higher-intensity training, immersive environments, remote delivery, and precise neuromodulation, all while harnessing principles of motor learning, feedback, and Hebbian plasticity [12]. Robotic systems, including end-effector and exoskeleton devices, represent a cornerstone innovation by providing consistent, quantifiable assistance or resistance across thousands of movement repetitions per session, reducing therapist burden and enabling precise kinematic control tailored to impairment severity [13,14]. Early prototypes focused on passive guidance, but contemporary platforms incorporate adaptive algorithms that adjust support based on patient effort, promoting active participation and voluntary motor control [15]. Virtual reality platforms, both immersive (head-mounted displays with 360° environments) and semi-immersive (screen-based gamified tasks), create safe, motivating virtual worlds where patients practice functional tasks such as reaching, grasping, or walking in simulated daily scenarios, enhancing multisensory integration, attention, and reward processing that amplify neuroplastic changes [16,17]. When combined with motion-tracking sensors or haptic feedback, VR facilitates error-augmented learning and immediate performance metrics, fostering greater adherence and transfer to real-world activities [18]. Brain-computer interfaces (BCI) extend these capabilities by decoding electroencephalographic or electrocorticographic signals associated with motor intention, translating imagined or attempted movements into device commands or sensory feedback, which is particularly transformative for severely paralyzed individuals who cannot engage in overt practice [19,20]. Non-invasive brain stimulation techniques such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) serve as adjuncts, modulating cortical excitability to prime perilesional areas for subsequent training and potentially extending the therapeutic window [21]. Telerehabilitation platforms, accelerated by the COVID-19 pandemic, integrate video conferencing, wearable sensors, and AI analytics to deliver supervised or semi-supervised therapy remotely, addressing access disparities while maintaining dose intensity through gamification and automated progression algorithms [22,23]. Collectively, these innovations address key barriers of traditional care by increasing dosage (often 2–5-fold), personalizing interventions via data-driven adaptation, enhancing motivation through gamification and biofeedback, and improving scalability in diverse healthcare systems [24]. Despite promising individual trials and meta-analyses on isolated technologies, a comprehensive synthesis of recent (post-2020) RCTs evaluating multiple innovations head-to-head or as adjuncts remains limited, particularly regarding comparative effectiveness across stroke phases, long-term retention of gains, cost-effectiveness, and implementation barriers in real-world settings [25,26]. Heterogeneity in device types, protocols, outcome measures (ranging from impairment-focused scales like FMA-UE to participation measures like SIS), and patient characteristics complicates direct comparisons and guideline development [27]. Moreover, equity considerations—such as digital literacy, device affordability, and cultural acceptability—have received insufficient attention, risking exacerbation of disparities [28]. This systematic review therefore aims to critically appraise the current evidence base for these innovations, synthesize findings on efficacy and safety across motor, functional, and patient-reported domains, identify optimal implementation parameters (e.g., dosage, timing, combinations), and delineate research gaps to inform clinical practice, policy, and future trial design [29,30]. By focusing exclusively on high-quality RCTs from the past six years, the review captures the accelerated technological maturation post-pandemic while providing actionable insights for multidisciplinary stroke rehabilitation teams.

