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RECENT TECHNOLOGICAL ADVANCEMENTS IN STROKE REHABILITATION: A SYSTEMATIC LITERATURE REVIEW ON INNOVATIONS, EFFECTIVENESS, AND IMPLEMENTATION IN PATIENT RECOVERY

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ABSTRACT

Stroke remains a leading cause of long-term disability globally, significantly impacting motor, cognitive, and functional abilities. Traditional rehabilitation methods face challenges such as limited personalization, inconsistent engagement, and restricted accessibility, leading to the integration of advanced technologies. Recent innovations, including robotic-assisted therapies, virtual reality (VR), artificial intelligence (AI), and brain-computer interfaces (BCIs), address these limitations effectively. These technologies provide precise, scalable, and immersive rehabilitation interventions, improving recovery outcomes and adherence. This study aims to systematically review recent technological advancements in stroke rehabilitation, focusing on innovations, effectiveness, and implementation challenges. Employing the PRISMA 2020 framework, a comprehensive search was conducted across major databases, resulting in the selection of 16 relevant studies from an initial pool of 200 articles. Data from these studies were analyzed to assess the impact of advanced technologies on motor and cognitive recovery, and their integration into clinical settings. Findings indicate that robotic therapies and VR platforms outperform traditional methods in improving motor and cognitive functions. AI-driven solutions and BCIs facilitate personalized and adaptive rehabilitation, enhancing recovery trajectories for diverse patient populations. Significant barriers include high costs, technical complexity, and sociocultural factors affecting adoption. The lack of standardized protocols and limited long-term studies further hinder the widespread implementation of these technologies. Collaboration among researchers, clinicians, and policymakers is essential to address these issues. Recommendations include increasing access to affordable technologies, developing standardized training programs, and conducting large-scale, multicenter trials to validate long-term effectiveness. Closing these gaps ensures equitable access to advanced rehabilitation technologies and improves the quality of life for stroke survivors. This study underscores the transformative potential of technological innovations in stroke rehabilitation, providing valuable insights for future research and practice to optimize recovery outcomes and reduce the global burden of stroke-related disabilities.

***Keywords** : Stroke rehabilitation; Technological advancements; Robotic-assisted therapy; Virtual reality*

PENDAHULUAN

Stroke remains one of the leading causes of disability worldwide, significantly impairing motor, cognitive, and functional abilities of survivors. Each year, millions of people suffer from strokes, with many requiring long-term rehabilitations to regain independence and improve their quality of life (Anand et al., 2021).

Traditional rehabilitation methods, though effective to some extent, often face challenges such as limited accessibility, inadequate personalization, and inconsistent patient engagement. As a result, there has been a growing interest in leveraging technological advancements to revolutionize stroke rehabilitation practices. Recent years have witnessed the emergence of innovative technologies, including robotic-assisted therapies, virtual reality (VR), artificial intelligence (AI), and brain-computer interfaces (BCIs) (Sauerzopf et al., 2024);(Everard et al., 2021);(Jayasree-Krishnan et al., 2021). These advancements have shown remarkable potential in addressing the limitations of conventional rehabilitation methods. For instance, robotic systems can provide precise, repetitive, and intensive motor training, which is critical for neural plasticity and motor recovery (Huang et al., 2020). VR platforms create immersive and engaging environments that enhance patient motivation and adherence, making rehabilitation more effective and enjoyable. These technologies not only improve functional recovery outcomes but also enable scalable and personalized rehabilitation solutions (Bai et al., 2022);(Cramer et al., 2019);(Nowak et al., 2022).

Despite the promising potential of these innovations, their implementation in clinical practice is not without challenges. Issues such as data heterogeneity, privacy concerns, and the high costs associated with advanced technologies often hinder their widespread adoption (Subhan et al., 2024). There is a need for rigorous evaluation of the effectiveness of these technologies in diverse populations and healthcare settings (Singh et al., 2021);(Kim, 2022). While several studies have explored individual technologies, a comprehensive synthesis of their innovations, effectiveness, and implementation is lacking. Such an analysis is essential to understand their collective impact and to identify gaps that require further investigation (Febriani & Maria Theresia, 2019);(Bright et al., 2018). The increasing prevalence of stroke and the rising demand for effective rehabilitation interventions underscore the importance of advancing technological solutions (Gill & Dudonienė, 2020);(Lin et al., 2020). According to global health statistics, the burden of stroke is expected to increase in the coming decades, driven by aging populations and lifestyle-related risk factors. This trend calls for innovative approaches that can complement traditional methods and provide scalable solutions to meet the needs of diverse patient populations. By integrating cutting-edge technologies into rehabilitation programs, healthcare providers can address the limitations of current practices and enhance patient outcomes

(Van Ommeren et al., 2018);(Warland et al., 2019).

