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A Narrative Review

Advancing Neurorehabilitation Through Virtual Reality and Robotics: A Critical Narrative Review of Motor Recovery Technologies

Ayesha Rashid[1], Tehreem Mukhtar[1], Shumail Najam[1], Rija Khalid[1], Haroon Rasheed[1], Mubsirah Qamar[1], Maryam Shahid[1]

[1] The Superior University, Lahore, Pakistan

Correspondence: aaishkhan905@gmail.com

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ABSTRACT

Background: Neurological disorders such as stroke, spinal cord injury, and Parkinson's disease often lead to persistent motor deficits. Conventional rehabilitation is limited by insufficient therapy intensity and patient adherence. Virtual reality (VR) and robotics have been increasingly studied as adjunctive interventions to enhance motor recovery. Objective: To synthesize evidence from 2015–2025 on the effectiveness of VR and robotic technologies in motor neurorehabilitation, with attention to mechanisms, outcomes, limitations, and future directions. Methods: A narrative review was conducted using PubMed, Scopus, and Google Scholar. Eligible studies included randomized controlled trials, systematic reviews, and meta-analyses assessing VR and/or robotic interventions for motor recovery in patients with neurological motor impairments. Results: Across systematic reviews and meta-analyses, VR demonstrated small-to-moderate improvements in upper-limb function, particularly in stroke survivors, with immersive VR outperforming non-immersive systems (standardized mean differences ranging 0.3–0.5). Robotics improved activities of daily living and strength, especially in upper-limb rehabilitation, though effect sizes were modest when compared to dose-matched conventional therapy. Device comparisons showed end-effector robots favored for proximal arm recovery, while exoskeletons were more effective for distal hand function. Lower-limb robotics, including exoskeleton gait trainers, showed gains in gait speed and ambulation but with mixed evidence. Combined VR-robot interventions and brain–computer interface (BCI) systems showed preliminary additive effects, though evidence quality was low-to-moderate and most trials had <50 participants with short follow-up (<6 months). Conclusion: VR and robotics provide measurable but modest improvements in motor recovery and are best used as adjuncts to conventional therapy. Broader clinical adoption requires standardized protocols, inclusion of diverse populations, long-term outcome evaluation, and cost-effectiveness strategies.

Keywords: Neurorehabilitation; Virtual Reality; Robotics; Stroke; Motor Recovery; Brain–Computer Interface; Telerehabilitation.

INTRODUCTION

Neurological disorders such as stroke, spinal cord injury, traumatic brain injury, multiple sclerosis, and Parkinson's disease remain leading causes of long-term disability worldwide, often resulting in persistent motor impairments that substantially affect independence and quality of life. These conditions impose a major burden on healthcare systems and families, with rehabilitation being an essential component of management (1,2). Traditional neurorehabilitation strategies typically rely on repetitive, task-specific training aimed at promoting neuroplasticity. However, in routine practice, patients often receive less than the recommended intensity and duration of therapy due to workforce limitations and infrastructural constraints (3). As a result, conventional approaches frequently fail to deliver optimal recovery outcomes.

In recent years, virtual reality (VR) and robotic-assisted therapies have emerged as promising adjuncts to address these limitations. Robotic systems, including exoskeletons and end-effector devices, enable repetitive, precise, and task-oriented practice at adjustable levels of assistance or resistance, thereby extending the therapeutic capacity beyond what a single therapist can provide (4). Meanwhile, VR systems—both immersive and non-immersive—create interactive, multisensory environments that provide enriched feedback, real-time performance monitoring, and game-like engagement, which enhance motivation and adherence to therapy (5,6). When applied together, VR and robotics offer complementary benefits: robotics ensures intensity and biomechanical accuracy, while VR delivers engaging feedback and contextualized task practice (7–9).

This convergence of technology with rehabilitation principles aligns with core neurorehabilitation goals of maximizing dosage, enhancing motivation, and stimulating neuroplasticity. Recent systematic reviews and meta-analyses suggest that both VR and robotics, when used as adjuncts to conventional therapy, can lead to modest improvements in motor outcomes, particularly in stroke rehabilitation (10–12). Despite these encouraging findings, several challenges remain, including heterogeneity of protocols, small sample sizes, variable methodological quality, and concerns about cost-effectiveness and accessibility (13,14). Moreover, evidence beyond stroke populations—such as spinal cord injury, Parkinson's disease, or pediatric disorders—remains limited, hindering generalizability.

Given the rapid pace of innovation and increasing clinical interest, it is timely to critically appraise the current state of evidence, implementation challenges, and future directions in this field. The purpose of this narrative review is to synthesize peer-reviewed research published between 2015 and 2025 on the application of VR and robotic technologies in motor neurorehabilitation. Specifically, the review aims to: (1) evaluate current evidence on VR and robotic interventions for motor recovery, (2) compare their mechanisms, effectiveness, and limitations, (3) explore emerging trends such as artificial intelligence (AI), brain–computer interfaces (BCIs), and wearable technologies, and (4) highlight practical implications, research gaps, and policy considerations. By providing an integrated perspective, this review seeks to guide clinicians, researchers, and healthcare policymakers in advancing neurorehabilitation practices through technology-assisted interventions.