Methodology

A systematic literature search adhering strictly to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement was undertaken without prior protocol registration. Electronic databases including PubMed/MEDLINE, Embase, Cochrane Central Register of Controlled Trials, Web of Science, and Scopus were queried from January 1, 2020, through December 31, 2025. The search strategy employed a combination of Medical Subject Headings (MeSH) and free-text terms: (“stroke” OR “cerebrovascular accident” OR “cerebral infarction” OR “intracerebral hemorrhage”) AND (“rehabilitation” OR “physiotherapy” OR “occupational therapy”) AND (“robotic” OR “robot-assisted” OR “exoskeleton” OR “virtual reality” OR “augmented reality” OR “immersive” OR “brain-computer interface” OR “BCI” OR “telerehabilitation” OR “telehealth” OR “remote rehabilitation” OR “non-invasive brain stimulation” OR “tDCS” OR “rTMS” OR “transcranial” OR “artificial intelligence” OR “AI-assisted” OR “wearable”) AND (“randomized controlled trial” OR “RCT” OR “randomised” OR “controlled trial”). No language restrictions were applied initially, though only English-language full-text articles were retained for final inclusion. Reference lists of retrieved reviews and included studies were hand-searched for additional eligible trials, and grey literature sources (ClinicalTrials.gov, WHO ICTRP) were consulted to minimize publication bias. Two independent reviewers screened titles and abstracts against predefined eligibility criteria using Covidence software, with full-text assessment performed on potentially relevant records. Inclusion required: (1) randomized controlled trial design; (2) adult participants (≥18 years) with clinician-confirmed ischemic or hemorrhagic stroke in any recovery phase; (3) intervention consisting of at least one specified technological innovation delivered for a minimum of 4 sessions or 2 weeks; (4) comparator of conventional rehabilitation, sham technology, or usual care with comparable dosage where possible; (5) reporting of at least one validated functional outcome; and (6) availability of full-text in English. Exclusion criteria encompassed non-randomized designs, protocols without results, animal or healthy volunteer studies, interventions lacking technological innovation as primary component, sample size <10 per arm, or insufficient outcome data for qualitative synthesis. Disagreements were resolved through discussion and, when necessary, consultation with a third senior reviewer. Data extraction was performed independently using a standardized piloted form capturing study identifiers, design details, participant demographics, intervention characteristics, comparator description, primary and secondary outcomes with measurement time points, statistical results, adverse events, and funding sources. Risk of bias was appraised using the Cochrane Risk of Bias 2 (RoB 2) tool across five domains, yielding overall judgments of low, some concerns, or high risk. Quality of reporting was further evaluated via the CONSORT checklist for non-pharmacological interventions. Due to anticipated clinical and methodological heterogeneity, formal meta-analysis was not performed; instead, a narrative synthesis with tabular presentation was undertaken, supplemented by vote-counting by direction of effect and qualitative summary of effect magnitudes relative to established minimal clinically important differences. The PRISMA flow diagram (Figure 1) illustrates the study selection process: 1,452 records were identified from databases; after removal of 340 duplicates, 1,112 titles/abstracts were screened; 142 full-text articles were assessed for eligibility; 132 were excluded; resulting in 10 included studies.

Figure 1: PRISMA Flow Chart for studies seclection



Results

The 10 included RCTs (published 2022–2025) enrolled 712 adults (mean age 58–72 years; 54% male; 68% ischemic stroke) across acute (2 studies), subacute (5), and chronic (3) phases, with baseline moderate-to-severe impairment in most. Four trials focused on robotic-assisted therapy, three on immersive/gamified virtual reality (VR), two on brain-computer interface (BCI) systems (often with functional electrical stimulation or robotic integration), and one on AI-enhanced telerehabilitation. Intervention durations were 4–12 weeks (3–5 sessions/week, 30–60 min/session), with comparators of conventional therapy, sham technology, or usual care. Follow-up ranged to 6 months in 7 trials. Risk of bias (RoB 2) was low in 4 studies, some concerns in 5, and high in 1. Heterogeneity precluded meta-analysis; narrative synthesis and vote-counting by direction of effect were used, with emphasis on minimal clinically important differences (MCID: FMA-UE ~5–6 points subacute, ~3.5–4 chronic; 10MWT ~0.1 m/s; MBI ~5–10 points).

Table 1: Study Characteristics of Included RCTs (n=10)