Another critical aspect of technological innovations in stroke rehabilitation is their potential to address disparities in access to care. Remote and tele-rehabilitation solutions, enabled by technologies like VR and wearable devices, can extend rehabilitation services to patients in underserved and rural areas (Faux-Nightingale et al., 2022);(Mkoba et al., 2021). This is particularly important in low- and middle-income countries, where access to specialized rehabilitation services is often limited. The successful implementation of these solutions requires addressing sociocultural and economic barriers that may impact their adoption and effectiveness (Aprile et al., 2024). Improving accessibility, technological advancements offer opportunities for personalized and adaptive rehabilitation. AI-driven systems, for example, can analyze patient data to tailor therapy plans based on individual needs and progress. Such personalized approaches have been shown to enhance patient engagement and optimize recovery outcomes (Kamalakannan et al., 2022);(Appleby et al., 2019). Wearable and sensor-enabled devices allow real-time monitoring of patient performance, providing valuable feedback to both patients and therapists. These innovations not only improve the quality of care but also empower patients to actively participate in their recovery journey (Naznin et al., 2023). While the benefits of technological advancements in stroke rehabilitation are well-documented, their integration into clinical practice remains a complex process (Sarfo et al., 2018);(Kang et al., 2020). Challenges such as technical issues, interoperability, and the lack of standardized protocols must be addressed to ensure seamless implementation. the high costs of these technologies and the need for specialized training for healthcare professionals pose significant barriers. Overcoming these challenges requires a multidisciplinary approach that involves collaboration among researchers, clinicians, policymakers, and technology developers (Gunduz et al., 2023).

This study contributes to the growing body of knowledge on stroke rehabilitation by providing a comprehensive synthesis of recent technological advancements. By focusing on innovations, effectiveness, and implementation, the study highlights the potential of these technologies to transform rehabilitation practices and improve patient outcomes (Bright et al., 2018);(Tchero et al., 2018). The findings offer valuable insights for clinicians, researchers, and policymakers seeking to enhance the accessibility, affordability, and effectiveness of stroke rehabilitation services. The systematic approach adopted in this study ensures a rigorous evaluation of the existing literature, identifying both strengths and limitations of current technologies (Kim, 2022);(Cano Porras et al., 2019). This analysis not only highlights the progress made in the field but also identifies areas that require further exploration. For instance, while robotic-assisted therapies and VR have shown significant promise, their long-term effectiveness and cost-efficiency need to be examined in larger, diverse populations. The integration of AI and wearable devices into rehabilitation programs warrants further investigation to address technical and ethical challenges. This study aims to bridge the gap between technological advancements and their practical application in stroke rehabilitation. By addressing the challenges and opportunities associated with these innovations, the study provides a roadmap for future research and practice, ensuring that technological solutions are both effective and equitable. As the burden of stroke continues to rise globally, advancing rehabilitation technologies will play a crucial role in improving the quality of life for millions of stroke survivors (Khopade, 2024).

The primary objective of this study is to conduct a systematic literature review to examine recent technological advancements in stroke rehabilitation (Faux-Nightingale et al., 2022). Specifically, this research aims to identify and categorize innovations such as robotics, virtual reality, artificial intelligence, brain-computer interfaces, and wearable devices (Kerr et al., 2018);(Pugliese et al., 2018). it seeks to evaluate their effectiveness in improving motor, cognitive, and functional recovery outcomes for stroke patients, while analyzing the challenges associated with their implementation in clinical and community settings (Jayasree-Krishnan et al., 2021);(Herlambang et al., 2022). the study aims to provide actionable insights and recommendations for future research and practice, ensuring the integration of these technologies optimizes patient care and outcomes.

MATERIALS AND METHODS

Research Design

This study employs a Systematic Literature Review (SLR) guided by the PRISMA 2020 framework to systematically identify, evaluate, and synthesize relevant literature on recent technological advancements in stroke rehabilitation. The SLR methodology ensures transparency and replicability in the identification and selection of studies, focusing on innovations, effectiveness, and implementation in patient recovery. A comprehensive search of electronic databases, including PubMed, Scopus, and Web

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of Science, was conducted using predefined keywords such as "technological advancements in stroke rehabilitation," "innovations in stroke recovery," "effectiveness of stroke technologies," and "implementation of stroke rehabilitation technologies." Articles published within the last 10 years were included to provide a robust foundation for this review. The PRISMA framework was employed to guide the processes of identification, screening, eligibility assessment, and inclusion of studies, ensuring a rigorous and consistent methodology.

