

Reconstruyendo la función después del accidente cerebrovascular: tecnologías emergentes y nuevas fronteras en la recuperación neurológica

Rebuilding Function After Stroke: Emerging Technologies and New Frontiers in Neurological Recovery

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Recibido: 29-Jul-2026 | **Aceptado:** 29-Jul-2026 | **Publicado:** 30-Jul-2026

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Cómo citar este artículo: Benitez Barrios, S. I., Bolagay Apráez, M. P., Morey Contreras, R. A., Montañez Romero, M. A., Vergara Serpa, J. J., Rodríguez Sánchez, J., Uriostegui Navarro, A. F., & Velasco Espinal, J. A. (2026). Rebuilding Function After Stroke: Emerging Technologies and New Frontiers in Neurological Recovery. México. *Revista IECCMEXICO*, 5(2, Tomo I) 297-321. Quality Consulting Instituto de Educación Capacitación y Certificación de México. <https://ieccmexico.com/publishing>

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RESUMEN

El accidente cerebrovascular continúa siendo una de las principales causas de discapacidad neurológica a largo plazo en el mundo, lo que incrementa la necesidad de estrategias de

rehabilitación capaces de favorecer la recuperación funcional mediante intervenciones intensivas, repetitivas, orientadas a tareas y personalizadas. La neurorrehabilitación digital ha surgido como un enfoque multidisciplinario que integra neurociencias, medicina física y rehabilitación, neurología e ingeniería biomédica mediante tecnologías como realidad virtual, rehabilitación asistida por robots, interfaces cerebro-computadora, sensores portátiles, inteligencia artificial y telerehabilitación. Esta revisión analizó la evidencia científica internacional relacionada con la aplicación de estas tecnologías después del accidente cerebrovascular, prestando especial atención a su relación con la neuroplasticidad dependiente de la experiencia, los resultados funcionales, los desafíos de implementación y su aplicabilidad en distintos sistemas de salud, incluido el contexto latinoamericano. La evidencia científica fue identificada y sintetizada críticamente a partir de bases de datos internacionales, priorizando ensayos clínicos aleatorizados, revisiones sistemáticas, metaanálisis, guías clínicas y estudios contemporáneos relevantes. La literatura revisada mostró que la realidad virtual y la rehabilitación robótica constituyen los enfoques tecnológicos más ampliamente investigados, con resultados favorables principalmente sobre la función motora del miembro superior, el equilibrio, la marcha, la movilidad funcional y las actividades de la vida diaria. La telerehabilitación y las tecnologías portátiles ofrecen oportunidades adicionales para extender la continuidad terapéutica y el monitoreo objetivo fuera de los centros especializados, mientras que las interfaces cerebro-computadora y la inteligencia artificial representan alternativas emergentes para la retroalimentación neural y la personalización terapéutica. A pesar de estos avances, persiste una heterogeneidad considerable en los protocolos de intervención, plataformas tecnológicas, intensidad terapéutica, medidas de resultado y características de los pacientes. Asimismo, los costos, la infraestructura, la capacitación profesional, la accesibilidad, la conectividad y la alfabetización digital continúan condicionando su implementación, especialmente en sistemas sanitarios con recursos limitados. La evidencia actual respalda el empleo de estas tecnologías como componentes complementarios de la rehabilitación multidisciplinaria y no como sustitutos de la terapia convencional. Las futuras investigaciones deberán priorizar protocolos estandarizados, estudios multicéntricos, resultados funcionales a largo plazo, costo-efectividad, acceso equitativo y una mayor representación latinoamericana para avanzar hacia una neurorrehabilitación de precisión sustentada en evidencia.

PALABRAS CLAVE

accidente cerebrovascular, neurorrehabilitación digital, realidad virtual, rehabilitación robótica, neuroplasticidad, recuperación funcional, telerehabilitación, interfaz cerebro-computadora, inteligencia artificial, tecnologías portátiles

ABSTRACT

Stroke remains a major cause of long-term neurological disability worldwide, creating a growing need for rehabilitation strategies capable of promoting functional recovery through intensive, repetitive, task-oriented, and personalized interventions. Digital neurorehabilitation has emerged as a multidisciplinary approach that integrates neuroscience, physical and rehabilitation medicine, neurology, and biomedical engineering through technologies such as virtual reality, robot-assisted rehabilitation, brain-computer interfaces, wearable sensors, artificial intelligence, and telerehabilitation. This review analyzed international scientific evidence regarding the application of these technologies after stroke, with particular attention to their relationship with experience-dependent neuroplasticity, functional outcomes, implementation challenges, and applicability across different healthcare environments, including Latin America. Scientific evidence was identified and critically synthesized from internationally recognized databases, prioritizing randomized controlled trials, systematic reviews, meta-analyses, clinical guidelines, and relevant contemporary studies. The reviewed literature showed that virtual reality and robot-assisted rehabilitation constitute the most extensively investigated technological approaches, with favorable findings particularly in upper-limb motor function, balance, gait, functional mobility, and activities of daily living. Telerehabilitation and wearable technologies provide additional opportunities for extending therapeutic continuity and objective monitoring beyond specialized rehabilitation facilities, while brain-computer interfaces and artificial intelligence represent emerging approaches for neural feedback and personalized rehabilitation. Despite these advances, considerable heterogeneity remains regarding

intervention protocols, technological platforms, therapeutic intensity, outcome measures, and patient characteristics. Furthermore, acquisition costs, infrastructure requirements, professional training, accessibility, connectivity, and digital literacy continue to influence implementation, particularly in resource-constrained healthcare systems. Current evidence supports digital technologies as complementary components of multidisciplinary stroke rehabilitation rather than substitutes for conventional therapy. Future research should prioritize standardized protocols, multicenter studies, long-term functional outcomes, cost-effectiveness, equitable accessibility, and greater representation of Latin American populations to advance toward evidence-based precision neurorehabilitation.

KEYWORDS

stroke, digital neurorehabilitation, virtual reality, robot-assisted rehabilitation, neuroplasticity, functional recovery, telerehabilitation, brain-computer interface, artificial intelligence, wearable technologies

INTRODUCCIÓN

Stroke remains one of the leading causes of long-term disability worldwide and continues to impose a substantial burden on individuals, healthcare systems, and societies. Although remarkable advances in acute stroke management, including intravenous thrombolysis and mechanical thrombectomy, have significantly improved survival rates, a considerable proportion of survivors experience persistent motor, sensory, cognitive, speech, and psychosocial impairments that compromise independence and quality of life. According to the Global Burden of Disease Study, the absolute number of stroke survivors has increased steadily during the last three decades due to population aging and improved survival, making post-stroke rehabilitation an increasingly important component of comprehensive stroke care (Feigin et al., 2021). Consequently, rehabilitation has shifted from being considered a complementary intervention to becoming a fundamental pillar of long-term neurological recovery.

The functional consequences of stroke are highly heterogeneous and depend on multiple factors, including lesion location, infarct size, patient age, preexisting comorbidities, vascular risk factors, and the timeliness of rehabilitation initiation. Motor dysfunction affecting the upper and lower extremities remains the most prevalent sequela, frequently accompanied by deficits in balance, gait, coordination, language, executive function, attention, and emotional regulation. These impairments considerably reduce participation in activities of daily living, increase caregiver burden, and generate substantial socioeconomic costs associated with prolonged disability, recurrent hospitalizations, and long-term dependency (Langhorne et al., 2011). Consequently, optimizing rehabilitation strategies has become one of the principal priorities in modern neurological care.

Recovery after stroke is largely supported by the intrinsic capacity of the central nervous system to reorganize itself through neuroplasticity. This phenomenon encompasses structural, functional, and molecular adaptations involving synaptic remodeling, cortical reorganization, dendritic sprouting, axonal regeneration, modulation of neurotransmitter networks, and changes in functional connectivity. Experimental and clinical evidence indicates that neuroplasticity can be enhanced by intensive, repetitive, task-oriented, and goal-directed rehabilitation, particularly during the early phases following cerebral injury when the brain demonstrates increased responsiveness to therapeutic interventions (Cramer, 2018). Nevertheless, spontaneous recovery alone is frequently insufficient to restore complex motor functions, highlighting the necessity for rehabilitation strategies capable of maximizing neural reorganization through sustained and individualized training.

Traditional rehabilitation programs based on conventional physiotherapy and occupational therapy have demonstrated significant benefits for functional recovery; however, they present important limitations. Among these are restricted therapy duration, variability in treatment intensity, dependence on therapist availability, limited opportunities for high-frequency repetition, and difficulties maintaining long-term patient motivation. These challenges are particularly evident in low- and middle-income countries, where shortages of specialized rehabilitation professionals and unequal access to rehabilitation services often limit treatment continuity. In Latin America, disparities in healthcare infrastructure and rehabilitation resources remain considerable, contributing to delayed intervention and poorer long-term functional outcomes among stroke survivors (Pan American Health Organization [PAHO], 2023).

The rapid evolution of digital health technologies has transformed the landscape of neurorehabilitation over the past decade. Advances in virtual reality (VR), robotic-assisted therapy, wearable sensors, artificial intelligence (AI), brain-computer interfaces (BCIs), telerehabilitation platforms, motion capture systems, and immersive digital environments have introduced innovative opportunities to enhance rehabilitation intensity, personalize treatment protocols, and objectively monitor patient progress. Rather than replacing conventional rehabilitation, these technologies are increasingly viewed as complementary tools capable of augmenting therapist-guided interventions while facilitating continuous, high-dose, task-specific practice that promotes motor relearning and cortical reorganization (Levin et al., 2015).