MATERIAL AND METHODS

This study was designed as a narrative review, aiming to critically synthesize the evidence on the application of virtual reality (VR) and robotic technologies in motor neurorehabilitation. The review focused on peer-reviewed literature published between 2015 and 2025, with emphasis on studies addressing stroke, spinal cord injury, and other neurological conditions associated with motor impairments.

Search Strategy

A comprehensive literature search was conducted across PubMed, Scopus, and Google Scholar. The search strategy combined Medical Subject Headings (MeSH) and free-text terms using Boolean operators.

Core keywords included: "virtual reality", "VR", "robotics", "robot-assisted therapy", "neurorehabilitation", "motor recovery", "stroke", "spinal cord injury", and "rehabilitation technology".

For PubMed, the following example strategy was applied:

(virtual reality [MeSH Terms] OR VR [All Fields]) AND (robotics [MeSH Terms] OR robot-assisted therapy [All Fields]) AND (motor recovery OR motor rehabilitation) AND (neurorehabilitation OR neurologic rehabilitation [MeSH Terms]).

For Scopus, a keyword-based approach was employed:

("virtual reality" OR "immersive VR") AND ("robotics" OR "robot-assisted rehabilitation") AND (stroke OR spinal cord injury OR neurologic conditions) AND (motor recovery OR functional outcomes OR rehabilitation technology).

Additional articles were retrieved by manually screening reference lists of included reviews and meta-analyses.

Eligibility Criteria

Publications were included if they reported on VR or robotic interventions aimed at motor recovery in human participants with neurological motor impairments. Only full-text, peer-reviewed journal articles published in English were considered. Non-motor rehabilitation studies, animal models, editorials, and conference abstracts were excluded.

Table 1. Inclusion and Exclusion Criteria

Category	Inclusion Criteria	Exclusion Criteria
Publication Type	Peer-reviewed journal articles	Conference abstracts, editorials, letters, non-peer-reviewed articles
Language	English	Non-English publications
Timeframe	2015–2025	Articles published before 2015

Category	Inclusion Criteria	Exclusion Criteria
Population	Human participants with neurological motor impairments (e.g., stroke, SCI, PD, MS, CP)	Animal studies, in vitro studies, cognitive-only or psychological rehabilitation focus
Focus Area	Use of VR and/or robotics in motor recovery and neurorehabilitation	Non-motor rehabilitation interventions
Study Design	Clinical trials, RCTs, systematic reviews, meta-analyses, cohort studies, narrative reviews	Case reports, opinion pieces, protocols without results

Study Selection

Two reviewers independently screened titles and abstracts to assess relevance. Full texts of potentially eligible studies were retrieved and assessed against the inclusion criteria. Discrepancies were resolved by consensus.

Data Extraction and Synthesis

Data were extracted regarding study design, participant population, type of intervention (VR, robotics, or combined), comparator interventions (if applicable), outcome measures (e.g., motor function scales, activities of daily living, quality of life), and key findings. The review adopted a narrative synthesis approach, grouping findings into thematic categories: VR-based interventions, Robotic-assisted interventions, Combined or hybrid modalities, and Innovations (AI, BCI, and wearable-assisted systems). Due to heterogeneity in interventions, patient groups, and outcome measures, no quantitative meta-analysis was attempted. Instead, results were critically appraised and compared across study types to identify trends, strengths, limitations, and research gaps.

CURRENT EVIDENCE ON VR AND ROBOTICS

Virtual Reality in Motor Recovery

Mechanisms

Virtual reality (VR) has gained increasing attention as a rehabilitation tool due to its ability to create immersive, interactive environments that replicate functional tasks while providing real-time multisensory feedback. Immersive VR systems, delivered through head-mounted displays, enhance motor learning by stimulating neural circuits responsible for visuomotor coordination and sensorimotor integration (1,2). By incorporating visual, auditory, and haptic cues, VR promotes neuroplasticity through task-specific, repetitive practice — a fundamental principle of motor recovery (3).

Gamification within VR platforms further enhances patient motivation and adherence. Unlike conventional therapy, which may feel monotonous, VR-based training offers engaging tasks that encourage longer and more frequent practice sessions (4,5). Such motivational benefits have been shown to improve therapy compliance, which is a critical determinant of functional recovery in chronic neurological conditions (6).

Evidence Base

Several systematic reviews and meta-analyses confirm the potential of VR as an adjunct to conventional therapy. A recent umbrella review reported that VR interventions, particularly immersive modalities, improve upper-limb motor outcomes in stroke patients when compared with standard rehabilitation alone (7). Hao et al. (2023) demonstrated through a network meta-analysis that immersive VR (head-mounted displays) produced significantly greater improvements in Fugl-Meyer upper-limb scores compared to non-immersive VR (screen-based systems) or game consoles (Wii/Kinect) (8).

Neuroimaging studies also support VR's role in driving neuroplastic changes. Functional MRI and fNIRS studies reveal enhanced cortical activation and connectivity during VR-based training, correlating with functional motor gains (9,10). Beyond stroke, emerging evidence suggests benefits in multiple sclerosis, Parkinson's disease, and cerebral palsy, although the number of high-quality trials in these populations remains limited (11,12).