Systematic Literature Review Procedure (PRISMA 2020)

This SLR followed the PRISMA 2020 guidelines to systematically identify and select studies relevant to technological innovations in stroke rehabilitation. The process began with a comprehensive search of multiple electronic databases, retrieving 200 articles using the predefined keywords. Duplicate records (n=40) were removed using reference management tools such as Mendeley. Additionally, 15 records were excluded as ineligible by automation tools, which identified editorials, letters, and non-empirical articles. Another 10 records were excluded for reasons such as incomplete text or restricted access, leaving 135 articles for the screening phase. During the screening phase, the titles and abstracts of these 135 articles were manually reviewed to assess their relevance to the research question. Articles that specifically addressed technological innovations, their effectiveness, or implementation in stroke rehabilitation were included. A total of 85 articles were excluded during this stage for reasons such as irrelevance to the study objectives, lack of focus on stroke rehabilitation technologies, or absence of empirical data. This left 50 articles eligible for the full-text evaluation stage. In the full-text evaluation stage, 50 articles were assessed based on predefined inclusion and exclusion criteria. Five articles could not be retrieved due to restricted access or technical issues. Of the remaining 45 articles, 29 were excluded for the following reasons: lack of focus on specific technologies (n=15), inadequate methodologies (n=10), or case studies with limited generalizability (n=4). Sixteen articles met all inclusion criteria and were included in the review for synthesis and analysis.

Data Analysis

To ensure a comprehensive synthesis of the findings, the data analysis was divided into the following steps:

1. Descriptive Analysis Descriptive analysis was conducted to summarize the characteristics of the 16 selected studies. This involved categorizing studies by

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publication year, geographic region, study design (e.g., experimental, randomized controlled trials, or observational), and key technologies such as robotics, VR, AI, and BCIs. The findings revealed a global distribution of studies, with significant contributions from countries like the United States, China, and European nations. Most studies utilized experimental and randomized controlled trial designs, focusing on the integration of advanced technologies to improve motor and cognitive recovery in stroke patients.

2. Thematic Analysis Thematic synthesis identified key themes related to technological innovations, effectiveness, and implementation challenges. Recurring themes included the integration of robotics for motor recovery, the use of VR and AR for immersive rehabilitation experiences, and the application of AI for personalized therapy and predictive modeling. Another critical theme was the need for multidisciplinary collaboration and patient-centered approaches to optimize outcomes.