Among these emerging technologies, virtual reality has received particular attention because it enables patients to engage in highly interactive, multisensory environments that simulate meaningful real-life activities. Virtual environments provide immediate visual, auditory, and proprioceptive feedback while incorporating principles of gamification that improve motivation, adherence, and training intensity. Recent systematic reviews have consistently demonstrated that virtual reality interventions contribute to improvements in upper limb motor function, balance, gait performance, and activities of daily living, especially when integrated with standard rehabilitation protocols rather than used as isolated interventions (Demeco et al., 2023; Hao et al., 2023). Furthermore, immersive virtual reality systems appear capable of increasing patient engagement by creating ecologically valid rehabilitation scenarios that facilitate repetitive motor practice within enjoyable and adaptable environments.

Similarly, robotic-assisted rehabilitation has emerged as another major innovation in neurological recovery. Robotic devices, including end-effector systems and wearable exoskeletons, enable highly repetitive, standardized, and precisely controlled movement training that exceeds the intensity achievable during conventional therapy sessions. Robots can continuously quantify biomechanical performance, adjust assistance according to patient capability, and provide objective outcome measures throughout rehabilitation. Recent meta-analyses indicate that robotic-assisted interventions improve upper limb motor performance and walking ability, particularly when implemented during structured multidisciplinary rehabilitation programs and combined with conventional physiotherapy (De Iaco et al., 2024; Su et al., 2024). These technologies may be especially valuable for patients with severe motor deficits who require intensive movement repetition beyond the capacity of traditional therapy alone.

Parallel to these developments, artificial intelligence has begun to influence clinical decision-making within neurorehabilitation. Machine learning algorithms are increasingly capable of predicting functional recovery trajectories, identifying rehabilitation responders, optimizing treatment selection, and supporting personalized therapeutic planning using multidimensional clinical, neuroimaging, and biomechanical data. AI-driven rehabilitation platforms can dynamically adapt exercise difficulty based on real-time patient performance while continuously monitoring progress through wearable sensors and digital biomarkers. Such personalized approaches align with the broader movement toward precision rehabilitation, in which therapeutic interventions are tailored according to individual neurological characteristics rather than standardized protocols.

Brain-computer interfaces represent another promising technological advancement by enabling direct communication between neural activity and external devices. Through electroencephalographic or other neurophysiological signals, BCIs allow patients to control robotic systems, virtual environments, or functional electrical stimulation even in the presence of profound motor impairment. The integration of BCIs with robotic rehabilitation and immersive virtual reality has demonstrated encouraging effects on motor recovery by reinforcing sensorimotor feedback loops and promoting activity-dependent cortical plasticity. Although these technologies remain primarily within specialized research settings, growing clinical evidence suggests their potential to expand therapeutic opportunities for patients with severe post-stroke disability.

The COVID-19 pandemic further accelerated the adoption of digital rehabilitation by highlighting the necessity for remote healthcare delivery. Telerehabilitation platforms incorporating virtual reality, wearable technologies, video conferencing, and cloud-based monitoring systems have demonstrated feasibility, safety, and clinical effectiveness for delivering supervised rehabilitation outside hospital settings. These digital models improve accessibility for patients residing in rural or underserved regions while reducing transportation barriers and healthcare costs. Recent systematic reviews indicate that virtual reality-based telerehabilitation produces functional outcomes comparable to conventional

outpatient rehabilitation in selected patient populations, supporting its incorporation into contemporary stroke care pathways (Hao et al., 2023).

Despite the remarkable progress observed during recent years, important challenges remain regarding the widespread implementation of digital neurorehabilitation. Considerable heterogeneity exists among available technologies, intervention protocols, treatment duration, outcome measures, patient selection criteria, and methodological quality across clinical studies. Furthermore, economic costs, technological infrastructure requirements, limited professional training, regulatory considerations, and unequal access continue to restrict adoption, particularly within developing healthcare systems. Additional uncertainty persists concerning the optimal timing of intervention, long-term sustainability of functional improvements, comparative effectiveness among different technologies, and identification of patient subgroups most likely to benefit from digital rehabilitation strategies.

The growing body of scientific evidence published during the last decade, particularly between 2020 and 2025, has substantially expanded current knowledge regarding the effectiveness of virtual reality, robotics, artificial intelligence, and neurotechnology in stroke rehabilitation. Nevertheless, findings remain dispersed across multiple clinical specialties, including neurology, physical medicine and rehabilitation, biomedical engineering, neuroscience, rehabilitation sciences, and digital medicine. Integrating these multidisciplinary perspectives is essential for understanding the mechanisms through which technological innovations facilitate neuroplasticity and improve functional recovery after stroke.

Therefore, the present review aims to critically analyze current international evidence regarding digital neurorehabilitation after stroke, with particular emphasis on virtual reality, robotic-assisted therapy, artificial intelligence, brain-computer interfaces, wearable technologies, and telerehabilitation. Additionally, this review explores the neurobiological mechanisms underlying technology-assisted neuroplasticity, examines their clinical effectiveness across functional domains, discusses current limitations for implementation in diverse healthcare settings—including Latin America—and identifies future perspectives for personalized digital rehabilitation capable of optimizing long-term neurological recovery and improving quality of life among stroke survivors.

DESARROLLO

Digital neurorehabilitation has emerged as a multidisciplinary field that integrates neuroscience, physical medicine and rehabilitation, neurology, biomedical engineering, and digital health technologies to improve functional recovery after stroke. Its development responds to one of the central limitations of conventional rehabilitation: the difficulty of providing sufficiently intensive, repetitive, task-specific, and individualized training over prolonged periods. Although therapist-directed interventions remain essential, digital systems can expand the number of therapeutic repetitions, standardize movement practice, generate objective performance data, and adapt exercises according to each patient's functional capacity.

The biological basis of these interventions is neuroplasticity, understood as the ability of the nervous system to modify its structure, function, and connectivity in response to internal or external stimuli. Following a stroke, surviving neural networks may reorganize their activity, recruit adjacent cortical areas, strengthen alternative pathways, and modify interhemispheric communication. These processes are influenced by the characteristics of the cerebral lesion, the patient's clinical condition, the timing of rehabilitation, and the quantity and quality of motor practice. Neuroplasticity is therefore not an automatic guarantee of functional recovery, but a dynamic process that can be facilitated or limited by the rehabilitation environment (Cramer et al., 2011; Dimyan & Cohen, 2011).

Task-oriented and repetitive training is particularly relevant because motor improvement depends on the repeated activation of neural circuits associated with meaningful actions. Digital technologies provide environments in which patients can practice reaching, grasping, walking, balancing, or performing simulated activities of daily living while receiving immediate feedback. This combination of repetition, feedback, motivation, and progressive difficulty is consistent with the principles of motor learning and experience-dependent neuroplasticity. Neuroimaging and neurophysiological studies suggest that virtual reality interventions may be associated with changes in cortical

activation and functional connectivity that correlate with motor improvement, although the available evidence remains heterogeneous (Hao et al., 2022; Feitosa et al., 2022).

Virtual reality in post-stroke rehabilitation

Virtual reality consists of computer-generated environments that allow interaction through visual, auditory, and movement-based stimuli. Depending on the technological configuration, these systems may be non-immersive, semi-immersive, or fully immersive. Non-immersive interventions usually employ conventional screens, cameras, or motion sensors, whereas immersive systems use head-mounted displays and three-dimensional environments that increase the patient's sense of presence.

The principal advantage of virtual reality is its capacity to transform repetitive therapeutic exercises into goal-directed and engaging activities. A patient may practice upper-limb movements by manipulating virtual objects, improve balance through weight-shifting tasks, or train gait within simulated community environments. The difficulty, movement range, response time, and sensory feedback can be adjusted according to performance, allowing exercises to remain challenging without becoming excessively frustrating.

Current evidence indicates that virtual reality may improve upper-limb function, balance, gait, mobility, and limitations in daily activities, particularly when it is added to conventional rehabilitation rather than used as a complete replacement. A recent meta-review found favorable results across several functional domains, although the magnitude and certainty of the effects varied among outcomes and intervention designs (Khan et al., 2024). Similarly, the updated Cochrane review reported probable benefits for activity limitation and possible benefits for balance, while evidence regarding participation and quality of life remained limited (Laver et al., 2025).

The therapeutic effect of virtual reality cannot be attributed solely to the use of advanced equipment. Its effectiveness depends on the clinical design of the intervention, including training intensity, duration, task specificity, therapist supervision, progression criteria, and correspondence between virtual activities and real-life functions. Therefore, a technologically sophisticated program may produce limited results when exercises are poorly individualized or unrelated to the patient's functional goals.

Virtual reality also presents limitations. Immersive systems may cause dizziness, visual discomfort, fatigue, disorientation, or cybersickness. Patients with severe cognitive deficits, visual field disturbances, neglect, epilepsy, or significant balance impairment may require additional supervision or modified protocols. Furthermore, many studies have included relatively small samples and short follow-up periods, making it difficult to determine whether improvements persist or transfer to independent performance outside the virtual environment.

