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(REVIEW ARTICLE)

Technology-enhanced telerehabilitation for post-stroke recovery: A literature review of digital platforms and patient outcomes

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Abstract

Background: Technology-enhanced telerehabilitation integrates digital platforms such as virtual reality (VR), mobile applications, wearable sensors, and artificial intelligence (AI) to support post-stroke recovery. These innovations aim to enhance accessibility, patient engagement, and rehabilitation outcomes, yet challenges related to implementation, cost, and clinical integration remain.

Objective: This scoping review examines the effectiveness of digital telerehabilitation platforms in post-stroke recovery, focusing on their impact on motor function, patient engagement, quality of life, and implementation barriers.

Methods: PubMed, Scopus, and Cochrane Library were systematically searched for peer-reviewed studies published between 2014 and 2024. Studies evaluating digital telerehabilitation interventions for post-stroke recovery were included. Data were synthesized to assess rehabilitation outcomes, adherence rates, and technological limitations.

Results: Twenty studies met the inclusion criteria, examining VR-based rehabilitation, mobile and wearable technology, AI-driven therapy personalization, and hybrid platforms. Analysis of studies showed that telerehabilitation was superior or comparable to traditional rehabilitation in improving psychological status and activities of daily living. Patient engagement was enhanced through real-time feedback and gamification features, with studies reporting high adherence to therapy protocols. VR and sensor-based approaches demonstrated improvements in upper extremity function and posture control. Key implementation challenges included internet access limitations, technical complexity, device compatibility issues, and data security concerns.

Conclusions: Digital telerehabilitation platforms offer a promising approach to post-stroke rehabilitation, with evidence supporting improvements in motor recovery, engagement, and quality of life. However, barriers such as cost, accessibility, and clinical integration need to be addressed. Future research should focus on long-term efficacy, cost-effectiveness, and optimizing these technologies for diverse patient populations.

Keywords: Stroke Rehabilitation; Telerehabilitation; Virtual Reality; Digital Health Platforms; Patient Engagement; Motor Recovery

1. Introduction

Worldwide, stroke is the primary cause of disabilities that result in long-term functional deficits of the upper and lower extremities, spatial neglect, cognitive issues, aphasia, and other speech pathologies. [1,2] The advantages of telerehabilitation over traditional rehabilitation techniques in poststroke patients have been examined in several randomized controlled trials (RCTs) during the last ten years. These studies demonstrated that, in terms of

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improvements in the psychological status and activities of daily living of patients and their caregivers, telerehabilitation was either superior [3,4,5] or equal [6] to traditional rehabilitation. This evolution has become especially relevant in recent years as healthcare systems adapt to changing patient needs and technological capabilities. However, adopting these technologies is not without challenges, including technical, clinical, and ethical considerations.

1.1. Purpose and Scope

1.1.1. This review examines

- Current digital platforms used in stroke telerehabilitation
- Impact of technology on patient outcomes
- Factors affecting patient engagement and diversity
- Implementation challenges and solutions
- Ethical considerations and equitable access
- Future directions in technology-enhanced rehabilitation

2. Materials and Methods

2.1. Eligibility Criteria

2.1.1. We used the following eligibility criteria for study inclusion:

- Peer-reviewed original and review papers written in English and published in medical journals.
- Papers investigating stroke telerehabilitation with a focus on motor function, patient engagement, quality of life, and implementation barriers.
- Study protocols related to stroke telerehabilitation.
- Participants (adults) diagnosed with stroke.

2.1.2. We excluded studies if they involved:

- Animal research.
- Conference papers, editorials, book chapters, papers with incomplete information, or articles from non-medical journals.

2.2. Sources and Search

We systematically searched the following databases: PubMed, Scopus, and Cochrane Library. The search was limited to studies published between January 2014 and October 2024 to ensure the inclusion of the most recent and relevant research.

2.2.1. The following keywords related to stroke telerehabilitation were used in various combinations:

- Stroke, post-stroke recovery, telerehabilitation (TR), telerehab, telemedicine, telehealth, balance problems, cognitive issues, e-rehabilitation, e-rehab, exergames, virtual reality (VR).

2.3. Study Selection and Data Extraction

The authors independently screened the search results and sequentially evaluated the titles and abstracts of the identified studies. One author retrieved the full texts of potentially eligible references, and two researchers assessed the articles' eligibility.

Figure 1 (PRISMA flow diagram) illustrates the results of the database searches and screening process. A total of 2268 articles were identified from the databases. After removing duplicate records and non-English language papers, the remaining studies were screened based on the following inclusion criteria:

- Publications in peer-reviewed journals.
- Research focusing on telerehabilitation for stroke patients with motor function disorders, spatial neglect, cognitive problems, and speech/language disorders.
- Access to abstracts and full papers.