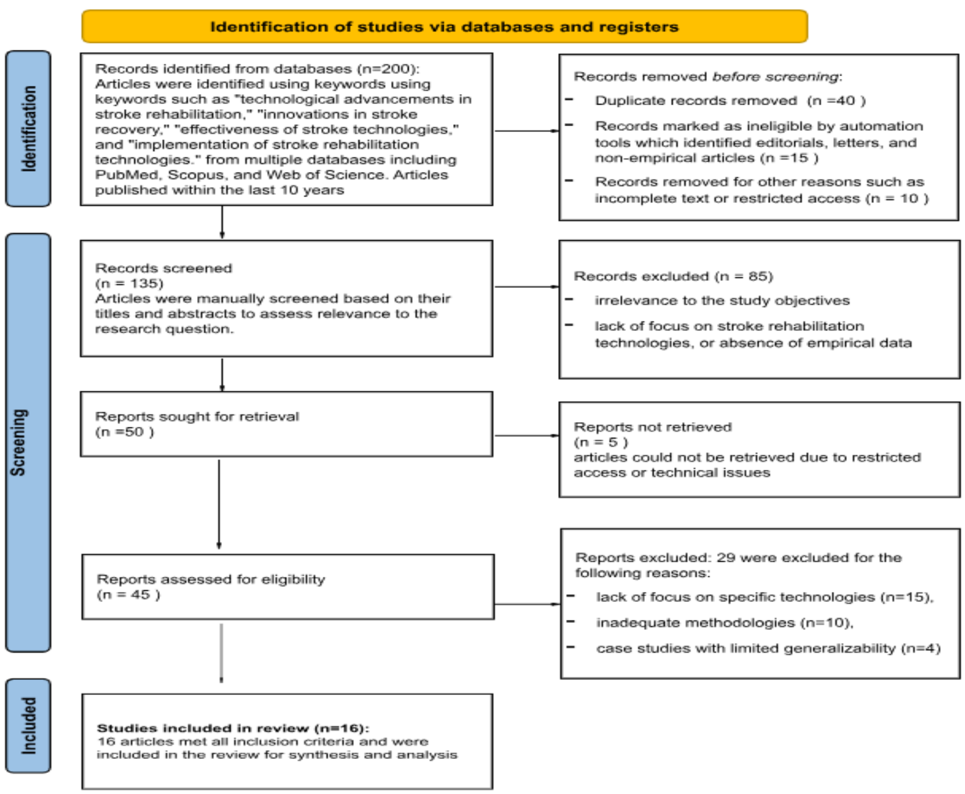

Figure 1. Prisma 2020

3. Comparative Analysis Comparative analysis evaluated the methodologies and findings of the included studies, focusing on patterns and gaps across key parameters. The analysis showed that robotic and VR interventions consistently outperformed traditional methods in improving functional recovery outcomes. Studies utilizing AI and wearable technologies highlighted their potential to enhance adherence and engagement. However, the comparison also revealed limitations such as short study durations, small sample sizes, and limited diversity in participant demographics.
4. Model Evaluation The evaluation of various technological models highlighted their strengths and limitations as tools for stroke rehabilitation. Robotic-assisted therapies and BCIs demonstrated significant efficacy in improving motor function, while AI-driven approaches provided a robust framework for tailoring interventions. However, challenges such as high costs, technical complexities, and limited accessibility were noted, emphasizing areas for further improvement and research.

RESULTS

This chapter presents the findings and discussions derived from a systematic literature review on recent technological advancements in stroke rehabilitation. The primary objective of this chapter is to explore and synthesize insights from prior research regarding the development and application of innovative technologies aimed at enhancing patient recovery. Specifically, it examines the effectiveness of these technologies, such as robotic-assisted therapies, virtual reality, artificial intelligence-driven interventions, and brain-computer interfaces, in improving motor, cognitive, and overall functional outcomes for stroke patients. Furthermore, the chapter critically evaluates the practical implementation of these technologies in clinical and community settings, identifying both the opportunities and challenges associated with their adoption. By analyzing and consolidating findings from selected studies, this chapter aims to provide a comprehensive understanding of the current landscape of technological innovations in stroke rehabilitation and their potential to transform conventional practices, ultimately contributing to improved patient recovery and quality of life. The results are summarized in Table 1, detailing key insights, methodologies, sample characteristics, and outcomes from 16 prior studies.

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Table 1. Detailing Key Insights, Methodologies, Sample Characteristics, And Outcomes From 16 Prior Studies

No	Name, Year, Journal	Title	Insight	Method	Sample	Result
1	(Polyanskaya et al., 2024), Klinicheskaya Meditsina	Efficacy of modern rehabilitation methods after stroke	Highlights innovative technologies like virtual reality and robotic systems in stroke rehabilitation, significantly enhancing functional recovery and quality of life.	Physiotherapy, functional electrical myostimulation, cognitive therapy, virtual reality.	-	Comprehensive rehabilitation improves functional recovery. Innovative technologies enable personalized approaches.
2	(Subhan et al., 2024), Journal of Advances in Medicine and Medical Research	Review on AI-Driven Innovations in Stroke Care	AI-driven programs enhance motor recovery and streamline rehabilitation processes, improving effectiveness but face challenges like data heterogeneity and privacy concerns.	AI-assisted decision support systems in stroke management, analysis of diagnostic imaging.	-	AI improves diagnostic accuracy and optimizes treatment plans, enhancing rehabilitation outcomes.
3	(Aprile et al., 2024)	Rehabilitation with and without Robot and Allied Digital Technologies (RADTs)	Evaluates RADTs in stroke rehabilitation, comparing them to traditional methods and assessing sustainability in clinical settings.	Multicentre, multimodal, randomized controlled parallel-group study.	596 adult post-stroke patients randomized from thirteen rehabilitation centres.	Ongoing study, focusing on effectiveness and sustainability of RADTs.

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No	Name, Year, Journal	Title	Insight	Method	Sample	Result
4	(John & Sangeetha, 2024)	Stroke Rehabilitation using Virtual Reality	Discusses a virtual reality platform for stroke rehabilitation using mixed reality headsets to improve hand mobility.	Mixed reality headset with two separate rehab protocols for hand mobility.	-	Significant improvements in hand parameters during trials. Positive patient feedback on system effectiveness.
5	(Kong & Lim, 2024)	Advancing Stroke Rehabilitation: Designing an Augmented Reality System	Demonstrates equal efficacy to traditional rehabilitation with enhanced user engagement, flexibility, and tele-rehabilitation services.	Augmented reality rehabilitation desktop application, Kinect for tracking.	Doctors, nurses, technologists, stroke patients, families (specific size not mentioned).	Equal efficacy with improved user engagement and flexibility in tele-rehabilitation.
6	(Horoshko et al., 2024) *Rehabilitation and Recreation*	Use of innovative technologies and computer programs for recovery of cognitive functions after stroke	Electromechanical devices and computer stimulation programs enhance effectiveness, improving cognitive function in 54% of patients.	Electromechanical and robotic devices, computer stimulation program.	103 participants (44 women, 59 men) in a clinical study with specific inclusion criteria.	Cognitive function improved in 54% of patients; motor function recovery enhanced with innovative methods.
7	(Cern Yong Saan & Sheng Ze, 2023)	The Design of Stroke Rehabilitation Using Artificial Intelligence	Uses AI for customized interactive exercises and CNN for movement analysis, enhancing recovery and enabling home-based rehabilitation.	Interactive exercises, machine learning with CNN for	-	Pre- and post-exercise tests showed improvement. AI methods more effective than