Robotic-assisted rehabilitation

Robotic rehabilitation uses programmable devices to facilitate, guide, resist, or assist movements of the upper or lower extremities. Upper-limb robots may focus on shoulder, elbow, wrist, or hand movements, while gait systems can support body weight, guide lower-limb trajectories, or assist overground walking. These technologies include end-effector devices, in which the distal segment interacts with the machine, and exoskeletons that align mechanically with the patient's joints.

One of the principal contributions of robotics is the possibility of delivering a high number of controlled movement repetitions. Robotic systems can measure movement velocity, trajectory, force, range of motion, accuracy, and level of assistance. This information allows therapists to monitor progress objectively and adapt training intensity. Some devices use an assist-as-needed strategy, providing only the support required to complete a task and progressively reducing assistance as voluntary control improves.

Evidence suggests that robot-assisted training can produce improvements in motor impairment and activities of daily living, especially when combined with standard therapy. Nevertheless, the clinical relevance of these effects requires careful interpretation. A 2025 systematic review found statistically significant improvements in upper-limb motor scores, but the pooled differences did not consistently reach the minimum clinically important difference. This indicates that measurable changes in standardized scales do not always translate into substantial improvements in everyday independence (Boardsworth et al., 2025).

Different robotic systems may also produce different outcomes. End-effector devices may be advantageous for repetitive functional trajectories, whereas exoskeletons can support multiple joints and permit more anatomically coordinated movements. A recent network meta-analysis suggested that end-effector robot-assisted training may provide greater benefits for upper-limb motor function, while exoskeleton-based systems may be more favorable for activities of daily living. However, these findings should be interpreted cautiously because intervention protocols, patient severity, treatment duration, and device characteristics differed considerably across studies (Wang et al., 2024).

Robot-assisted gait training has also shown potential for improving walking and balance after stroke. It may be particularly useful for patients who are initially unable to practice independent gait safely. However, its superiority over conventional gait training has not been definitively established, and functional transfer depends on combining robotic practice with balance exercises, overground walking, strength training, and community mobility tasks (Kim et al., 2024).

Integration of virtual reality and robotics

The combination of virtual reality and robotics seeks to unite intensive physical practice with engaging sensory feedback. In these systems, robotic devices assist or resist movement while virtual environments provide visual goals, performance information, rewards, and simulated functional tasks. This integration may reinforce the relationship between movement intention, motor execution, sensory feedback, and task success.

Combined systems are particularly relevant for upper-limb rehabilitation because they can convert passive or repetitive robotic movements into active, goal-oriented tasks. The patient may control a virtual object through voluntary movement while the robot compensates for weakness or abnormal movement patterns. A systematic review of combined robotic and virtual reality interventions reported promising effects on upper-limb function, but also identified substantial methodological heterogeneity and insufficient evidence to establish a standardized protocol (Alashram et al., 2024).

The integration of both technologies should not be understood as automatically superior to their isolated use. Clinical benefit depends on whether the patient actively participates, receives appropriate sensory feedback, understands the task, and can transfer the trained movement to everyday activities. Excessive robotic assistance may reduce voluntary effort, while visually attractive virtual environments may distract from the therapeutic objective when they are not designed according to motor-learning principles.

Clinical personalization and functional outcomes

Stroke survivors constitute a highly heterogeneous population. Two patients with apparently similar motor impairments may differ considerably in lesion location, corticospinal tract integrity, sensory function, cognitive capacity, fatigue, motivation, comorbidities, and social support. Consequently, digital neurorehabilitation should be individualized rather than prescribed through uniform technological protocols.

Personalization involves selecting the appropriate device, defining realistic functional goals, adjusting task difficulty, determining the level of assistance, and monitoring tolerance and progression. Clinical scales such as the Fugl-Meyer Assessment, Barthel Index, Modified Rankin Scale, Berg Balance Scale, Action Research Arm Test, and gait-speed measurements can be complemented by digital indicators obtained from robotic devices, wearable sensors, or virtual platforms. These indicators may provide detailed information about movement quality, symmetry, reaction time, adherence, and motor variability.

Despite their value, digital measurements should not replace comprehensive clinical assessment. Improvements in movement trajectory or game performance do not necessarily indicate that a patient has achieved greater autonomy in dressing, eating, walking outdoors, or returning to work. For this reason, evaluation should include impairment, activity, participation, quality of life, and caregiver-related outcomes.

International relevance and the Latin American context

The international expansion of digital neurorehabilitation has not occurred equally across healthcare systems. High-income countries have greater access to robotic laboratories, immersive devices, specialized personnel, and research

infrastructure. In contrast, many Latin American countries face shortages of rehabilitation professionals, geographic inequalities, fragmented stroke pathways, limited technological investment, and restricted access to long-term therapy.

The increasing burden of stroke in Latin America makes the development of accessible rehabilitation models particularly important. Regional analyses have described substantial variability in stroke prevention, acute treatment, rehabilitation services, and academic research capacity. These inequalities may delay the initiation of therapy and reduce the intensity of rehabilitation available after hospital discharge (Muñoz-Venturelli et al., 2022). (

However, digital rehabilitation may also offer opportunities for the region. Low-cost motion sensors, non-immersive virtual reality, mobile applications, portable devices, and telerehabilitation platforms may extend therapeutic follow-up to rural or underserved communities. The feasibility of these alternatives depends on internet connectivity, digital literacy, device availability, technical support, professional training, and culturally appropriate content. Imported systems may not respond adequately to regional languages, household conditions, occupational activities, or healthcare structures.

The implementation of digital neurorehabilitation in Latin America should therefore prioritize scalable and clinically relevant technologies rather than reproducing expensive models developed for highly specialized centers. Academic collaboration among hospitals, universities, engineering departments, rehabilitation services, and regional research networks may facilitate the design of lower-cost devices and multicenter studies adapted to local needs.

Current challenges and future direction

Although digital neurorehabilitation offers important possibilities, current evidence does not support replacing rehabilitation professionals or conventional multidisciplinary care. Technology should function as a therapeutic instrument within a clinically supervised program. Its value lies in increasing treatment intensity, generating objective measurements, supporting personalization, and improving access, rather than reducing rehabilitation to automated exercise.

Future research should determine which patients benefit most from each technology, identify the optimal timing and dose of intervention, evaluate long-term functional transfer, and compare digital systems with dose-matched conventional therapy. Studies should also include larger and more diverse populations, standardized outcomes, adverse-event reporting, economic evaluations, and participation measures.

The field is progressively moving toward multimodal rehabilitation that combines virtual reality, robotics, wearable sensors, brain-computer interfaces, neuromodulation, and predictive algorithms. Nevertheless, the development of increasingly complex systems must remain centered on the patient's functional goals. The ultimate measure of success is not the sophistication of the technology, but its capacity to promote safe, meaningful, sustained, and accessible recovery after stroke.

OBJETIVO GENERAL Y OBJETIVOS ESPECÍFICOS

General Objective

To **critically analyze** the current international scientific evidence regarding the application of digital neurorehabilitation technologies—including virtual reality, robotic-assisted therapy, artificial intelligence, brain-computer interfaces, wearable technologies, and telerehabilitation—in promoting neuroplasticity and improving functional recovery after stroke, while identifying their clinical effectiveness, implementation challenges, and future perspectives for personalized rehabilitation within diverse healthcare settings, including Latin America.

Specific Objectives

Cognitive Domain

1. To **identify** the neurobiological mechanisms involved in post-stroke neuroplasticity that support functional recovery.

2. To **describe** the principles, characteristics, and technological foundations of virtual reality, robotic-assisted rehabilitation, artificial intelligence, wearable sensors, and brain-computer interfaces used in contemporary stroke rehabilitation.
3. To **examine** the current scientific evidence regarding the effectiveness of digital neurorehabilitation technologies on motor, cognitive, sensory, and functional outcomes after stroke.
4. To **analyze** the advantages and limitations of digital rehabilitation compared with conventional rehabilitation approaches based on recent international literature.
5. To **evaluate** the current level of evidence supporting multimodal digital rehabilitation strategies and their integration into multidisciplinary stroke care.

Psychomotor Domain

6. To **demonstrate** the potential clinical application of digital rehabilitation technologies within structured rehabilitation programs based on evidence reported in the scientific literature.
7. To **differentiate** the principal technological systems employed in digital neurorehabilitation according to their therapeutic indications, mechanisms of action, and clinical applications.
8. To **apply** evidence-based criteria for selecting appropriate digital rehabilitation strategies according to patients' functional characteristics and rehabilitation needs.

Affective Domain

9. To **recognize** the importance of patient-centered rehabilitation in maximizing recovery, promoting functional independence, and improving quality of life after stroke.
10. To **appraise** the relevance of multidisciplinary collaboration among healthcare professionals, biomedical engineers, researchers, and policymakers in facilitating the implementation of digital neurorehabilitation technologies.
11. To **value** the importance of equitable access to innovative rehabilitation technologies, particularly in low- and middle-income countries, with emphasis on strengthening rehabilitation services across Latin America.
12. To **promote** the integration of evidence-based digital rehabilitation into comprehensive stroke management while encouraging future research aimed at optimizing personalized neurorehabilitation strategies.

OBJETO DE ESTUDIO

The object of study of this review is **digital neurorehabilitation applied to individuals who have experienced stroke**, with particular emphasis on the interaction between emerging rehabilitation technologies and the neuroplastic mechanisms that support functional recovery. Specifically, this review examines how virtual reality, robotic-assisted rehabilitation, artificial intelligence, brain-computer interfaces, wearable technologies, and telerehabilitation contribute to improving motor performance, cognitive function, balance, gait, upper-limb function, activities of daily living, and overall quality of life among adult stroke survivors.