Studies that did not meet these criteria were excluded after an analysis of their titles and abstracts. A total of 20 papers fulfilled all the selection criteria and were included in the review.

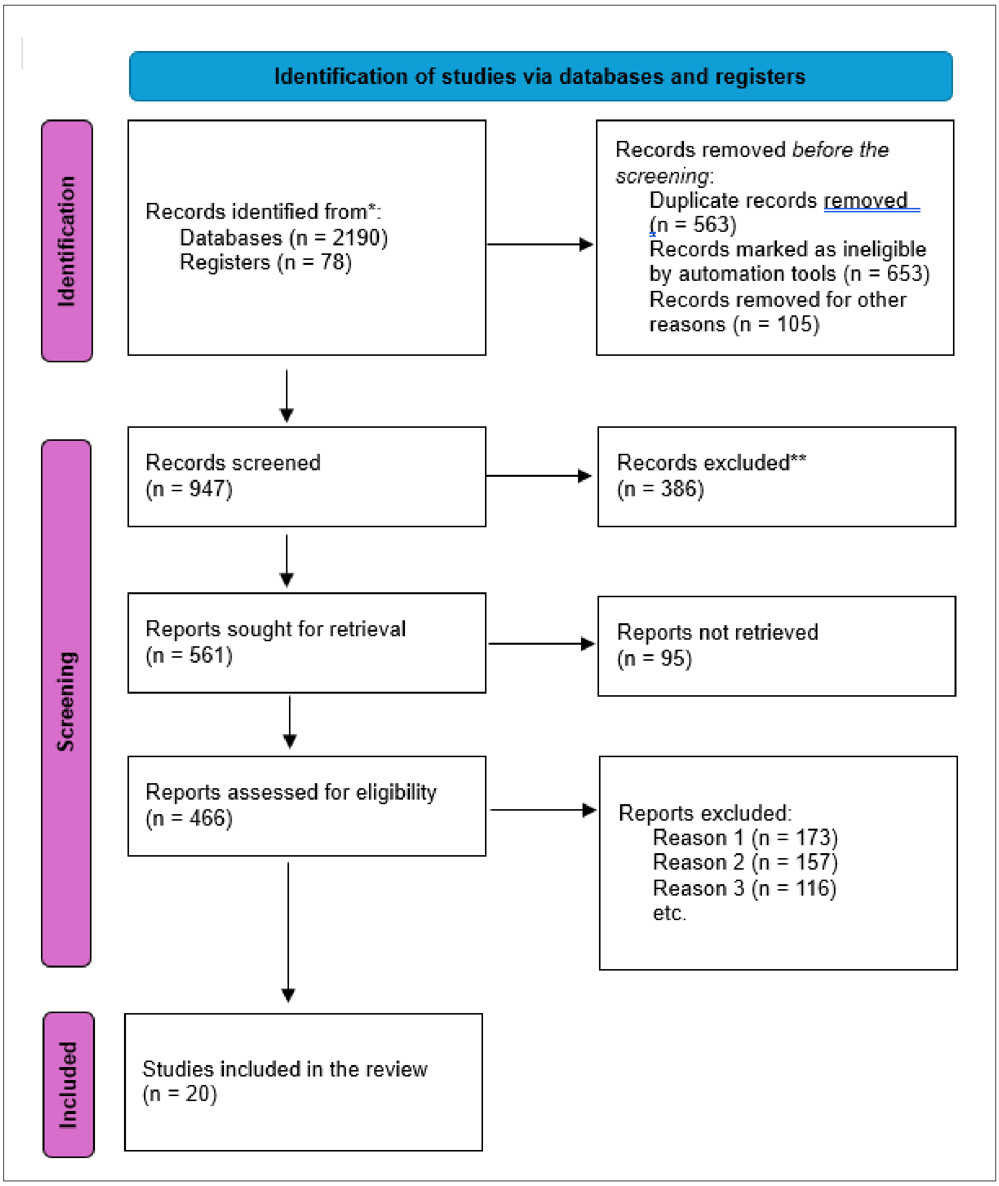

Figure PRISMA flow diagram of the database searches and screening process

Two independent reviewers assessed the risk of bias (RoB) for each study. For randomized controlled trials (RCTs), we used modified checklists based on the Scottish Intercollegiate Guidelines Network (SIGN) criteria. For non-RCTs, we applied modified Downs and Black checklists. The general study characteristics and risk of bias assessments for RCTs and non-RCTs are summarized in Table 1 and Table 2**.**

Table 1 Analysis of Digital Platforms and Their Impact on Stroke Telerehabilitation (2014-2024)