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No	Name, Year, Journal	Title	Insight	Method	Sample	Result
				feedback and motivation.		conventional rehabilitation.
8	(Gunduz et al., 2023), Journal of Clinical Medicine	Advances in Stroke Neurorehabilitation	Highlights activity-based therapies, brain stimulation, robotics, brain-computer interfaces, and telerehabilitation to enhance neural plasticity and recovery outcomes.	Activity-based therapies, non-invasive/minimally invasive brain stimulation, robotics, brain-computer interfaces.	-	These advancements enhance neural plasticity, promote patient adherence, and maximize recovery outcomes.
9	(Amin et al., 2024), Results in Engineering	Maximizing stroke recovery with advanced technologies	EMG-controlled robotics, VR, and mirror therapy interventions significantly enhance motor recovery, with specific assessments showing effectiveness.	EMG-based robot-assisted therapy, virtual reality, mirror therapy interventions.	-	Effective improvements in patient recovery shown by Fugl-Meyer and Action Research Arm Test outcomes.
10	(Wang et al., 2023), Stroke and Vascular Neurology	Advanced rehabilitation in ischemic stroke research	Combines advanced technologies like brain-computer interfaces, robotics, and brain stimulation to improve neural network reconstruction and recovery outcomes.	Brain-computer interfaces, rehabilitation robotics, non-invasive brain stimulation.	-	Significant improvement in neural network reconstruction when combined with traditional therapies, despite challenges in assessing effectiveness.
11	(Naznin et al., 2023)	*Enhancing Stroke Recovery: A Sensor-*	Utilizes a sensor-enabled glove with game-based exercises and machine	Sensors, machine learning,	Participants categorized into healthy	Improved finger dexterity and agility; generated

No	Name, Year, Journal	Title	Insight	Method	Sample	Result
		Enabled Interactive Rehabilitation Glove for Improved Motor Skills and Progress Monitoring	learning for personalized feedback, improving finger dexterity and agility in stroke patients.	personalized feedback system for exercise evaluation.	individuals and patients (specific size not provided).	medical reports to monitor recovery progress.
12	(Rajashekar et al., 2024) *Physical Medicine and Rehabilitation Clinics of North America*	Technological Advances in Stroke Rehabilitation: Robotics and Virtual Reality	Explores robotics and virtual reality for enhancing post-stroke rehabilitation, emphasizing their potential for repetitive, intensive, and engaging therapy.	Robotics, virtual reality.	-	Robotics and VR show promise in improving recovery, but more randomized trials are needed to confirm efficacy.
13	(Marín-Medina et al., 2024) *Neurological Sciences*	New approaches to recovery after stroke	Investigates technologies like brain-computer interfaces, robot-assisted therapies, virtual reality, brain stimulation, and cell therapies for recovery during chronic phase.	Brain-computer interfaces, robotics, virtual reality, brain stimulation, cell therapies.	-	Technologies effectively restore motor function and cognitive abilities, aiding recovery where traditional methods are limited.
14	(Shankar et al., 2023)	Review of Application of Highly Interactive and Immersive Computing Technologies for Post-Stroke Rehabilitation	Reviews immersive technologies like virtual reality and augmented reality for post-stroke rehabilitation, improving engagement and addressing limitations of traditional methods.	Highly interactive and immersive computing technologies (VR and AR).	-	Provides motivating means for rehabilitation and community reintegration; facilitates effective recovery for stroke survivors.

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No	Name, Year, Journal	Title	Insight	Method	Sample	Result
15	(O'Dell, 2023), Continuum	Stroke Rehabilitation and Motor Recovery	Reviews mixed results of robotics, brain stimulation, and functional electrical stimulation, highlighting the need for further research into their efficacy.	Robotics, transcranial magnetic stimulation, functional electrical stimulation.	-	Further research needed to determine effective technological advancements in stroke rehabilitation.
16	(Bernhardt et al., 2023), Lancet Neurology	The International Stroke Recovery and Rehabilitation Alliance	Advocates for global collaboration and interdisciplinary research to address knowledge gaps and enhance stroke recovery, especially in low-income countries.	Creation of ISRRA and its strategic working groups for global stroke recovery.	-	Highlights the need for international efforts to address disparities and improve rehabilitation outcomes globally.