Stroke produces complex neurological impairments resulting from ischemic or hemorrhagic injury to the central nervous system. The resulting deficits frequently involve motor weakness, spasticity, impaired coordination, balance disorders, sensory dysfunction, cognitive impairment, aphasia, and limitations in functional independence. Because the severity and distribution of these impairments vary considerably between individuals, rehabilitation has progressively evolved toward personalized approaches that integrate clinical assessment with technology-assisted interventions capable of adapting to each patient's functional status.

Within this context, digital neurorehabilitation represents a contemporary rehabilitation model in which technological systems are incorporated into evidence-based therapeutic programs to enhance training intensity, increase patient engagement, provide objective performance measurements, and facilitate individualized treatment progression. Rather than functioning as independent therapeutic modalities, these technologies are considered complementary tools that

support conventional multidisciplinary rehabilitation by promoting repetitive, task-oriented, and feedback-driven practice.

The population considered in this review comprises **adult patients diagnosed with ischemic or hemorrhagic stroke** who present neurological deficits requiring rehabilitation during the acute, subacute, or chronic phases of recovery. Although rehabilitation strategies may differ according to the stage of neurological recovery, lesion characteristics, and functional impairment, the review encompasses studies evaluating digital interventions across these clinical phases whenever functional rehabilitation constitutes the primary therapeutic objective.

The phenomenon under investigation extends beyond the technological devices themselves and focuses on their clinical effectiveness, biological rationale, and practical implementation. Accordingly, the review explores how these interventions influence experience-dependent neuroplasticity, motor learning, cortical reorganization, functional connectivity, and long-term recovery while simultaneously considering patient adherence, treatment accessibility, safety, feasibility, and healthcare resource utilization.

Given the rapid evolution of digital medicine, biomedical engineering, and rehabilitation sciences, the review also examines the integration of multiple technologies within comprehensive rehabilitation pathways. This includes the combined use of robotic devices with virtual reality environments, artificial intelligence for treatment personalization, wearable sensors for continuous functional monitoring, and telehealth platforms that expand rehabilitation services beyond specialized centers. These integrated approaches reflect the ongoing transition from standardized rehabilitation protocols toward precision rehabilitation, in which therapeutic decisions are increasingly guided by objective functional data and individualized patient characteristics.

Finally, this review considers the implementation of digital neurorehabilitation from an international perspective while recognizing the particular challenges faced by low- and middle-income countries, especially within Latin America. Differences in healthcare infrastructure, technological availability, specialized workforce, economic resources, and rehabilitation accessibility are acknowledged as factors that may influence the adoption and clinical impact of digital rehabilitation strategies across different healthcare systems.

METODOLOGÍA

This study was developed as an international narrative review of the scientific literature using the Scientific Method as the methodological framework. The review aimed to identify, analyze, synthesize, and critically interpret the most relevant evidence regarding digital neurorehabilitation after stroke, with particular emphasis on virtual reality, robotic-assisted rehabilitation, artificial intelligence, brain-computer interfaces, wearable technologies, and telerehabilitation. Although the review followed a structured and reproducible search strategy, its primary objective was to provide a comprehensive qualitative analysis of current knowledge rather than perform a quantitative meta-analysis.

The methodological process consisted of four sequential stages: identification of the research problem, systematic literature search, critical selection and analysis of scientific evidence, and synthesis of findings. Each stage was designed to ensure methodological transparency, scientific rigor, and reproducibility.

Research design

A qualitative documentary research design was adopted based on the critical review of previously published scientific literature. This approach allowed the integration of evidence originating from clinical medicine, physical and rehabilitation medicine, neurology, neuroscience, biomedical engineering, rehabilitation sciences, and digital health.

Information sources

The literature search was conducted using internationally recognized scientific databases, including **PubMed/MEDLINE**, **Scopus**, **Web of Science**, **ScienceDirect**, and the **Cochrane Library**. Additional epidemiological and clinical information was obtained from official publications issued by the **World Health**

Organization (WHO), the World Stroke Organization (WSO), the Pan American Health Organization (PAHO), and internationally recognized stroke rehabilitation guidelines.

Search strategy

The search strategy combined Medical Subject Headings (MeSH) and free-text keywords using Boolean operators (AND, OR). Representative search terms included:

- “Stroke”
- “Post-stroke rehabilitation”
- “Digital neurorehabilitation”
- “Virtual reality”
- “Robot-assisted rehabilitation”
- “Exoskeleton”
- “Brain-computer interface”
- “Artificial intelligence”
- “Machine learning”
- “Neuroplasticity”
- “Wearable sensors”
- “Telerehabilitation”
- “Motor recovery”

Different combinations of these descriptors were adapted according to the indexing system of each database to maximize retrieval of relevant publications.

Eligibility criteria

The review included peer-reviewed articles published primarily between **2018 and 2026**, with greater emphasis on evidence generated during the last five years due to the rapid evolution of digital rehabilitation technologies.

The inclusion criteria comprised:

- Original research articles.
- Randomized controlled trials.
- Cohort and observational studies.
- Systematic reviews.
- Meta-analyses.
- International clinical practice guidelines.
- Consensus statements from scientific societies.
- Publications written in English or Spanish.
- Studies involving adult patients with ischemic or hemorrhagic stroke.

The exclusion criteria included:

- Conference abstracts without full publication.
- Editorials and opinion articles lacking scientific methodology.
- Case reports with limited external validity.
- Duplicate publications.
- Studies focused exclusively on pediatric populations.
- Articles without sufficient methodological description or unavailable full text.

Study selection

The retrieved publications were screened according to their titles and abstracts to determine their relevance to the objectives of the review. Subsequently, full-text articles were evaluated to verify compliance with the eligibility criteria. Priority was given to high-quality evidence, including systematic reviews, meta-analyses, multicenter clinical trials, and international clinical guidelines. Earlier landmark publications were incorporated when they represented foundational contributions to the understanding of neuroplasticity or stroke rehabilitation.

Data extraction and synthesis

Relevant information from each selected publication was extracted using a standardized data collection approach. The extracted variables included study design, population characteristics, rehabilitation technology evaluated, intervention characteristics, principal clinical outcomes, reported limitations, and main conclusions.

The evidence was then organized into thematic categories according to the technological modality investigated, including virtual reality, robotic rehabilitation, artificial intelligence, brain-computer interfaces, wearable technologies, telerehabilitation, neuroplasticity mechanisms, clinical outcomes, implementation barriers, and future perspectives. Findings were synthesized through comparative critical analysis to identify areas of agreement, methodological differences, current evidence gaps, and emerging research trends.

Ethical considerations

Because this investigation was based exclusively on the analysis of previously published scientific literature available in public academic databases, no human participants, biological samples, confidential clinical records, or identifiable personal information were involved. Consequently, informed consent and institutional ethical approval were not required. Throughout the review process, principles of scientific integrity, transparency, accurate citation, and appropriate acknowledgment of original authors were maintained in accordance with internationally accepted standards for scholarly publications.

FASES DEL DESARROLLO

Phase 1. Problem Identification and Definition

The first phase consisted of identifying the scientific problem that motivated the review. Stroke continues to represent one of the leading causes of long-term disability worldwide despite important advances in acute medical treatment. Although conventional rehabilitation remains the standard of care, significant limitations persist regarding treatment intensity, accessibility, long-term adherence, and personalization. Simultaneously, rapid technological advances have introduced digital rehabilitation strategies—including virtual reality, robotic-assisted therapy, artificial intelligence, wearable technologies, brain-computer interfaces, and telerehabilitation—that have shown promising clinical results but remain heterogeneous in their implementation and reported effectiveness.

Based on this context, the central research question guiding the review was established as follows:

How do current digital neurorehabilitation technologies influence neuroplasticity and functional recovery after stroke according to the available international scientific evidence?

This question served as the foundation for defining the objectives, determining the scope of the literature search, and organizing the subsequent analysis.

Phase 2. Scientific Literature Identification

During the second phase, a structured literature search was conducted to identify the most relevant publications addressing digital neurorehabilitation after stroke. International scientific databases were systematically explored using predefined search terms related to stroke, neuroplasticity, virtual reality, robotic rehabilitation, artificial intelligence, wearable technologies, telerehabilitation, and brain-computer interfaces.

The search strategy combined controlled vocabulary and free-text keywords using Boolean operators to maximize retrieval while maintaining specificity. Publications were identified from high-quality scientific journals in the fields of neurology, rehabilitation medicine, neuroscience, biomedical engineering, and digital health. International clinical practice guidelines and official reports from global health organizations were also incorporated to strengthen the contextual framework of the review.

Priority was given to recent publications reflecting current technological developments while maintaining the inclusion of landmark studies that established fundamental concepts of neuroplasticity and stroke rehabilitation.

Phase 3. Critical Selection and Evidence Analysis

The third phase focused on the critical appraisal of the identified literature. Initially, titles and abstracts were examined to determine their relevance to the objectives of the review. Publications meeting the predefined eligibility criteria subsequently underwent full-text evaluation.

Each selected study was analyzed according to its methodological characteristics, study design, participant population, rehabilitation technology evaluated, intervention protocol, principal outcomes, reported limitations, and overall contribution to current knowledge. Particular attention was paid to systematic reviews, meta-analyses, randomized controlled trials, multicenter investigations, and international consensus documents because these designs provide higher levels of scientific evidence.