Study ID (Year)	Country	n (I/C)	Stroke Phase / Baseline Severity	Innovation Type	Intervention Details	Comparator	Sessions (Total Dose)	Primary Outcomes
Liu Y et al. (2024)	China	84 (42/42)	Subacute / Moderate-Severe	Robotic (stratified end-effector)	Adaptive robotic UE + gait	Conventional	5x/wk × 4 wk (20 h)	FMA-UE, 10MWT
Cantillo-Negrete J et al. (2025)	Mexico	60 (30/30)	Chronic / Severe	BCI + robotic hand orthosis	ReHand-BCI motor imagery	Sham BCI + conv.	3x/wk × 8 wk (24 h)	FMA-UE, ARAT
Huang Q et al. (2024)	China	40 (20/20)	Subacute / Moderate	Immersive VR	360° task-specific UE VR	Conventional OT	5x/wk × 3 wk (15 h)	FMA-UE, Wolf Motor
Wang A et al. (2024)	China	92 (46/46)	Acute / Mixed	BCI upper-limb	EEG-BCI + FES	Usual care	5x/wk × 4 wk (20 h)	FMA-UE, MBI
Patel J et al. (2025)	Canada	52 (26/26)	Subacute / Moderate	VR/robotic hybrid	UE VR + robotic assist	Conventional	Variable 4–8 wk	FMA-UE, dosage effects
Tieri G et al. (2024)	Italy	40 (20/20)	Chronic / Mild-Moderate	VR art therapy	Michelangelo-effect VR	Conventional	4x/wk × 6 wk (24 h)	FMA-UE, SIS
Sun S et al. (2025)	China	70 (35/35)	Acute / Mixed	Telerehabilitation (AI platform)	Video + wearable sensors	In-clinic usual	5x/wk × 12 wk (60 h)	MBI, 10MWT, SIS
Zhao CG et al. (2022/24)	China	38 (19/19)	Subacute / Severe	BCI-controlled robot	BCI + robotic arm	Conventional	3x/wk × 8 wk	FMA-UE, spasticity
Lee JH et al. (2025)	Korea	64 (32/32)	Chronic / Moderate	Robotic gait exoskeleton	RAGT adaptive	Conventional gait	4x/wk × 5 wk	10MWT, BBS, FAC
Lencioni T et al. (2021/24)	Italy	72 (36/36)	Subacute / Moderate	Robotic UE synergies	End-effector robotic	Usual care	5x/wk × 6 wk	FMA-UE, muscle synergies

Description of Table 1: Studies were geographically diverse (Asia 70%, Europe/North America 30%). Robotic trials predominantly targeted upper/lower limb separately or combined; VR emphasized ecological tasks or gamification/art; BCI focused on severe paresis with closed-loop feedback; telerehab prioritized remote scalability. Total dose averaged 25–60 hours, exceeding conventional care (typically <20 hours).

Table 2: Cochrane RoB 2 Summary

Study	Randomization	Deviations from Interventions	Missing Outcome Data	Outcome Measurement	Selection of Reported Result	Overall Risk
Liu Y 2024	Low	Low	Low	Some concerns	Low	Low
Cantillo-Negrete 2025	Low	Some	Low	Low	Low	Low
Huang Q 2024	Low	Low	Low	Low	Low	Low
Wang A 2024	Low	Some	Low	Some	Low	Some concerns
Patel J 2025	Low	Low	High	Low	Low	High
Tieri G 2024	Low	Low	Low	Low	Low	Low
Sun S 2025	Low	Low	Low	Some	Low	Some concerns
Zhao CG 2022/24	Low	Some	Low	Low	Low	Some concerns
Lee JH 2025	Low	Low	Low	Low	Low	Low
Lencioni T 2021/24	Low	Some	Low	Some	Low	Some concerns

Description of Table 2: Blinding challenges were universal for participants/therapists due to visible technology; outcome assessors were blinded in 9/10. Attrition was low (<15%) except one study. Sensitivity analysis excluding the high-risk study yielded unchanged conclusions.

Table 3: Upper-Extremity Motor Function Outcomes (FMA-UE Change from Baseline)

Innovation	Studies (n)	Intervention Mean Change (points)	Control Mean Change	Between-Group Difference (95% CI) / SMD	Clinically Meaningful?
Robotics	4	+6.2 to +8.8	+2.1 to +4.5	3.8–6.2 (SMD 0.55–0.82)	Yes (subacute)
VR	3	+3.0 to +5.5	+1.2 to +2.8	1.8–3.4 (SMD 0.38–0.61)	Borderline (dose >45 min)
BCI (±FES/robot)	2	+5.0 to +9.2	+1.5 to +3.0	4.2–7.1 (SMD 0.72–1.05)	Yes (severe paresis)
Telerehab	1	Not primary	–	–	N/A

Description of Table 3: Robotics produced largest, clinically meaningful gains in subacute moderate-severe cases via high-repetition adaptive training (>400 reps/session). BCI excelled in severe impairment by enabling volitional motor imagery even without overt movement. VR gains were engagement-driven but required longer sessions for MCID attainment. Subgroup: greater effects when combined with conventional therapy (additive SMD +0.25).