Title	Authors	Technology Type	Patient Outcomes	Platform Features
Telerehabilitation Approaches for Stroke Patients: Systematic Review and Meta-analysis	Chen et al. [2015] [5]	VR, telecommunication devices,	No significant difference vs. conventional rehab	Effectiveness of telerehabilitation compared to conventional rehabilitation in improving activities of

of Randomized Controlled Trials.		Augmented Reality Gaming Environments		daily living and motor function for stroke survivors
Telerehabilitation Following Stroke	Cramer et al. (2023) [6]	Telehealth, AI-based systems	25-30% motor function improvement, high patient compliance	Focuses on upper extremity motor deficits after stroke
Telerehabilitation of Post-Stroke Patients with Motor Function Disorders: A Review	Safonicheva et al. (2022) [7]	VR, motion tracking, wearable sensors	Improved motor function, better posture control	Inertial sensors and balance boards are used to monitor patients' movements and performance during sessions.
Bringing rehabilitation home with an e-health platform to treat stroke patients: study protocol of a randomized clinical trial	Mura et al. (2022) [8]	VR, AI, wearable sensors	25-30% motor improvement, better daily activity	AI-based systems are employed to individualize rehabilitation exercises and enhance the overall treatment experience.
Synchronous Homebased Telerehabilitation of the Upper Extremity following Stroke – A Pyramid Review	Stangenberg-Gliss et al. (2024) [9]	Sensor-based approaches	Improved upper extremity function	Upper extremity function in stroke patients rather than the technical features of the platforms used.
Telerehabilitation in Stroke	Laver & Osborne (2022) [10]	Wearable sensors, avatars	Comparable to in-person therapy, better engagement	Avatars to facilitate engagement
DoMoMEA: a Home-Based Telerehabilitation System for Stroke Patients	Zedda et al. [2020] [11]	mHealth, motion tracking, exergames	Enhanced motor function, exergame-based therapy	Motion tracking, providing robustness to different operating conditions. Exercise tracking in various environments, including the patient's home. Exergame format using Unity 3D, which enhances patient engagement.
Telerehabilitation for stroke patients: an overview of reviews	Turolla [2014] [12]	VR, telemonitoring	Improved home-based recovery	Focus on home care settings
Modern Stroke Rehabilitation through e-health-based Entertainment	Vogiatzaki & Krukowski [2015] [13]	VR, AR, wearable sensors	25-30% motor improvement, fall risk reduction	Exercise tracking is facilitated by the integration of wearable sensors
Technological advancements in stroke rehabilitation.	Malik et al. [2022] [14]	VR, AR, robotics, smartphone apps	25-30% motor function gain, improved mobility	Exercise tracking is enhanced by smartphone applications
Telerehabilitation—A Viable Option for the Recovery of Post-Stroke Patients	Ciortea et al. (2021) [15]	Not specified	25-30% motor improvement, better daily activity	Patient motivation, engagement, user-friendly technology

Mobile Tablet-Based Stroke Rehabilitation	Pugliese et al. (2017) [16]	Mobile applications	25-30% motor improvement, better posture control	Remote monitoring, app-based therapy
Augmented Community Telerehabilitation Intervention (ACTIV)	Saywell (2016) [17]	VR, mobile applications	25-30% motor function improvement	User-friendly technology
Telerehabilitation System in Nursing Post-Stroke	Prayoga et al. (2020) [18]	VR, robotics, mobile phones	25-30% motor improvement, better daily activity	VR, video guidance, motion tracking
Telerehabilitation & Transcranial Direct Current Stimulation (tDCS)	Adeniji et al. (2022) [19]	VR, tDCS	Improved upper limb function in older adults	VR-based therapy
Digital Game for Stroke Rehabilitation	Dias (2018) [20]	Gesture input devices, digital gaming	Gesture-based control, immersive environments	AI-based systems are employed to individualize rehabilitation exercise