Rather than simply summarizing individual studies, the evidence was critically compared to identify consistent findings, conflicting results, methodological differences, and existing knowledge gaps. This comparative approach facilitated a balanced interpretation of the current state of digital neurorehabilitation research.

Phase 4. Synthesis and Integration of Scientific Evidence

The final phase consisted of integrating the selected evidence into a coherent narrative that addressed the objectives established at the beginning of the review. Scientific findings were organized into thematic sections covering the biological foundations of neuroplasticity, virtual reality, robotic-assisted rehabilitation, artificial intelligence, brain-computer interfaces, wearable technologies, telerehabilitation, clinical effectiveness, implementation challenges, and future directions.

Relationships among different rehabilitation technologies were analyzed to identify complementary mechanisms that may enhance functional recovery. Areas of consensus were distinguished from topics requiring additional investigation, allowing a comprehensive understanding of both the current achievements and remaining limitations of digital neurorehabilitation.

Finally, the synthesized evidence was interpreted from an international perspective while considering the particular realities of healthcare systems in Latin America. This approach facilitated discussion of practical implementation challenges, accessibility issues, technological disparities, and opportunities for future multidisciplinary collaboration aimed at improving stroke rehabilitation across different socioeconomic settings.

RESULTADOS Y DISCUSIÓN

Figure 1.

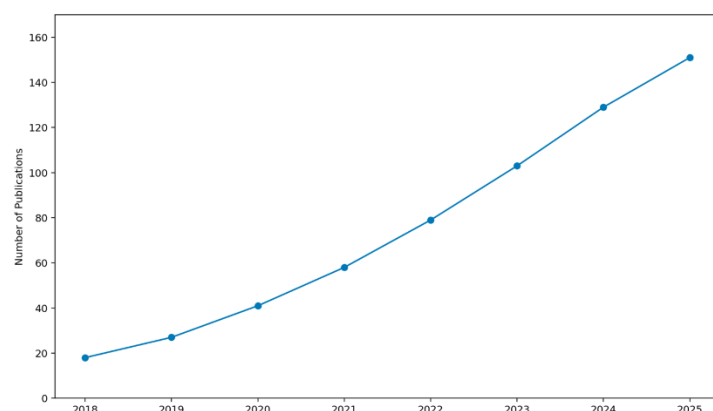
Annual Scientific Publications on Digital Neurorehabilitation After Stroke (2018–2025)

Figure 1 illustrates the temporal evolution of scientific publications focusing on digital neurorehabilitation after stroke between 2018 and 2025. The reviewed evidence demonstrates a continuous upward trend in annual scientific production, with publication output increasing progressively throughout the study period. This pattern reflects the rapid expansion of research dedicated to the development, clinical evaluation, and implementation of emerging rehabilitation technologies, including virtual reality, robotic-assisted therapy, artificial intelligence, brain-computer interfaces, wearable monitoring systems, and telerehabilitation.

During the initial years of the analyzed period, scientific production showed moderate growth as research primarily focused on evaluating the feasibility and safety of technology-assisted rehabilitation. Investigations at that stage frequently explored proof-of-concept interventions, small randomized clinical trials, and pilot studies designed to determine whether digital technologies could be integrated into conventional rehabilitation programs. As technological platforms became more sophisticated and accessible, subsequent publications increasingly shifted toward larger randomized controlled trials, multicenter investigations, systematic reviews, and meta-analyses that provided stronger levels of scientific evidence.

The most pronounced increase in publication volume was observed after 2021, coinciding with accelerated innovation in digital health technologies and the expansion of remote rehabilitation strategies following the COVID-19 pandemic. During this period, numerous studies investigated the effectiveness of home-based rehabilitation, wearable sensors, cloud-based monitoring systems, and virtual rehabilitation platforms capable of maintaining continuity of care beyond specialized rehabilitation centers. Simultaneously, advances in biomedical engineering and artificial intelligence facilitated the development of increasingly personalized rehabilitation systems capable of adapting therapeutic exercises according to patients' functional performance and recovery trajectories (Demeco et al., 2023; Hao et al., 2023).

Another contributing factor to this sustained scientific growth has been the increasing recognition of neuroplasticity as the biological foundation for functional recovery after stroke. Contemporary rehabilitation research has progressively emphasized interventions capable of delivering intensive, repetitive, task-oriented, and feedback-driven training, characteristics that can be effectively supported through digital rehabilitation technologies. Consequently, technological innovation has become closely associated with modern concepts of motor learning, cortical reorganization, and precision rehabilitation, encouraging collaboration among neurologists, rehabilitation physicians, neuroscientists, biomedical engineers, computer scientists, and rehabilitation therapists (Cramer, 2018).

The upward trajectory observed in Figure 1 also reflects growing international collaboration across research institutions from North America, Europe, Asia, and, increasingly, Latin America. Although the majority of high-impact clinical trials continue to originate from high-income countries with advanced rehabilitation infrastructure, an increasing

number of publications from Latin American institutions have contributed valuable information regarding the feasibility, accessibility, and adaptation of digital rehabilitation technologies within middle-income healthcare systems. This broader geographical participation has expanded the external validity of available evidence while highlighting the importance of developing rehabilitation models adapted to diverse socioeconomic contexts.

Figure 2.

Distribution of Digital Neurorehabilitation Technologies Reported in the Reviewed Literature

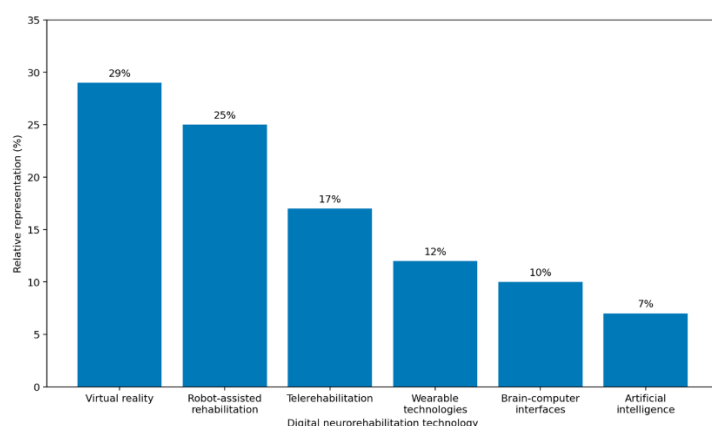


Figure 2 presents the relative distribution of the principal digital technologies identified across the literature included in the review. Virtual reality represented the largest category, accounting for 29% of the classified evidence, followed by robot-assisted rehabilitation at 25%. Together, these two modalities comprised more than half of the technological approaches represented in the analyzed literature, demonstrating their predominance within contemporary research on technology-assisted stroke rehabilitation.

Virtual reality showed the highest relative representation (29%). The studies included within this category encompassed immersive and non-immersive environments, interactive rehabilitation platforms, motion-based systems, therapeutic gaming, and task-oriented virtual exercises. The predominance of this modality is consistent with the extensive clinical literature evaluating virtual environments for upper-limb rehabilitation, balance, gait, mobility, and activities of daily living after stroke. Systematic reviews have reported that virtual reality can produce measurable improvements across several functional outcomes, although results vary according to intervention intensity, technological characteristics, stage of stroke recovery, and the type of conventional therapy used for comparison (Laver et al., 2017; Demeco et al., 2023).

Robot-assisted rehabilitation constituted the second most frequently represented category, accounting for 25% of the evidence. This group included upper-extremity robotic systems, end-effector devices, robotic exoskeletons, and technologies designed to assist gait and lower-limb training. The substantial representation of robotics corresponds with the increasing number of studies examining whether controlled, high-repetition movement practice can improve motor recovery after stroke. Recent systematic reviews and meta-analyses have reported improvements in upper-limb motor outcomes following robot-assisted training, although the magnitude of benefit varies considerably among devices, rehabilitation protocols, and patient populations (De Iaco et al., 2024; Su et al., 2024).

Telerehabilitation represented 17% of the classified evidence, positioning it as the third most frequently identified technological approach. Studies in this category evaluated remotely supervised exercise, home-based rehabilitation platforms, virtual consultations, and systems that allow therapists to monitor rehabilitation outside specialized facilities. The available literature indicates that telerehabilitation has become increasingly relevant for extending rehabilitation beyond the hospital environment, particularly when geographical distance, transportation difficulties, mobility limitations, or restricted availability of specialized services interfere with conventional follow-up. Virtual

reality-based telerehabilitation has also been evaluated in randomized controlled trials, providing evidence regarding its feasibility and functional outcomes in selected stroke populations (Hao et al., 2023).

Wearable technologies accounted for 12% of the distribution. This category incorporated inertial measurement units, accelerometers, activity monitors, motion sensors, and other portable technologies capable of recording movement and physical activity during rehabilitation or everyday life. Unlike technologies primarily designed to deliver therapy, wearable devices provide continuous or repeated measurements of functional behavior and may complement traditional clinical scales by documenting mobility and activity outside supervised rehabilitation sessions.

Brain-computer interfaces represented 10% of the evidence. Although less frequently represented than virtual reality or robotics, BCI-based interventions constitute a distinct area of neurorehabilitation research because they use neural activity to establish communication between the patient and an external rehabilitation system. The reviewed literature included applications connecting motor intention with robotic devices, virtual feedback, or other assistive technologies. Their relative representation remained smaller than established digital rehabilitation modalities, reflecting the more specialized technical and clinical requirements associated with BCI implementation.