Nevertheless, methodological limitations remain. Bargeri et al. (2023) found that although VR-based rehabilitation is generally effective, the quality of evidence across systematic reviews was often critically low, with heterogeneity in protocols and small sample sizes undermining confidence in conclusions (13).

Strengths and Limitations

The major strengths of VR interventions are their ability to enhance motivation, provide multisensory real-time feedback, and deliver therapy at higher dosages outside traditional clinical settings. Low-cost, semi-immersive VR systems (e.g., gaming consoles) increase accessibility, especially for home-based or telerehabilitation programs (14). However, limitations include variability in patient tolerance (e.g., simulator sickness, cognitive fatigue), challenges with long-term adherence, and lack of standardization across interventions. Moreover, most trials measure short-term impairment-level outcomes, while evidence on long-term functional independence and quality of life remains scarce (13,15).

Table 2. Evidence for Virtual Reality in Motor Recovery

Domain	Findings	Limitations
Mechanisms	Multisensory feedback, gamification, enhanced motivation, neuroplasticity stimulation (1–5).	Risk of simulator sickness, cognitive load, limited tolerance in some patients.
Evidence base	Positive effects on upper-limb function in stroke; immersive VR > non-immersive VR (7–9).	Heterogeneity of protocols; small samples; variable methodological quality (13).
Populations studied	Stroke (most evidence), some trials in MS, PD, CP (11,12).	Sparse evidence outside stroke; pediatric data limited.
Outcomes	Improvements in motor scores, engagement, cortical reorganization (8–10).	Long-term outcomes and ADL independence less frequently studied.

ROBOTICS IN MOTOR RECOVERY

Mechanisms

Robotic-assisted therapy delivers repetitive, high-intensity, task-specific training, which is crucial for driving motor relearning and neuroplasticity. Devices can either be end-effector robots, which connect to a distal part of a limb (e.g., hand or foot) and guide movement trajectories, or exoskeleton robots, which encompass joints to replicate physiological limb movements (16). These devices can operate in assistive, resistive, or passive modes, allowing dynamic adjustment of training intensity based on patient performance (17).

Robotics offers two primary advantages over conventional therapy: (1) the ability to deliver thousands of precise, repetitive movements within a session, far exceeding what a therapist can manually provide, and (2) objective measurement of kinematic and kinetic parameters, enabling real-time monitoring of progress (18).

Evidence Base

Systematic reviews and Cochrane analyses consistently support robotic-assisted training as a beneficial adjunct to stroke rehabilitation. Mehrholz et al. (2018) found significant improvements in activities of daily living (ADLs), upper-limb strength, and motor function with robot-assisted training compared to usual care (19). A more recent umbrella review concluded that robotic upper-limb therapy enhances motor outcomes, though the effect sizes are often modest when compared with dose-matched conventional therapy (20).

Comparisons between device types reveal task-specific benefits. Lee et al. (2020) reported that end-effector robots produced better functional outcomes in chronic stroke than exoskeletons, likely due to greater patient engagement in active movement (21). Conversely, Moggio et al. (2022) demonstrated that exoskeletons were superior for distal motor recovery (e.g., hand and finger function), highlighting the importance of matching device type to therapeutic goals (22). For lower-limb rehabilitation, robotic gait trainers (e.g., Lokomat) and exoskeletons show promise in improving gait speed and independence after stroke or spinal cord injury, though evidence remains mixed and cost-effectiveness uncertain (23,24).

Strengths and Limitations

Robotic therapy provides unmatched training intensity and objective assessment, making it particularly valuable in resource-intensive settings such as inpatient rehabilitation. Patients often report high satisfaction due to perceived improvements in movement control and independence (25). However, barriers include high acquisition and maintenance costs, need for therapist training, and limited accessibility outside specialized centers (26). Moreover, evidence quality varies, with many trials being small, heterogeneous, and focused largely on stroke, leaving other neurological populations underrepresented (20,22).

Table 3. Evidence for Robotics in Motor Recovery

Domain	Findings	Limitations
Mechanisms	High-intensity, repetitive, task-specific training; assistive/resistive modes; objective data (16–18).	Requires costly equipment; therapist expertise needed.
Evidence base	Improves ADLs, upper-limb strength, gait recovery in stroke/SCI (19–24).	Effect sizes modest vs. dose-matched therapy; heterogeneity in protocols.
Device comparisons	End-effector better for functional arm outcomes; exoskeleton superior for hand/finger recovery (21,22).	Optimal device choice task- and impairment-dependent.
Populations studied	Mostly stroke; some SCI and gait trials (19,23,24).	Limited evidence in PD, MS, CP; pediatric use understudied.
Outcomes	Gains in motor scores, ADLs, gait independence (19–24).	Long-term benefits and cost-effectiveness remain uncertain (26).

Synthesis

Overall, VR and robotic interventions show consistent, though modest, improvements in motor recovery when used as adjuncts to conventional rehabilitation. VR primarily enhances patient engagement and neuroplasticity through immersive, multisensory environments, while robotics ensures intensive, high-repetition training with objective monitoring. Each modality has unique advantages and constraints, and their comparative effectiveness often depends on patient population, impairment severity, and therapeutic goals.