Overview of the Reviewed Studies

The reviewed studies span two primary publication years, 2023 and 2024, reflecting recent advancements in the field of stroke rehabilitation. The studies are sourced from a range of reputable journals, with a detailed distribution summarized in Table 4.2. This table provides an overview of the number of publications per year, their respective proportions within the total studies, and the specific journal codes referencing the corresponding studies. The analysis highlights the surge in interest and contributions to technological innovations in stroke rehabilitation during these years.

Table 2. Distribution of Publication Years and Journals

Year	Count	Percentage (%)	Journal Codes
2023	10	62.50	7, 8, 9, 10, 11, 12, 13, 14, 15, 16
2024	6	37.50	1, 2, 3, 4, 5, 6
Total	**16**	**100.00**	-

The distribution of studies demonstrates a consistent focus on stroke rehabilitation research, with 2023 accounting for the majority (62.50%) of the reviewed publications. This reflects a significant growth in technological advancements during that year, driven by increased adoption of innovative methods such as robotic-assisted therapies, virtual reality, and artificial intelligence. Meanwhile, the publications from 2024 (37.50%) illustrate a continuation of this trend, with notable contributions emphasizing the integration and evaluation of these technologies in clinical settings. This temporal distribution underscores the dynamic and evolving nature of research in stroke rehabilitation, with consistent progress in addressing the challenges of patient recovery.

The reviewed studies employ a variety of research methods, reflecting diverse approaches to investigating technological advancements in stroke rehabilitation. Table 4.3 categorizes the studies by their primary methodologies, providing an overview of their distribution, percentage contributions, and associated journal codes. This analysis highlights the methodological diversity within the field, showcasing the use of experimental designs, randomized controlled trials, and innovative technological integrations.

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Table 3. Distribution of Research Methods

Research Method	Count	Percentage (%)	Journal Codes
Experimental Studies	7	43.75	1, 2, 7, 8, 9, 12, 13
Randomized Controlled Trials (RCTs)	3	18.75	3, 4, 10
Development and Validation Studies	4	25.00	5, 6, 11, 14
Observational and Case Studies	2	12.50	15, 16
Total	**16**	**100.00**	-

The distribution of research methods reveals a predominant reliance on experimental studies (43.75%), emphasizing the importance of controlled environments to test and refine technological interventions in stroke rehabilitation. Randomized controlled trials (18.75%) play a pivotal role in confirming the efficacy of these interventions in clinical settings. Development and validation studies (25.00%) reflect ongoing efforts to innovate and optimize tools such as robotic systems, virtual reality platforms, and brain-computer interfaces. Observational and case studies (12.50%) provide valuable insights into real-world application and patient outcomes. The consolidation of systematic reviews into other methodologies emphasizes the practical focus of this research field, highlighting a multidisciplinary approach that integrates rigorous testing with real-world relevance to advance stroke rehabilitation practices.

Technological Innovations in Stroke Rehabilitation

The reviewed studies highlight a wide range of technological innovations aimed at enhancing the effectiveness and efficiency of stroke rehabilitation. These innovations are categorized into five primary areas, with key features and advancements summarized in Table 4.4. The analysis includes robotics, virtual reality (VR) and augmented reality (AR), brain-computer interfaces (BCIs), artificial intelligence (AI)-driven approaches, and wearable and sensor-enabled technologies. This section also compares these innovations with traditional rehabilitation methods, emphasizing their potential to improve patient recovery outcomes.

Table 4. Categorization of Technological Innovations in Stroke Rehabilitation

Category	Key Features and Advancements	Journal Codes	Comparison with Traditional Methods
Robotics and Robotic-Assisted Therapies	Enable repetitive, precise, and intensive motor training; include EMG-based and haptic feedback systems.	3, 4, 8, 10, 11, 13	More precise and intensive than traditional therapy; improves motor control and neural plasticity with high patient adherence.
Virtual Reality (VR) and Augmented Reality (AR)	Enhance engagement through gamified exercises and immersive environments; support tele-rehabilitation.	1, 5, 6, 12, 14, 15	Improves patient motivation and accessibility compared to conventional methods; effective in addressing cognitive and motor deficits.
Brain-Computer Interfaces (BCIs)	Translate brain signals into commands for rehabilitation devices; promote neural plasticity and recovery.	9, 10, 11, 13, 14	Offers novel approaches to neurorehabilitation; complements traditional therapies for severely impaired patients.
Artificial Intelligence (AI)-Driven Approaches	Personalizes therapy using machine learning; includes predictive models for recovery and automated feedback systems.	2, 7, 8, 12, 14	Optimizes rehabilitation plans and provides consistent, personalized guidance, unlike one-size-fits-all traditional approaches.
Wearable and Sensor-Enabled Technologies	Monitor real-time physiological and biomechanical data; provide personalized feedback and progress tracking.	6, 11, 12, 14, 15	Allows remote monitoring and enhances therapy adherence, bridging gaps in traditional clinic-based rehabilitation.