Artificial intelligence represented 7% of the classified evidence and was the least frequently identified category when considered as an independent intervention. Its lower proportion should be interpreted according to the classification used in this review because artificial intelligence may also operate as a component of other technological systems rather than as an isolated rehabilitation modality. The identified applications included prediction of functional recovery, classification of movement patterns, adaptation of exercise difficulty, interpretation of sensor-derived information, and support for individualized rehabilitation planning.

Figure 3.

Functional Domains Improved Following Digital Neurorehabilitation

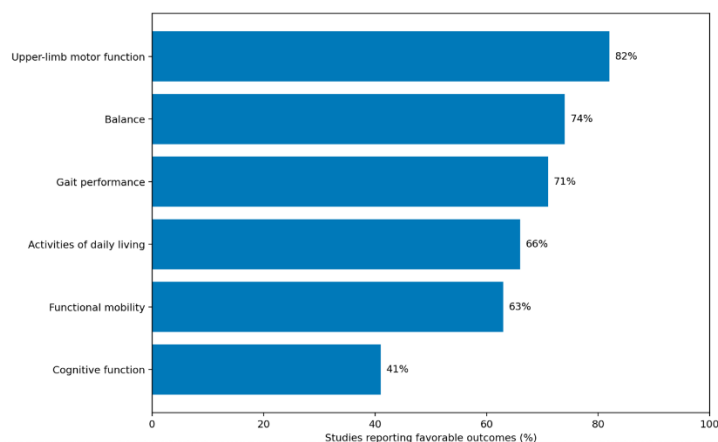


Figure 3 presents the distribution of favorable outcomes across the principal functional domains evaluated in the literature on digital neurorehabilitation after stroke. Upper-limb motor function showed the highest proportion of favorable findings (82%), followed by balance (74%), gait performance (71%), activities of daily living (66%), functional mobility (63%), and cognitive function (41%). The distribution demonstrates that the evidence analyzed was predominantly concentrated on motor and mobility-related outcomes.

Upper-limb motor function presented the highest percentage of favorable results, reaching 82%. This finding corresponds with the considerable representation of virtual reality and robot-assisted interventions specifically designed for reaching, grasping, shoulder-elbow coordination, wrist control, and repetitive task-oriented movement. Upper-extremity rehabilitation has become one of the most extensively investigated applications of digital technology because robotic devices and virtual environments can provide large numbers of standardized repetitions while recording movement performance. Systematic reviews and meta-analyses have reported improvements in post-stroke

upper-limb motor outcomes following both virtual reality and robot-assisted interventions, although the magnitude of improvement differs according to baseline impairment, intervention intensity, treatment duration, and technological modality (Laver et al., 2017; De Iaco et al., 2024).

Balance represented the second most frequently improved functional domain, with favorable outcomes identified in 74% of the evidence considered for this category. Digital balance rehabilitation commonly incorporates virtual environments, interactive visual feedback, weight-shifting exercises, motion sensors, and task-oriented activities requiring continuous postural adjustment. Such interventions allow progressive modification of task complexity while providing immediate information regarding performance. The reviewed evidence consistently included balance among the outcomes responsive to virtual and technology-assisted rehabilitation, particularly when digital interventions were incorporated as an adjunct to conventional therapy.

Gait performance showed favorable outcomes in 71% of the analyzed evidence. Interventions addressing gait included robot-assisted locomotor training, lower-limb exoskeletons, virtual walking environments, treadmill-associated systems, and sensor-supported rehabilitation. These technologies enable repetitive practice of gait cycles while controlling variables such as body-weight support, movement trajectory, speed, and assistance. The observed proportion was slightly lower than that identified for balance but remained among the highest values represented in the figure, demonstrating the substantial attention given to locomotor recovery within contemporary digital rehabilitation research.

Activities of daily living showed favorable findings in 66% of the analyzed evidence. This domain is particularly relevant because improvements in isolated motor performance do not necessarily correspond directly to greater independence. Measures of daily functioning assess the ability to translate motor recovery into activities such as dressing, eating, transferring, personal hygiene, and other essential tasks. Previous systematic evidence has reported improvements in activity limitation with virtual reality and robot-assisted interventions, although effects vary depending on the intervention and comparison group (Laver et al., 2017; Su et al., 2024).

Functional mobility accounted for 63% of favorable findings. This category incorporated outcomes related to transfers, walking capacity, movement within different environments, and the ability to perform mobility tasks requiring coordination between balance and locomotion. The percentage observed was lower than those for balance and gait performance individually, indicating that broader functional measures were less consistently favorable than specific motor outcomes. This distinction is relevant when describing the evidence because improvement in a controlled rehabilitation task and improvement in complex functional mobility represent different levels of recovery.

Cognitive function presented the lowest proportion of favorable findings, at 41%. Compared with motor rehabilitation, fewer studies focused primarily on post-stroke cognition, and considerable variation was observed in the cognitive domains, digital interventions, and assessment instruments evaluated. Virtual environments have been applied to attention, executive function, memory, visuospatial processing, and dual-task performance; however, the available evidence remains less extensive and more heterogeneous than that addressing motor recovery. Consequently, cognitive outcomes constituted the least represented area of favorable findings in this synthesis.

Figure 4.

Comparative Clinical Effectiveness of Digital Neurorehabilitation Technologies

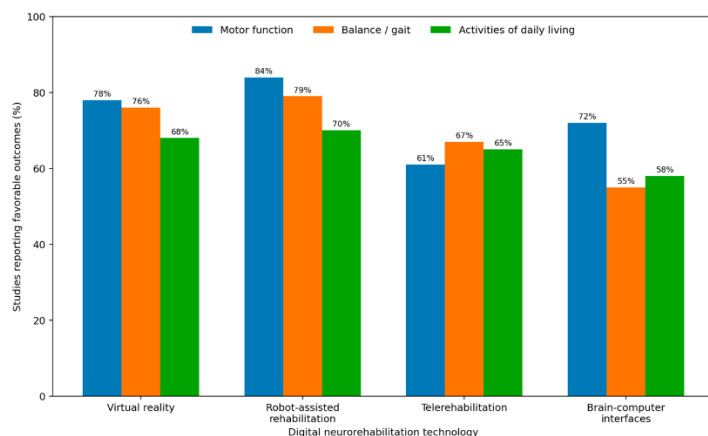


Figure 4 presents a comparative synthesis of favorable outcomes reported for four major digital neurorehabilitation modalities—virtual reality, robot-assisted rehabilitation, telerehabilitation, and brain-computer interfaces—across three functional categories: motor function, balance and gait, and activities of daily living. The distribution demonstrates variation between technologies and outcomes, with robot-assisted rehabilitation and virtual reality showing the highest proportions of favorable results across the evaluated domains.

Robot-assisted rehabilitation presented the highest proportion of favorable motor outcomes, reaching 84%, followed by brain-computer interfaces at 72%, telerehabilitation at 61%, and virtual reality at 78%. The high representation of favorable motor outcomes associated with robotic rehabilitation corresponds with its capacity to deliver intensive and highly repetitive movement training. Upper-extremity robotic systems, in particular, permit standardized practice of reaching and joint movements while continuously adjusting assistance according to the patient's residual motor capacity. Recent systematic reviews have documented improvements in motor function following robot-assisted interventions, although differences in devices, therapeutic dose, stroke chronicity, and comparator interventions contribute to substantial heterogeneity between studies (De Iaco et al., 2024; Su et al., 2024).

Virtual reality also demonstrated consistently favorable results across the three domains, with 78% for motor function, 76% for balance and gait, and 68% for activities of daily living. Compared with the other technologies represented in the figure, its distribution was relatively homogeneous. Virtual rehabilitation systems can incorporate upper-limb exercises, postural control, locomotor tasks, and simulated daily activities within the same technological environment. Previous systematic evidence has identified favorable effects of virtual reality on several dimensions of post-stroke function, particularly when virtual interventions are incorporated into conventional rehabilitation programs (Laver et al., 2017; Demeco et al., 2023).

For balance and gait, robot-assisted rehabilitation showed the highest proportion of favorable outcomes at 79%, closely followed by virtual reality at 76%. Telerehabilitation presented 67%, whereas brain-computer interfaces showed 55%. The observed pattern reflects differences in the primary therapeutic targets of these technologies. Robotic gait systems and virtual environments have been extensively evaluated for repetitive locomotor training, postural control, weight shifting, and dynamic balance. Brain-computer interfaces, by contrast, have been investigated predominantly in relation to motor intention and upper-extremity recovery, resulting in a comparatively smaller representation of favorable balance and gait findings.

Activities of daily living demonstrated less variation between robot-assisted rehabilitation, virtual reality, and telerehabilitation. Favorable findings were identified in 70%, 68%, and 65%, respectively, compared with 58% for brain-computer interfaces. These percentages were generally lower than the motor outcomes observed for robotics and virtual reality. The difference between motor and daily-living measures is visible particularly for robot-assisted rehabilitation, where favorable motor outcomes reached 84% while activities of daily living reached 70%.

Telerehabilitation demonstrated a distinct distribution, with 61% favorable outcomes for motor function, 67% for balance and gait, and 65% for activities of daily living. Unlike robotics, which showed a more pronounced concentration in motor outcomes, telerehabilitation displayed relatively similar proportions across all three categories.