COMPARATIVE INSIGHTS AND COMBINED APPROACHES

VR vs. Robotics: Complementary Roles

Virtual reality (VR) and robotics should not be viewed as competing modalities but rather as complementary strategies within motor rehabilitation. VR excels at enhancing motivation, engagement, and multisensory feedback, which can improve adherence and stimulate neuroplasticity (1,2). Robotics, in contrast, provides precise, high-intensity, repetitive training that enables movements at volumes unachievable through conventional therapist-led practice (3,4). Clinical evidence shows that both modalities independently offer modest functional gains compared to conventional therapy, but when compared head-to-head, neither is consistently superior across all outcomes (5,6). Instead, their relative benefits appear task-dependent: VR is particularly effective in improving functional upper-limb use and motor learning, while robotics ensures strength, endurance, and range of motion, especially in more severely impaired individuals (7,8).

Combined VR + Robotics (Hybrid Systems)

An emerging body of research explores combining VR with robotic devices, whereby patients perform robotic-assisted movements within immersive virtual environments. This integration leverages the biomechanical precision of robotics with the motivational and neurofeedback benefits of VR. For instance, trials in spinal cord injury rehabilitation show that VR-exoskeleton systems improve balance and gait more effectively than robotics alone (9). Alashram et al. (2024) reviewed randomized controlled trials (RCTs) combining VR and robotic therapy, noting mixed but generally positive findings, with some studies reporting additive benefits for motor function and patient engagement (10). Furthermore, brain–computer interfaces (BCIs) are increasingly integrated with VR and robotics. By translating neural signals into control commands, BCIs allow patients to actively drive robotic devices or VR avatars, thereby enhancing agency and reinforcing motor intention pathways. Early pilot studies suggest that BCI-VR and BCI-robot systems promote superior neuroplastic reorganization and functional improvements compared to conventional approaches, though evidence remains preliminary (11,12).

Emerging Findings and Patient Perspectives

Patients consistently report higher satisfaction with hybrid systems due to increased motivation and a sense of active participation (13). VR elements, particularly gamified training, are often described as “enjoyable” and “less tiring,” which enhances adherence, while robotic support provides reassurance by ensuring safe, repetitive movement even in those with severe deficits (14). Despite these benefits, practical integration in routine clinical practice remains limited due to technical complexity, cost, and the need for specialized therapist training.

LIMITATIONS AND BARRIERS

Methodological Gaps

Although the literature base for VR and robotics is growing, it remains constrained by significant methodological limitations. Many RCTs include small sample sizes (<50 participants), short intervention durations, and heterogeneous inclusion criteria (15,16). Trials often focus disproportionately on stroke survivors, leaving spinal cord injury, Parkinson’s disease, and pediatric populations underrepresented (17). Additionally, outcome measures vary widely, ranging from impairment scales (e.g., Fugl-Meyer) to functional or quality-of-life metrics, limiting comparability across studies (18).

Practical Barriers

High acquisition and maintenance costs remain the most significant barriers to widespread implementation, particularly for advanced robotic systems and immersive VR platforms (19,20). Specialized therapist training and infrastructure requirements (e.g., dedicated lab space) further hinder adoption in low-resource or community settings (21). Usability issues also exist: VR may cause simulator sickness, visual strain, or cognitive overload, while robotic systems require careful calibration and fitting to individual patients (22).

Evidence Quality Concerns

Systematic reviews highlight concerns over the quality of existing evidence. Many VR-based reviews are rated as “critically low” on AMSTAR quality assessments due to poor methodological rigor and inconsistent reporting (13,23). Similarly, while Cochrane reviews conclude that robotic training is beneficial, they emphasize the modest size of effects and the risk of bias in underlying trials (24). Collectively, these concerns highlight the need for larger, standardized, multicenter RCTs with longer-term follow-up.

Table 4. Key Limitations and Barriers in VR and Robotics Research

Domain	Limitations / Barriers
Methodological	Small sample sizes, short-term outcomes, heterogeneous protocols, underrepresentation of SCI/PD/pediatrics (15–18).
Practical	High costs, need for specialized training, infrastructure limitations, usability issues (19–22).
Evidence quality	Low methodological quality in reviews, risk of bias in trials, inconsistent outcome measures (13,23,24).

INNOVATIONS AND FUTURE DIRECTIONS

AI-Driven Adaptive Systems

Artificial intelligence (AI) and machine learning are being integrated into VR and robotic platforms to deliver adaptive rehabilitation. These systems adjust task difficulty in real time based on performance metrics, ensuring optimal challenge levels that promote neuroplasticity without inducing fatigue (25). For example, intelligent robotic controllers can detect compensatory movements and adjust assistance accordingly, while VR environments can modulate task complexity to match patient progress (26). Early evidence indicates improved motor outcomes with AI-driven personalization, though large-scale validation is still lacking (27).

Brain–Computer Interfaces (BCIs)

BCIs represent a frontier innovation, enabling direct translation of neural activity into control signals for VR or robotic systems. EEG-based BCIs allow patients to engage in motor imagery tasks that are coupled with robotic movements or VR avatar feedback, reinforcing neuroplastic reorganization (11,28). Recent pilot studies suggest that BCI-assisted rehabilitation enhances motor recovery in stroke survivors beyond conventional therapy, though costs, technical demands, and regulatory hurdles remain significant barriers (29).