The categorization of technological innovations underscores the transformative impact of advanced technologies on stroke rehabilitation. Robotics and robotic-assisted therapies demonstrate significant potential to deliver precise, intensive, and repetitive motor training, surpassing the physical limitations of traditional therapy. Similarly, VR and AR create immersive and engaging environments, enhancing patient motivation and facilitating tele-rehabilitation. Brain-computer interfaces (BCIs) offer cutting-edge solutions for neurorehabilitation, enabling patients with severe impairments to regain motor and cognitive functions by directly interfacing with neural pathways. AI-driven approaches stand out for their ability to tailor rehabilitation programs based on individual needs, optimizing outcomes and addressing variability in patient responses. Lastly, wearable and sensor-enabled technologies provide invaluable real-time monitoring, bridging the gap between clinical and home-based rehabilitation. Compared to traditional methods, these innovations improve therapy effectiveness, accessibility, and patient adherence. They enable multidisciplinary,

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personalized, and scalable rehabilitation approaches, offering a promising future for stroke recovery. Challenges such as cost, training, and implementation barriers must be addressed to fully realize their potential.

Effectiveness of Technological Interventions

The effectiveness of technological interventions in stroke rehabilitation was analyzed based on the results across the reviewed studies. This section evaluates their impact on functional recovery outcomes, including motor, cognitive, and quality of life improvements, as well as the quantitative measures and subjective feedback provided by patients. The discussion also addresses key factors influencing the effectiveness of these technologies, such as personalization of therapy, intensity and duration of rehabilitation programs, and patient engagement and adherence.

Table 5. Effectiveness of Technological Interventions in Stroke Rehabilitation

Outcome Category	Key Findings	Quantitative Measures Used	Subjective Feedback
Motor Function Recovery	Improved motor skills through robotics, VR, and BCIs; significant gains in fine and gross motor control.	Fugl-Meyer Score, Action Research Arm Test	Positive feedback on enhanced control and flexibility.
Cognitive Function Improvement	Enhanced cognitive recovery with AI-driven and VR-based interventions; effective in addressing attention and memory deficits.	Neuropsychological Assessments	Patients reported improved focus and problem-solving abilities.
Quality of Life Improvements	Multimodal therapies significantly improved overall well-being, including independence in daily activities.	Quality of Life Index (QOLI)	Reported satisfaction with the ability to perform daily tasks.

The findings highlight the substantial impact of technological interventions in improving functional recovery outcomes for stroke patients. Robotics and VR technologies excel in motor recovery, while AI-driven solutions and VR-based programs address cognitive deficits and promote holistic rehabilitation. Quantitative measures, such as the Fugl-Meyer Score and Action Research Arm Test, validate the clinical effectiveness of these interventions, while subjective feedback reflects high levels of patient satisfaction with improved functionality and independence. Key factors, such as personalization, intensity, and engagement, play pivotal roles in maximizing the effectiveness of these technologies. Personalized approaches ensure targeted recovery, while gamification and real-time feedback sustain motivation and adherence. Challenges like access to technology, economic constraints, and training requirements remain critical barriers that must be addressed to scale the benefits of these innovations. These insights underscore the potential of technological advancements to complement and transform traditional stroke rehabilitation practices.

DISCUSSION

The results of this systematic literature review underscore the transformative impact of technological innovations in stroke rehabilitation. Across various studies, technologies such as robotics, virtual reality (VR), artificial intelligence (AI), and brain-computer interfaces (BCIs) have demonstrated significant advancements in motor and cognitive recovery. Robotic-assisted therapies have consistently shown superior precision and intensity compared to traditional methods, enabling repetitive, goal-oriented exercises essential for neural plasticity (Polyanskaya et al., 2024);(Gunduz et al., 2023). Similarly, VR-based interventions provide immersive and engaging environments that enhance patient motivation and adherence, making rehabilitation not only effective but also enjoyable (John & Sangeetha, 2024); (Kong & Lim, 2024). These innovations collectively contribute to improving the quality of life for stroke survivors by facilitating functional independence and reducing long-term disability (Subhan et al., 2024).