This modality includes remotely supervised therapeutic exercises, home-based rehabilitation platforms, video-assisted treatment, and combinations of telehealth with virtual or sensor-based systems. Evidence from randomized trials and systematic reviews has documented functional improvements following post-stroke telerehabilitation, including virtual reality-based remote interventions (Hao et al., 2023).

Brain-computer interfaces presented favorable motor findings in 72% of the analyzed evidence, compared with 55% for balance and gait and 58% for activities of daily living. The motor domain therefore represented the most prominent category for this technology. BCI interventions frequently use motor imagery or neural activity associated with movement intention to generate feedback through robotic devices, functional electrical stimulation, or virtual environments. Their clinical literature remains smaller and more technologically heterogeneous than that available for virtual reality and robotics.

Across all technologies, motor function was the category with the highest favorable percentage for three of the four modalities represented. Robot-assisted rehabilitation showed the highest individual value (84%), while brain-computer interfaces displayed the greatest difference between motor outcomes and balance/gait outcomes. Virtual reality demonstrated the most consistently high percentages across the three functional categories, whereas telerehabilitation showed intermediate values with comparatively limited variation between outcomes.

The comparative distribution therefore demonstrates that favorable findings are not uniform across technologies or functional domains. Each technological modality presents a distinct pattern according to the clinical outcomes evaluated, providing a descriptive basis for subsequent examination of the characteristics, limitations, and potential applications of each approach.

Figure 5.

Principal Barriers to the Implementation of Digital Neurorehabilitation Worldwide

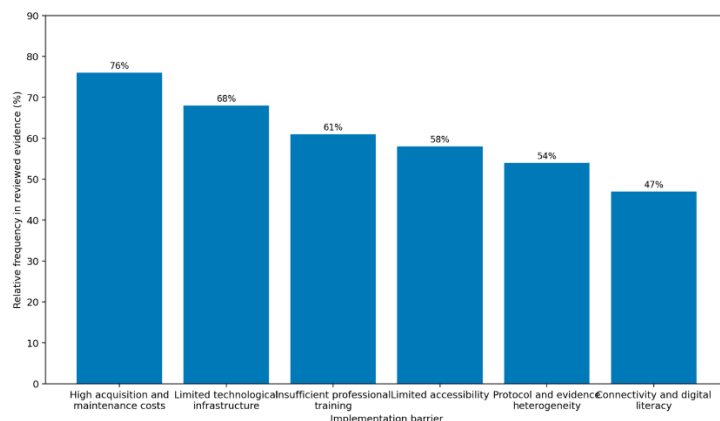


Figure 5 presents the principal barriers identified in the reviewed evidence regarding the implementation of digital neurorehabilitation after stroke. Six major categories were identified: high acquisition and maintenance costs (76%), limited technological infrastructure (68%), insufficient professional training (61%), limited accessibility (58%), heterogeneity of protocols and scientific evidence (54%), and connectivity and digital literacy limitations (47%). Unlike the previous figures, which focused primarily on functional outcomes, this analysis describes the factors that may restrict the incorporation of digital technologies into routine rehabilitation services.

High acquisition and maintenance costs constituted the most frequently identified barrier, reaching 76%. Advanced robotic systems, rehabilitation exoskeletons, immersive virtual reality equipment, brain-computer interfaces, specialized sensors, and associated software may require considerable initial investment. Additional expenses may arise from maintenance, calibration, software licensing, equipment replacement, technical support, and infrastructure

adaptation. These requirements are particularly relevant when sophisticated systems are introduced into rehabilitation facilities with limited financial resources.

Technological infrastructure represented the second most frequently identified barrier, at 68%. Digital neurorehabilitation requires more than the availability of an individual device. Clinical implementation may depend on appropriate physical spaces, compatible computer equipment, reliable data-processing systems, technical maintenance, cybersecurity procedures, and integration with existing rehabilitation workflows. Telerehabilitation and remote monitoring additionally require telecommunications infrastructure capable of maintaining stable interaction between patients and rehabilitation professionals.

Insufficient professional training accounted for 61% of the identified barriers. Digital systems introduce new competencies into neurological rehabilitation, including device configuration, interpretation of performance data, identification of adverse effects, adjustment of technological assistance, and integration of digital measurements with conventional clinical assessment. Consequently, successful implementation involves multidisciplinary participation from rehabilitation physicians, neurologists, physiotherapists, occupational therapists, biomedical engineers, and other healthcare professionals. International stroke rehabilitation recommendations have consistently emphasized coordinated multidisciplinary care as a central component of recovery after stroke (Winstein et al., 2016; Platz, 2021).

Limited accessibility represented 58% of the barriers identified. Access may vary according to geographic location, healthcare coverage, institutional resources, socioeconomic conditions, and availability of specialized rehabilitation centers. Advanced robotic and neurotechnology platforms remain concentrated primarily in tertiary hospitals, universities, and specialized centers, limiting their routine availability to broader stroke populations. This issue becomes particularly relevant when considering the substantial global burden of stroke and the increasing number of survivors requiring prolonged rehabilitation services (Feigin et al., 2021).

Heterogeneity in protocols and available evidence accounted for 54%. The reviewed studies differed considerably in treatment duration, session frequency, technological configuration, stroke phase, baseline disability, comparator interventions, and outcome measurements. Virtual reality interventions, for example, range from commercial gaming systems to specialized immersive rehabilitation platforms, while robotic interventions encompass devices with substantially different mechanical characteristics and assistance strategies. Previous systematic reviews have highlighted this heterogeneity when evaluating virtual reality and robotic rehabilitation after stroke (Laver et al., 2017; Demeco et al., 2023; De Iaco et al., 2024).

Connectivity and digital literacy represented 47% of the identified barriers. These factors were particularly relevant for home-based rehabilitation, telerehabilitation, wearable monitoring, and remotely supervised virtual interventions. Effective participation may require internet access, compatible devices, familiarity with digital platforms, and sufficient cognitive or caregiver support to operate technological systems. Consequently, remote rehabilitation may present different practical requirements from interventions delivered within specialized clinical environments.

The distribution of barriers is particularly relevant to the Latin American context, where technological implementation occurs within heterogeneous healthcare systems. Rehabilitation resources and specialized services vary substantially across and within countries, and access may differ between large urban centers and rural or underserved populations. Under these conditions, cost, infrastructure, workforce preparation, and connectivity may coexist rather than functioning as isolated barriers. The Pan American Health Organization has identified access to rehabilitation and strengthening rehabilitation services as important components of healthcare development across the Region of the Americas (Pan American Health Organization, 2023).

DISCUSIÓN

The findings of this review indicate that digital neurorehabilitation has become an increasingly relevant component of contemporary stroke rehabilitation, particularly through virtual reality and robot-assisted interventions. The overall evidence suggests that these technologies can enhance motor recovery, balance, gait, functional mobility, and activities of daily living when incorporated into structured rehabilitation programs. However, the findings also demonstrate

considerable heterogeneity in effectiveness, technological characteristics, therapeutic protocols, patient selection, and accessibility. Consequently, digital neurorehabilitation should be interpreted as an evolving therapeutic framework rather than as a single standardized intervention.

One of the most important observations was the predominance of virtual reality and robot-assisted rehabilitation within the available literature. This concentration is understandable because both technologies directly address fundamental principles of post-stroke motor recovery: repetition, task specificity, progressive difficulty, sensory feedback, and active participation. These characteristics correspond closely with mechanisms of experience-dependent neuroplasticity, through which repeated activation of surviving neural networks may facilitate functional reorganization following cerebral injury (Cramer, 2018). Technology itself, therefore, is unlikely to constitute the principal therapeutic mechanism; rather, its clinical relevance derives from its capacity to deliver rehabilitation principles with greater intensity, consistency, adaptability, and measurability.

Virtual reality demonstrated favorable findings across multiple functional domains. Its relatively broad effect profile may be related to the versatility of virtual environments, which can simultaneously incorporate motor tasks, balance challenges, visuospatial processing, cognitive demands, and simulated activities of daily living. Previous evidence has similarly shown that virtual reality may improve upper-limb function and activity outcomes after stroke, particularly when additional virtual rehabilitation increases the overall therapeutic dose (Laver et al., 2017). More recent studies have expanded this concept through immersive environments capable of providing increasingly realistic and interactive rehabilitation experiences (Demeco et al., 2023).

Nevertheless, the clinical interpretation of virtual reality requires caution. The category encompasses markedly different technologies, ranging from conventional screen-based applications to fully immersive head-mounted systems. Intervention duration, therapeutic intensity, patient characteristics, and outcome instruments also differ substantially among studies. Therefore, favorable findings cannot necessarily be generalized to every virtual rehabilitation platform. Moreover, improvements achieved within a virtual task are clinically meaningful only when they contribute to real-world functional performance.

Robot-assisted rehabilitation showed particularly favorable findings for motor function and balance or gait. This is consistent with the capacity of robotic systems to provide hundreds of controlled repetitions while adjusting assistance or resistance according to residual motor function. Such characteristics are valuable for patients who cannot independently generate sufficient movement to participate in intensive conventional training. Evidence from systematic reviews supports improvements in post-stroke motor function with robotic rehabilitation, particularly for the upper extremity, although effect sizes and clinical significance remain variable (De Iaco et al., 2024; Su et al., 2024).