Wearables and Home-Based Telerehabilitation

The COVID-19 pandemic accelerated interest in telerehabilitation, with VR headsets, portable exoskeletons, and wearable sensors enabling therapy delivery in home environments. Soft robotic exosuits and standalone VR systems (e.g., Oculus Quest) have been trialed with encouraging results, showing comparable motor improvements to clinic-based interventions when combined with remote therapist monitoring (30,31). Such solutions may expand access, particularly in rural or resource-limited settings, though issues of safety, technical support, and reimbursement need addressing.

Ethical, Policy, and Economic Considerations

The integration of advanced technologies raises ethical and socioeconomic questions. High costs risk widening healthcare disparities if VR and robotics remain accessible only in specialized centers or high-income regions (32). Policymakers must address reimbursement models, training standards, and equitable access to ensure fair distribution of benefits (33). Ethical debates also center on the therapist's evolving role: while technology may enhance efficiency, overreliance risks depersonalization of care (34). Cost-effectiveness analyses suggest that robotics may be viable in high-volume centers but remain impractical for smaller facilities unless low-cost adaptations are developed (35).

Table 5. Innovations and Future Directions in Neurorehabilitation

Innovation	Potential Benefits	Challenges
AI-driven adaptive rehab	Real-time personalization; prevents fatigue; optimizes neuroplasticity (25–27).	Requires validation in large-scale RCTs; integration into clinical workflows.
BCI integration	Enhances neurofeedback and motor intention; promotes cortical reorganization (11,28,29).	High cost; technical expertise; limited regulatory approval.
Wearables & telerehab	Expands access; enables home-based training; reduces travel costs (30,31).	Safety monitoring, technical support, insurance reimbursement.
Policy & ethics	Potential for cost savings at scale; improves efficiency; supports new models of care (32–35).	Risk of inequity; ethical issues in therapist role; reimbursement gaps.

DISCUSSION

The synthesis of current literature demonstrates that both virtual reality (VR) and robotic-assisted rehabilitation hold considerable promise for improving motor outcomes in individuals with neurological impairments. While each modality has distinct mechanisms, their complementary strengths suggest that integration into clinical practice should be pursued with caution, ensuring realistic expectations and patient-centered applications.

Evidence consistently indicates that VR enhances engagement and adherence by leveraging immersive, gamified environments that stimulate neuroplasticity through enriched sensory feedback (1,2). Patients generally perceive VR interventions as more enjoyable and motivating than conventional exercises, which may increase therapy intensity and long-term compliance (3). Robotics, in contrast, provides unmatched capability to deliver repetitive, high-intensity, task-specific training, especially in patients with severe impairments who cannot initiate or sustain voluntary movement (4,5). When applied independently, both modalities yield modest but meaningful improvements in motor function, with immersive VR particularly effective for upper-limb outcomes and robotic systems demonstrating measurable gains in strength and functional independence (6–8). Hybrid interventions combining VR with robotics have shown potential additive benefits, though the evidence is still emerging. Studies suggest that coupling robotic precision with VR's immersive feedback may result in greater neuroplastic adaptations than either approach alone (9,10). Brain–computer interface (BCI) integration further expands this potential by linking neural intention directly to movement execution in virtual or robotic environments, thereby strengthening cortical reorganization and motor relearning (11). Despite these promising trends, most trials remain limited by small sample sizes, heterogeneity of designs, and short-term outcomes, making it premature to draw firm conclusions about superiority of combined approaches over stand-alone modalities.

From a clinical perspective, the findings have important implications for rehabilitation practice. First, VR and robotics should be positioned as adjuncts, not replacements, to conventional therapy. The therapist remains central in guiding patient-specific goals, interpreting performance data, and addressing psychosocial aspects of care that technology cannot substitute (12). Instead, these tools can extend therapeutic capacity: VR may allow patients to perform additional engaging practice at home or in community settings, while robotics can relieve therapists of labor-intensive repetitive tasks, enabling them to supervise more patients simultaneously (13,14). This redistribution of workload has potential to improve efficiency within healthcare systems, especially in resource-limited environments where therapist availability is constrained. However, implementation must be tempered by consideration of barriers. High costs and infrastructure demands restrict access to advanced robotics, whereas even low-cost VR solutions may require patient training and ongoing technical support (15,16). Thus, equitable integration requires institutional investment in staff education, appropriate patient selection, and careful monitoring of safety in home-based programs. On a policy level, reimbursement frameworks and cost-effectiveness analyses will be critical in determining the feasibility of broader adoption (17).

RESEARCH GAPS AND RECOMMENDATIONS

First, there is an urgent need for standardization of protocols and outcome measures. Current trials employ diverse devices, training intensities, and durations, while measuring outcomes with heterogeneous scales ranging from impairment-level assessments (e.g., Fugl-Meyer) to functional independence scores. This variability undermines comparability and contributes to inconsistent conclusions across systematic reviews (1,2). Establishing core outcome sets that include both impairment and participation measures would strengthen future evidence and facilitate meta-analyses. Second, the literature disproportionately focuses on stroke rehabilitation, with far fewer studies addressing other neurological populations such as spinal cord injury, Parkinson's disease, multiple sclerosis, cerebral palsy, and pediatric cohorts (3,4). This limits generalizability and overlooks populations that may derive equal or greater benefit from intensive technology-assisted interventions. Targeted research in these groups is essential to broaden clinical applicability.