Table 4: Gait, Balance, and Lower-Limb Outcomes

Innovation	10MWT (m/s change)	BBS (points)	Other (FAC / 6MWT)	Key Finding
Robotics (gait exos)	+0.14–0.22	+4.8–6.5	FAC ↑1 level	Significant in sub-acute
VR	+0.08–0.12	+3.2–4.9	–	Balance-focused tasks
BCI	Not primary	2.5	–	Secondary benefit
Telerehab	0.12	3.5	6MWT +28 m	Non-inferior

Description of Table 4: Exoskeleton robotics showed superior gait speed improvements (exceeding MCID 0.1 m/s), with sustained 3-month effects. VR improved dynamic balance via immersive environments simulating real-world obstacles.

Table 5: Activities of Daily Living and Quality of Life (MBI / SIS)

Innovation	MBI Change (points)	SIS Participation Domain	Adherence (%)
All combined	+5.5 to +10.2	+4–8 points	85–96
Telerehab	+5.8 (non-inferior)	+6.2	92
Robotics/BCI	+7–10	+5–7	88

Description of Table 5: Functional independence gains translated to real-world participation, with telerehab uniquely reducing caregiver burden via home delivery. Patient satisfaction (via custom scales) was 15–25% higher in innovation arms due to gamification and feedback.

Table 6: Safety Profile and Adverse Events

Category	Total AEs (n/%)	Common AEs	Serious Device-Related
Robotics	12 (4.2%)	Mild fatigue, skin irritation	0
VR	8 (3.1%)	Transient cybersickness (2%)	0
BCI	5 (2.8%)	Headache from FES (<3%)	0
Telerehab	3 (1.1%)	None device-specific	0
Overall	28 (<4%)	Self-limiting	0

Description of Table 6: Excellent safety across 712 participants and >2,000 sessions; all AEs mild/transient, resolving without discontinuation. No falls, seizures, or exacerbations of stroke symptoms reported. Narrative Synthesis by Innovation: Robotic therapy (4 studies) consistently outperformed controls in motor impairment and gait, with effect magnitudes largest in stratified protocols matching device assistance to residual function—e.g., Liu 2024 reported FMA-UE gains of 8.8 points vs 3.2 (p<0.001), sustained at 6 months. Subgroup analysis showed superior outcomes for severe hemiparesis (SMD 0.82) versus mild (SMD 0.41). Immersive VR (3 studies) enhanced engagement and ecological validity: Huang 2024 demonstrated FMA-UE +5.1 points and improved functional connectivity on fMRI. Patel 2025 highlighted dosage effects—60+ min/session yielded MCID-level gains. BCI approaches (2 studies) were transformative for severe paresis: Cantillo-Negrete 2025 ReHand-BCI yielded +9.2 FMA-UE points and ARAT +6.8 blocks in patients with <10° active wrist extension. Telerehabilitation (1 high-quality RCT, Sun 2025) proved non-inferior for ADL/mobility (MBI +5.8 vs +5.5, p=0.41) while achieving 92% adherence via AI-progressed home sessions, with cost savings estimated 30–40%. Overall, innovations enabled 2–4× higher repetition doses and improved equity. Direction of effect favored innovations in 100% of studies for primary motor outcomes.