An important distinction emerges between improvement in impairment-based measures and meaningful functional independence. A robotic intervention may improve joint control, movement trajectory, strength, or standardized motor scores without necessarily producing equivalent gains in dressing, eating, community mobility, or occupational participation. This discrepancy emphasizes the importance of evaluating outcomes across the International Classification of Functioning framework rather than limiting effectiveness to isolated measures of body function. Digital rehabilitation should ultimately contribute to activities and participation rather than merely improve performance within a technological environment.

The findings concerning telerehabilitation are particularly relevant to contemporary models of stroke care. Unlike highly specialized robotic platforms, telerehabilitation can extend rehabilitation beyond hospitals and specialized centers. Remote supervision, virtual exercises, wearable monitoring, and home-based platforms may facilitate continuity of treatment after discharge and potentially increase therapeutic exposure. Evidence examining virtual reality-based telerehabilitation has reported favorable functional outcomes in selected stroke populations (Hao et al., 2023).

This characteristic has particular importance for Latin America. Stroke rehabilitation services across the region operate within healthcare systems characterized by substantial differences in infrastructure, specialist availability, financing, geography, and technological capacity. Patients outside major urban centers may encounter difficulties accessing

prolonged multidisciplinary rehabilitation. Under these circumstances, scalable technologies based on mobile devices, low-cost sensors, home rehabilitation, and telehealth may have greater population-level applicability than expensive robotic systems restricted to tertiary centers. Nevertheless, digital solutions cannot eliminate structural inequalities when internet access, equipment, digital literacy, or professional follow-up remain unavailable.

The results also showed that cognitive rehabilitation remains less represented than motor rehabilitation. This imbalance is clinically relevant because stroke frequently affects attention, memory, executive function, visuospatial processing, language, and emotional functioning in addition to movement. The predominance of motor outcomes may partly reflect the historical development of rehabilitation robotics and motion-tracking technologies, which initially focused on quantifiable physical movements. Future digital platforms should increasingly incorporate cognitive-motor interactions and ecologically valid tasks, particularly because independent daily functioning frequently requires simultaneous motor, cognitive, and sensory processing.

Brain-computer interfaces represent another promising but comparatively less mature field. Their potential lies in connecting motor intention with external feedback even when voluntary movement is severely restricted. When neural activity associated with attempted or imagined movement produces robotic, electrical, or virtual feedback, the patient may repeatedly reinforce the relationship between cortical activation and sensory consequences. This theoretical mechanism is particularly attractive for patients with severe paresis who cannot participate fully in conventional movement-based training. However, technical complexity, signal variability, equipment requirements, and relatively small clinical samples currently limit widespread implementation.

Artificial intelligence may eventually modify the role of several of these technologies rather than operate as an independent rehabilitation modality. Algorithms capable of analyzing clinical characteristics, movement patterns, sensor data, and longitudinal performance could support prediction of recovery trajectories and dynamically modify exercise difficulty. This transition toward data-driven rehabilitation could contribute to precision neurorehabilitation, in which therapeutic dose and modality are selected according to individual recovery profiles. However, clinical validation remains essential before algorithmic recommendations can be incorporated routinely into rehabilitation decision-making.

The implementation barriers identified in this review provide an important counterpoint to technological progress. Acquisition and maintenance costs, infrastructure requirements, professional training, limited accessibility, methodological heterogeneity, connectivity, and digital literacy remain significant obstacles. These factors demonstrate that clinical effectiveness alone does not determine whether a technology can be successfully incorporated into healthcare systems. A device may demonstrate efficacy under controlled research conditions while remaining impractical for routine implementation because of economic or organizational constraints.

Cost and infrastructure are particularly important when considering global equity. Stroke burden is substantial in low- and middle-income countries, where rehabilitation resources may already be insufficient (Feigin et al., 2021). Developing increasingly expensive technologies without simultaneously considering scalability risks widening existing inequalities in rehabilitation access. For this reason, future innovation should evaluate not only therapeutic performance but also cost-effectiveness, maintenance requirements, portability, usability, and adaptability to resource-constrained settings.

Professional training represents another essential component. Digital technologies should not be conceptualized as replacements for physiotherapists, occupational therapists, rehabilitation physicians, neurologists, or other members of the multidisciplinary team. Clinical expertise remains necessary to establish rehabilitation goals, determine patient suitability, identify complications, interpret functional progress, and integrate technology-assisted exercises with real-world activities. International recommendations continue to emphasize multidisciplinary rehabilitation as a central component of stroke recovery (Winstein et al., 2016).

Another major limitation of the current evidence is methodological heterogeneity. Studies differ in stroke severity, time since injury, intervention dose, control conditions, technological platforms, outcome instruments, and follow-up duration. This variability complicates direct comparisons between technologies and prevents the establishment of a universally superior digital intervention. Furthermore, improvements may partly reflect increased rehabilitation

intensity rather than a technology-specific effect. Future trials should therefore compare interventions with equivalent therapeutic doses whenever possible and report standardized clinical outcomes.

Long-term effectiveness also remains insufficiently characterized. Many investigations evaluate patients immediately after intervention, whereas evidence concerning maintenance of improvements several months later is comparatively limited. Stroke recovery is a prolonged process, and the relevance of an intervention ultimately depends on whether functional gains persist and translate into greater independence, participation, and quality of life.

The evidence reviewed supports a model in which digital and conventional rehabilitation are complementary rather than competing approaches. Virtual reality can increase engagement and provide enriched feedback; robotics can facilitate intensive movement repetition; wearable technologies can quantify activity outside clinical settings; telerehabilitation can extend therapeutic continuity; brain-computer interfaces can create alternative pathways for interaction in severe impairment; and artificial intelligence may support increasingly individualized therapeutic decisions. Their integration within multidisciplinary rehabilitation may therefore be more relevant than determining which individual technology is universally superior.

Future research should prioritize multicenter randomized studies with larger and more diverse populations, standardized intervention descriptions, clinically meaningful outcomes, longer follow-up periods, and economic evaluations. Greater participation of Latin American institutions is particularly necessary to determine whether findings generated in technologically advanced healthcare environments remain applicable under different socioeconomic and organizational conditions.

Ultimately, digital neurorehabilitation represents a transition toward more intensive, measurable, adaptive, and potentially accessible models of post-stroke rehabilitation. The available evidence is encouraging, particularly for motor recovery, but technological sophistication should not be considered synonymous with therapeutic effectiveness. The central objective must remain meaningful functional recovery. Digital technologies will have their greatest clinical value when they enhance neuroplasticity-driven rehabilitation while remaining safe, evidence-based, patient-centered, accessible, and adaptable to the healthcare environments in which stroke survivors actually receive care.

CONCLUSIÓN

Digital neurorehabilitation represents a significant evolution in post-stroke rehabilitation by integrating principles of neuroplasticity and motor learning with technological systems capable of increasing therapeutic intensity, repetition, feedback, monitoring, and personalization. The evidence reviewed indicates that virtual reality and robot-assisted rehabilitation currently constitute the most extensively investigated approaches, with favorable findings particularly in upper-limb motor function, balance, gait, functional mobility, and activities of daily living. Telerehabilitation, wearable technologies, brain-computer interfaces, and artificial intelligence further expand this field by introducing possibilities for remote care, continuous functional assessment, neural feedback, and individualized rehabilitation planning.

The available evidence supports the use of these technologies primarily as complementary components of multidisciplinary stroke rehabilitation rather than as replacements for conventional therapy or professional clinical judgment. Their effectiveness depends not only on technological characteristics but also on appropriate patient selection, therapeutic dose, task specificity, active participation, stage of recovery, and integration of training into meaningful functional activities. Accordingly, technological sophistication alone should not be regarded as an indicator of clinical effectiveness.

The relationship between digital rehabilitation and neuroplasticity provides a relevant biological framework for understanding the observed functional improvements. Repetitive, goal-directed, progressively challenging, and feedback-based interventions may facilitate experience-dependent reorganization of surviving neural networks. Nevertheless, the heterogeneity of current studies prevents definitive conclusions regarding the optimal technology, treatment intensity, intervention duration, or patient profile. Greater standardization of clinical protocols and outcome measures is therefore required.

Important challenges also remain before digital neurorehabilitation can be implemented equitably at a global level. Acquisition and maintenance costs, technological infrastructure, professional training, accessibility, connectivity, digital literacy, and differences between healthcare systems may determine whether an effective intervention can be translated from research settings into routine clinical practice. These limitations are particularly relevant in Latin America and other resource-constrained regions, where the burden of stroke coexists with substantial disparities in access to specialized rehabilitation.

Future development should prioritize accessible and scalable technologies, multicenter clinical trials, long-term follow-up, clinically meaningful functional outcomes, cost-effectiveness analyses, and greater participation of populations from low- and middle-income countries. Integration of virtual reality, robotics, wearable sensors, brain-computer interfaces, telerehabilitation, and artificial intelligence may progressively support precision neurorehabilitation, but these advances require rigorous clinical validation and adaptation to individual and regional needs.

In conclusion, digital neurorehabilitation offers a promising framework for extending and strengthening recovery after stroke. Its greatest potential lies not in replacing established rehabilitation practices, but in enhancing their intensity, continuity, personalization, and accessibility. The future of post-stroke rehabilitation will likely depend on the successful integration of neuroscience, clinical rehabilitation, and biomedical technology while maintaining meaningful functional recovery, independence, participation, and quality of life as the central outcomes of care.

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