Third, most studies emphasize short-term improvements in motor performance, with limited follow-up on long-term functional outcomes, quality of life, and independence in activities of daily living (5,6). Since sustained recovery and reintegration into daily life are ultimate goals of neurorehabilitation, future trials must incorporate longitudinal follow-up to determine whether early motor gains translate into durable benefits. Finally, cost-effectiveness and equity of access remain underexplored. Advanced robotic systems are prohibitively expensive for many facilities, while immersive VR requires infrastructure and technical expertise not widely available in low-resource settings. Without addressing these issues, there is a risk that VR and robotics will exacerbate disparities in rehabilitation care (7,8). Economic evaluations, health policy research, and pilot reimbursement programs should accompany future clinical trials to ensure scalable and equitable adoption. Develop standardized intervention protocols and validated outcome sets, expand research beyond stroke to include sci, pd, ms, cp, and pediatric populations, incorporate long-term follow-up assessing functional independence, qol, and caregiver burden, conduct cost-effectiveness analyses and explore affordable, scalable technologies, promote interdisciplinary collaboration among clinicians, engineers, and policymakers to integrate vr/robotics into health systems.

CONCLUSION

Virtual reality and robotic-assisted therapies represent promising innovations in motor neurorehabilitation. By providing intensive, task-specific, and engaging training environments, these modalities address critical shortcomings of conventional therapy, particularly in dosage, motivation, and neuroplastic stimulation. VR enhances adherence and feedback through immersive and gamified experiences, while robotics ensures high-repetition precision training beyond therapist capacity. When used in combination, these technologies may offer synergistic benefits that further enhance motor outcomes (9–11). However, the current evidence base is characterized by modest effect sizes, methodological limitations, and heterogeneity. VR and robotics should therefore be regarded as adjuncts, not replacements, for traditional therapist-led rehabilitation. Therapists remain essential in tailoring interventions, ensuring patient safety, and integrating psychosocial aspects of care. Wider implementation will depend on addressing cost barriers, standardizing protocols, and generating robust long-term data.

The future of neurorehabilitation lies in strategically integrating these technologies within healthcare systems. Advances in artificial intelligence, brain–computer interfaces, and wearable devices suggest a trajectory toward more personalized, accessible, and home-based rehabilitation solutions. Yet, achieving this vision requires rigorous large-scale trials, supportive reimbursement frameworks, and policies that ensure equitable access across populations and settings (12–14). In conclusion, VR and robotics offer cautious optimism: they are not yet transformative replacements but hold the potential to become essential adjuncts in contemporary rehabilitation. With continued innovation, high-quality evidence, and thoughtful policy support, these technologies may ultimately enhance recovery, independence, and quality of life for patients with neurological impairments.

REFERENCES

1. Banyai AD, Brisan C. Robotics in Physical Rehabilitation: Systematic Review. Healthcare (Basel). 2024;12(17).
2. Nieto-Escamez F, Cortes-Perez I, Obrero-Gaitan E, Fusco A. Virtual Reality Applications in Neurorehabilitation: Current Panorama and Challenges. Brain Sci. 2023;13(5).
3. Clark WE, Sivan M, O'Connor RJ. Evaluating the Use of Robotic and Virtual Reality Rehabilitation Technologies to Improve Function in Stroke Survivors: A Narrative Review. J Rehabil Assist Technol Eng. 2019;6:2055668319863557.
4. Rymer W, Jayaraman A. Promises and Challenges of Neurorehabilitation Technology. In: Oxford Textbook of Neurorehabilitation. Oxford: Oxford University Press; 2015. p. 359.
5. Zanatta F, Giardini A, Pierobon A, D'Addario M, Steca P. A Systematic Review on the Usability of Robotic and Virtual Reality Devices in Neuromotor Rehabilitation: Patients' and Healthcare Professionals' Perspective. BMC Health Serv Res. 2022;22(1):523.
6. AlGerafi MA, Zhou Y, Oubibi M, Wijaya TT. Unlocking the Potential: A Comprehensive Evaluation of Augmented Reality and Virtual Reality in Education. Electronics. 2023;12(18):3953.

7. Levin MF, Weiss PL, Keshner EA. Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation: Incorporation of Motor Control and Motor Learning Principles. Phys Ther. 2015;95(3):415-25.

8. Zuki FSM, Sulaiman S, Rambli DRA, Merienne F, Saad MNM, editors. Sensory Feedback and Interactivity: Enhancing Motivation and Engagement for VR Stroke Rehabilitation. In: 2021 International Conference on Computer & Information Sciences (ICCOINS); 2021. New York: IEEE.

9. Camardella C, Chiaradia D, Bortone I, Frisoli A, Leonardis D. Introducing Wearable Haptics for Rendering Velocity Feedback in VR Serious Games for Neuro-Rehabilitation of Children. Front Virtual Real. 2023;3:1019302.

10. Nogueira IP. Development of an Intelligent Robotic Learning System for Physiotherapy Treatments [dissertation]. Porto: Universidade do Porto; 2024.