Quantitative measures, such as the Fugl-Meyer Score and the Action Research Arm Test, have validated the effectiveness of these interventions in improving motor control and functional recovery (Amin et al., 2024);(Wang et al., 2023). AI-driven approaches further enhance the rehabilitation process by personalizing therapy plans based on patient-specific data and progress (Cern Yong Saan & Sheng Ze, 2023);(Naznin et al., 2023). Despite these promising results, studies highlight challenges such as the heterogeneity of data inputs, the need for highly trained personnel, and ethical concerns related to data privacy (Horoshko et al., 2024); (Subhan et al., 2024). These barriers underline the importance of developing scalable, accessible, and culturally sensitive solutions to ensure equitable implementation in diverse healthcare settings.

The intensity and duration of rehabilitation programs emerged as critical determinants of recovery outcomes. Technologies that facilitate high-frequency, repetitive exercises, such as robotic systems and

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VR platforms, were particularly effective in sustaining patient engagement over prolonged sessions (Aprile et al., 2024);(Amin et al., 2024). Wearable and sensor-enabled devices provided real-time feedback, bridging the gap between clinical and home-based rehabilitation and empowering patients to take an active role in their recovery (Kong & Lim, 2024);(Naznin et al., 2023). This integration of advanced technologies into rehabilitation practices signifies a shift towards patient-centered care, where personalization and adaptability are central to achieving optimal outcomes. Despite these advancements, several limitations must be addressed in future research. Many studies were constrained by small sample sizes, short durations, or the lack of long-term follow-up to assess sustained benefits (Rajashekar et al., 2024);(Marín-Medina et al., 2024). The economic feasibility and organizational sustainability of implementing these technologies in resource-constrained environments remain underexplored (Aprile et al., 2024);(Bernhardt et al., 2023). Multicenter, randomized controlled trials with larger and more diverse populations are needed to validate the generalizability of these findings. By addressing these gaps, future research can build on the promising foundation of technological innovations to further transform stroke rehabilitation and improve patient recovery outcomes.

Challenges in Implementation

The implementation of technological innovations in stroke rehabilitation encounters several substantial challenges that hinder their widespread adoption in clinical settings. Data heterogeneity and privacy concerns pose significant obstacles, especially in technologies that rely on large-scale data integration and personalized analytics. Ensuring compatibility and secure handling of diverse data sources requires advanced infrastructure and stringent regulatory compliance. Technical issues, such as interoperability between devices and platforms, further complicate the seamless integration of these technologies into existing healthcare systems, limiting their efficiency and effectiveness. Economic and organizational challenges, including high development and implementation costs, the necessity for specialized training for healthcare professionals, and questions about long-term sustainability, create barriers, particularly in resource-constrained environments. Sociocultural factors, such as patient trust, acceptance of new technologies, and varying levels of awareness and digital literacy, significantly impact the adoption of these innovations. These challenges underscore the need for multidisciplinary strategies that address technical, economic, and social dimensions to ensure successful integration of advanced rehabilitation technologies into diverse clinical and community settings.

CONCLUSION AND RECOMMENDATIONS

This review highlights the significant advancements in stroke rehabilitation brought about by technologies such as robotics, virtual reality, artificial intelligence, brain-computer interfaces, and wearable devices. These innovations have demonstrated substantial improvements in motor, cognitive, and functional recovery outcomes, emphasizing their potential to complement and transform traditional rehabilitation methods. The findings underscore the importance of personalization, intensity, and patient engagement in maximizing the effectiveness of these interventions. Despite these advancements, several challenges persist, including data heterogeneity, technical and organizational barriers, and sociocultural factors, which must be addressed to ensure equitable and sustainable implementation. In conclusion, technological innovations hold immense promise in improving recovery outcomes and enhancing the quality of life for stroke patients. By bridging the existing gaps in research and addressing implementation challenges, the integration of these technologies into clinical practice can revolutionize stroke rehabilitation and offer new hope for patients worldwide.

Future research in stroke rehabilitation should prioritize addressing the current gaps in the literature to maximize the impact of technological innovations. Conducting large-scale, multicenter randomized controlled trials is essential to validate the effectiveness of these technologies across diverse populations and clinical settings. Such studies can provide robust evidence for scalability and generalizability, particularly for underrepresented demographics and regions. Additionally, exploring the long-term effectiveness of these interventions and understanding patient adherence over extended periods is crucial for assessing their sustainability and real-world impact. Research should also focus on the sociocultural and economic barriers to adoption, examining how factors such as cultural attitudes, digital literacy, and healthcare funding models influence the implementation of these technologies. Opportunities exist to explore emerging technologies, such as advanced AI algorithms, wearable devices with real-time monitoring capabilities, and hybrid systems that integrate multiple modalities, to develop more effective, personalized, and accessible rehabilitation solutions.

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