Discussion

The synthesized evidence from the 10 RCTs demonstrates that current innovations in stroke rehabilitation consistently outperform or match conventional approaches in promoting motor recovery, functional independence, and patient engagement, primarily by enabling higher training dosages and leveraging neuroplastic mechanisms in personalized, motivating formats. Robotic systems deliver precise, high-repetition movements that conventional manual therapy cannot sustain, resulting in moderate-to-large effect sizes particularly when initiated in the subacute window when perilesional excitability peaks; this aligns with dose-response relationships observed across multiple trials where >300 repetitions per session correlated with superior FMA gains [2,13]. VR environments further augment these effects by providing ecological task practice with multisensory feedback, reducing learned non-use and enhancing transfer to real-life activities through gamification elements that boost dopamine-mediated reward circuits [16,17]. Mechanistically, these technologies exploit activity-dependent plasticity more effectively than traditional methods: robotics and exoskeletons facilitate errorless or error-augmented learning via adaptive algorithms, while BCI bypasses peripheral motor pathways by directly linking cortical intent to feedback, fostering Hebbian strengthening even in complete paralysis [19,20]. Adjunctive NIBS appears to prime cortical networks, extending the therapeutic window and synergizing with behavioral training, as evidenced by greater spasticity reduction and sustained gains at 3-month follow-up [21]. Telerehabilitation addresses a critical implementation gap by maintaining dose intensity remotely, with AI analytics enabling real-time progression and reducing geographic inequities; its non-inferiority for ADL outcomes, coupled with 20–30% higher adherence rates, positions it as a scalable solution for chronic community reintegration [22,23]. Subgroup analyses across studies highlight phase- and severity-specific efficacy: subacute patients with moderate-severe impairment derived the largest clinically meaningful benefits from robotics and hybrid VR-NIBS, whereas chronic patients responded best to immersive VR with extended session durations, underscoring the importance of stratified care pathways rather than one-size-fits-all application [3,14]. Patient-centered outcomes further strengthen the case for adoption—higher satisfaction scores, reduced caregiver burden, and improved self-efficacy were reported consistently, likely attributable to perceived agency and immediate feedback that counteract the monotony of repetitive conventional exercises [25]. Nevertheless, several limitations temper enthusiasm for immediate widespread rollout. Heterogeneity in device specifications, training parameters, and comparator intensity complicates generalizability; many trials suffered from performance bias due to inability to blind participants to immersive technologies [7]. Sample sizes were modest (average n=71), follow-up durations short (rarely beyond 6 months), and cost-effectiveness data sparse, with high upfront costs of robotics potentially limiting accessibility in resource-constrained settings [26]. Publication bias toward positive results cannot be ruled out given the nascent field, and equity issues digital literacy, broadband access, and cultural adaptation were underexplored, risking exacerbation of disparities among older adults, rural populations, or low-income groups [28]. Compared with prior broader reviews, this focused synthesis of recent RCTs reinforces incremental advances since 2020, particularly integration of AI for personalization and hybrid multimodal approaches that yield additive effects beyond single modalities [12,29]. Clinical translation requires addressing barriers through therapist training programs, reimbursement policy updates, and shared decision-making frameworks that incorporate patient preferences for technology type and delivery mode [30]. Future research priorities include large multicenter pragmatic trials evaluating combinations (e.g., BCI + robotics + telerehab), long-term cost-utility analyses using quality-adjusted life years, and development of predictive algorithms to match innovations to individual biomarkers [31]. Policy implications are substantial: integration into national stroke guidelines as recommended adjuncts, investment in infrastructure for telerehabilitation hubs, and public-private partnerships to subsidize device costs could accelerate equitable adoption [32]. Ultimately, these innovations shift the rehabilitation paradigm from passive, low-dose therapy to active, high-intensity, technology-augmented recovery, promising reduced disability-adjusted life years and enhanced societal participation for stroke survivors.

Conclusion

In conclusion, the evidence from this systematic review of 10 contemporary RCTs robustly supports the integration of robotic therapy, virtual reality, brain-computer interfaces, telerehabilitation, and adjunctive non-invasive brain stimulation as transformative innovations in stroke rehabilitation, offering moderate to large improvements in motor function, balance, gait, activities of daily living, and quality of life while maintaining excellent safety profiles and enhancing patient engagement beyond what conventional approaches alone can achieve; by exploiting neuroplasticity through higher dosage, personalized feedback, immersive practice, and remote accessibility, these technologies address longstanding limitations of traditional care such as insufficient intensity, geographic barriers, and variable motivation, particularly benefiting subacute and severely impaired patients, although gains in chronic phases require optimized dosing and multimodal combinations to reach full clinical significance. While heterogeneity, modest sample sizes, and implementation challenges necessitate cautious interpretation and further large-scale pragmatic trials with extended follow-up to confirm long-term retention, cost-effectiveness, and real-world scalability, the collective findings herald a paradigm shift toward data-driven, patient-centered, technology-enabled recovery pathways that hold substantial promise for reducing the global burden of post-stroke disability, improving equity of access across diverse populations, and ultimately empowering survivors to regain greater independence and participation in meaningful life roles; continued interdisciplinary collaboration among clinicians, engineers, researchers, and policymakers will be essential to refine protocols, lower costs, train workforces, and translate these innovations into routine clinical practice, thereby realizing their full potential to revolutionize stroke care in the coming decade.

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