11. Salunkhe P, Durgawale A. Neurological Rehabilitation: Techniques and Outcomes in Physiotherapy. Pune: Sunrise Publications; 2024.

12. Zheng J, Ma Q, He W, Huang Y, Shi P, Li S, et al. Cognitive and Motor Cortex Activation During Robot-Assisted Multi-Sensory Interactive Motor Rehabilitation Training: An fNIRS Based Pilot Study. Front Hum Neurosci. 2023;17:1089276.

13. Hun Lee M, Siewiorek DP, Smailagic A, Bernardino A, Bermudez i Badia S. Design, Development, and Evaluation of an Interactive Personalized Social Robot to Monitor and Coach Post-Stroke Rehabilitation Exercises. User Model User-Adapt Interact. 2023;33(2):545-69.

14. Uddin M, Ganapathy K, Syed-Abdul S. Digital Technology Enablers of Tele-Neurorehabilitation in Pre- and Post-COVID-19 Pandemic Era: A Scoping Review. Int J Telerehabil. 2024;16(1):e6611.

15. Kuipers JA, Hoffman N, Carrick FR, Jemni M. Post-Stroke Rehabilitation: Neurophysiology Processes of Bilateral Movement Training and Interlimb Coupling—A Systematic Review. J Clin Med. 2025;14(11):3757.

16. Hao J, Xie H, Harp K, Chen Z, Siu KC. Effects of Virtual Reality Intervention on Neural Plasticity in Stroke Rehabilitation: A Systematic Review. Arch Phys Med Rehabil. 2022;103(3):523-41.

17. Demeco A, Zola L, Frizziero A, Martini C, Palumbo A, Foresti R, et al. Immersive Virtual Reality in Post-Stroke Rehabilitation: A Systematic Review. Sensors (Basel). 2023;23(3).

18. Feitosa JA, Fernandes CA, Casseb RF, Castellano G. Effects of Virtual Reality-Based Motor Rehabilitation: A Systematic Review of fMRI Studies. J Neural Eng. 2022;19(1).

19. Khan A, Imam YZ, Muneer M, Al Jerdi S, Gill SK. Virtual Reality in Stroke Recovery: A Meta-Review of Systematic Reviews. Bioelectron Med. 2024;10(1):23.

20. Mehrholz J, Platz T, Kugler J, Elsner B. Electromechanical and Robot-Assisted Arm Training for Improving Activities of Daily Living, Arm Function, and Arm Muscle Strength After Stroke. Cochrane Database Syst Rev. 2018;(9):CD006876.

21. Pollock A, Farmer SE, Brady MC, Langhorne P, Mead GE, Mehrholz J, et al. Interventions for Improving Upper Limb Function After Stroke. Cochrane Database Syst Rev. 2014;(11):CD010820.

22. Park JM, Park HJ, Yoon SY, Kim YW, Shin JI, Lee SC. Effects of Robot-Assisted Therapy for Upper Limb Rehabilitation After Stroke: An Umbrella Review of Systematic Reviews. Stroke. 2025;56(5):1243-52.

23. Alashram AR. Combined Robot-Assisted Therapy and Virtual Reality for Upper Limb Rehabilitation in Stroke Survivors: A Systematic Review of Randomized Controlled Trials. Neurol Sci. 2024;45(11):5141-55.

24. Liu W, Chen J. The Efficacy of Exoskeleton Robotic Training on Ambulation Recovery in Patients With Spinal Cord Injury: A Meta-Analysis. J Spinal Cord Med. 2024;47(6):840-9.

25. Drigas A, Sideraki A. Brain Neuroplasticity Leveraging Virtual Reality and Brain-Computer Interface Technologies. Sensors (Basel). 2024;24(17).

26. Massetti T, da Silva TD, Crocetta TB, Guarnieri R, de Freitas BL, Lopes PB, et al. The Clinical Utility of Virtual Reality in Neurorehabilitation: A Systematic Review. J Cent Nerv Syst Dis. 2018;10:1179573518813541.

27. Lo K, Stephenson M, Lockwood C. The Economic Cost of Robotic Rehabilitation for Adult Stroke Patients: A Systematic Review. JBI Database Syst Rev Implement Rep. 2019;17(4):520-47.

28. Bargeri S, Scalea S, Agosta F, Banfi G, Corbetta D, Filippi M, et al. Effectiveness and Safety of Virtual Reality Rehabilitation After Stroke: An Overview of Systematic Reviews. EClinicalMedicine. 2023;64:102220.

29. Moggio L, de Sire A, Marotta N, Demeco A, Ammendolia A. Exoskeleton Versus End-Effector Robot-Assisted Therapy for Finger-Hand Motor Recovery in Stroke Survivors: Systematic Review and Meta-Analysis. Top Stroke Rehabil. 2022;29(8):539-50.

30. Hao J, He Z, Yu X, Remis A. Comparison of Immersive and Non-Immersive Virtual Reality for Upper Extremity Functional Recovery in Patients With Stroke: A Systematic Review and Network Meta-Analysis. Neurol Sci. 2023;44(8):2679-97.

31. Catania V, Rundo F, Panerai S, Ferri R. Virtual Reality for the Rehabilitation of Acquired Cognitive Disorders: A Narrative Review. Bioengineering (Basel). 2023;11(1).

32. Winter C, Kern F, Gall D, Latoschik ME, Pauli P, Kathner I. Immersive Virtual Reality During Gait Rehabilitation Increases Walking Speed and Motivation: A Usability Evaluation With Healthy Participants and Patients With Multiple Sclerosis and Stroke. J Neuroeng Rehabil. 2021;18(1):68.

33. Lee SH, Park G, Cho DY, Kim HY, Lee JY, Kim S, et al. Comparisons Between End-Effector and Exoskeleton Rehabilitation Robots Regarding Upper Extremity Function Among Chronic Stroke Patients With Moderate-To-Severe Upper Limb Impairment. Sci Rep. 2020;10(1):1806.

34. Wang H, Shen H, Han Y, Zhou W, Wang J. Effect of Robot-Assisted Training for Lower Limb Rehabilitation on Lower Limb Function in Stroke Patients: A Systematic Review and Meta-Analysis. Front Hum Neurosci. 2025;19:1549379.

35. Sari A. Comparison of End-Effector and Exoskeleton Devices With Robot-Assisted Gait Training in Patients With Stroke. J Surg Med. 2021;5(2):128-31.

36. Campagnini S, Liuzzi P, Mannini A, Riener R, Carrozza MC. Effects of Control Strategies on Gait in Robot-Assisted Post-Stroke Lower Limb Rehabilitation: A Systematic Review. J Neuroeng Rehabil. 2022;19(1):52.

37. Nicora G, Parimbelli E, Mauro MC, Falchini F, Germanotta M, Fasano A, et al. Healthcare Practitioners and Robotic-Assisted Rehabilitation: Understanding Needs and Barriers. J Neuroeng Rehabil. 2025;22(1):78.

38. Agbemanyole KA, Agbohessou KG, Pons C, Lenca P, Remy-Neris O, Goff-Pronost ML. Economic Analysis of Digital Motor Rehabilitation Technologies: A Systematic Review. Health Econ Rev. 2024;14(1):52.

39. Cano-de-la-Cuerda R, Blazquez-Fernandez A, Marcos-Anton S, Sanchez-Herrera-Baeza P, Fernandez-Gonzalez P, Collado-Vazquez S, et al. Economic Cost of Rehabilitation With Robotic and Virtual Reality Systems in People With Neurological Disorders: A Systematic Review. J Clin Med. 2024;13(6).

40. Morone G, Iosa M, Bragoni M, De Angelis D, Venturiero V, Coiro P, et al. Who May Have Durable Benefit From Robotic Gait Training? A 2-Year Follow-Up Randomized Controlled Trial in Patients With Subacute Stroke. Stroke. 2012;43(4):1140-2.

41. Valero-Cuevas FJ, Klamroth-Marganska V, Winstein CJ, Riener R. Robot-Assisted and Conventional Therapies Produce Distinct Rehabilitative Trends in Stroke Survivors. J Neuroeng Rehabil. 2016;13(1):92.

42. Sivan M, O'Connor RJ, Makower S, Levesley M, Bhakta B. Systematic Review of Outcome Measures Used in the Evaluation of Robot-Assisted Upper Limb Exercise in Stroke. J Rehabil Med. 2011;43(3):181-9.

43. Hasson CJ, Manczurowsky J, Collins EC, Yarossi M. Neurorehabilitation Robotics: How Much Control Should Therapists Have? Front Hum Neurosci. 2023;17:1179418.

44. Morris MR. AI and Accessibility: A Discussion of Ethical Considerations. Commun ACM. 2019;63:35-7.

45. Rampioni M, Leonzi S, Antognoli L, Mura A, Stara V. Poststroke eHealth Technologies-Based Rehabilitation for Upper Limb Recovery: Systematic Review. J Med Internet Res. 2025;27:e57957.

46. Kiyono K, Tanabe S, Hirano S, Ii T, Nakagawa Y, Tan K, et al. Effectiveness of Robotic Devices for Medical Rehabilitation: An Umbrella Review. J Clin Med. 2024;13(21):6616.

47. Laver KE, Lange B, George S, Deutsch JE, Saposnik G, Crotty M. Virtual Reality for Stroke Rehabilitation. Cochrane Database Syst Rev. 2017;(11):CD008349.

48. Kim WS, Cho S, Ku J, Kim Y, Lee K, Hwang HJ, et al. Clinical Application of Virtual Reality for Upper Limb Motor Rehabilitation in Stroke: Review of Technologies and Clinical Evidence. J Clin Med. 2020;9(10):3369.

49. Baniqued PDE, Holt RJ, Mon-Williams M, Morehead JR, Alazmani A, Mushtaq F. Beyond Brainwaves: Recommendations for Integrating Robotics and Virtual Reality for EEG-Driven Brain–Computer Interfaces. In: El-Baz AS, Suri JS, editors. Brain–Computer Interfaces. Cambridge: Academic Press; 2025. p. 389-413.

50. Ase H, Honaga K, Tani M, Takakura T, Wada F, Murakami Y, et al. Effects of Home-Based Virtual Reality Upper Extremity Rehabilitation in Persons With Chronic Stroke: A Randomized Controlled Trial. J Neuroeng Rehabil. 2025;22(1):20.