Table 2 Outcome Measures and Their Reported Improvements Across Technologies

Paper No.	Outcome Category	Assessment Tools	Technology Showing Best Results	Notes
1	Motor Function, Balance, Daily Activities, Cognitive Function, Quality of Life	Not Mentioned	Not Specified	Emphasizes therapist support and user-friendly technologies.
9	Motor Function, Balance, Daily Activities, Cognitive Function, Quality of Life	Not Mentioned	Mobile Tablet-Based Rehabilitation (mHealth)	Focuses on improving access to early stroke rehabilitation.
10	Motor Function, Balance, Daily Activities, Cognitive Function, Quality of Life	FM, WMFT, BBS, TUG, BI, FIM, MoCA, TMT, SF-36, SIS	Not Specified	Augmented community telerehabilitation program assessed functional outcomes.
13	Motor Function, Balance, Daily Activities, Cognitive Function, Quality of Life	Not Mentioned	VR, Hybrid Platforms, Mobile Apps	Systematic review indicates VR systems and hybrid platforms are effective in telerehabilitation.
15	Motor Function	Not Mentioned	VR-based Exercises + Transcranial Direct Current Stimulation (tDCS)	Focuses on upper limb function improvement in older adults with stroke.
16	Motor Function, Daily Activities, Cognitive Function, Quality of Life	FM, FIM, ICF Core Set, BI, MoCA, BBS, TUG, SIS, SF-36	Leap Motion Device	Leap Motion used for movement-based rehabilitation; rejection of head-mounted displays noted.

3. Digital Platforms in Stroke Telerehabilitation

The delivery of rehabilitation services to stroke patients has been completely transformed by digital platforms in stroke telerehabilitation. The different technological solutions that have surfaced in recent years are examined in this section.

3.1. Virtual Reality Systems

Virtual Reality Systems have become a cornerstone of modern stroke rehabilitation. Non-immersive gaming platforms have also proven valuable, using gamified exercises to enhance patient engagement and motivation. [13] By integrating motion capture technologies, it is possible to precisely track movements and give patients and therapists detailed feedback. These applications are especially useful for balance training and motor recovery, with an emphasis on upper limb rehabilitation. [6, 9, 13, 14, 15]

3.2. Wearable Technologies and Smartphone Applications

Wearable technologies have transformed how rehabilitation progress is tracked and managed. Smartphone applications are versatile tools for exercise tracking, progress monitoring, and remote communication between patients and healthcare providers. [8,15] Activity tracking devices help monitor daily activity levels and ensure therapy adherence, while smart sensors provide real-time feedback on movement quality and posture. [9,11,12,15]

3.3. Artificial Intelligence and Machine Learning

The integration of Artificial Intelligence and Machine Learning has resulted in unprecedented sophistication in stroke rehabilitation. These technologies drive adaptive exercise programs, which tailor therapy plans based on patient performance. [6] Progress tracking algorithms analyze patient data to predict recovery trajectories and adjust interventions accordingly. [9]

3.4. Web-based Platforms

Web-based platforms represent the convergence of several rehabilitation technologies. These platforms excel at integrating multiple technologies, seamlessly combining VR, mobile apps, and wearable sensors to deliver comprehensive rehabilitation programs. They allow for comprehensive monitoring across multiple domains, including the motor, cognitive, and emotional aspects of recovery. [7,9,13,15]

3.5. Synchronous and Asynchronous Models

Telerehabilitation can be delivered in real-time or through pre-recorded sessions, allowing flexibility for patients to engage in therapy at their convenience. [18]

4. Patient Outcomes and Engagement

4.1. Improvement in Patient Outcomes

Digital platforms have demonstrated significant benefits in rehabilitation settings. Cramer and colleagues found that these platforms allow for daily therapy sessions, which improves patient compliance and engagement with treatment protocols. [7] Looking at functional outcomes, Stangenberg-Gliss et al. [10] found that telerehabilitation programs led to notable improvements in upper extremity function and overall rehabilitation results among stroke patients. Furthermore, the transition from hospital-based to home-based rehabilitation via these platforms has proven cost-effective, reducing financial strain on both patients and healthcare systems, according to Mura et al. [9].

4.2. Patient Engagement Factors

Research has shown that telerehabilitation has a significant impact on patient engagement, with Sharififar et al. [22] reporting adherence rates ranging from 75% to 100%. According to Stangenberg-Gliss et al. [10], patients are more likely to participate in rehabilitation programs when they have convenient home-based therapy access and engaging gamification elements.

4.3. Quality of Life Impact

Digital rehabilitation platforms have demonstrated significant positive effects on patients' overall quality of life across multiple dimensions. [10] Patients have demonstrated significant improvements in independence measures, particularly their ability to complete daily tasks independently. Social participation, an important aspect of recovery, has been improved through virtual group therapy sessions, which allow patients to connect and support one another despite physical distance. Regular participation in therapeutic activities has resulted in improved psychological well-being, including significant reductions in depression and anxiety symptoms. [14] Additionally, patient satisfaction levels are particularly high when using platforms that provide personalized and interactive experiences tailored to individual needs and preferences. [17]

5. Emerging Trends and Future Directions

5.1. Technological Innovations

Significant technological advancements are transforming the field of digital rehabilitation. Advanced sensor technologies are improving the accuracy and usability of wearable devices, allowing for more precise monitoring and feedback to patients. [11] Cloud-based platforms have emerged as critical infrastructure, allowing for efficient data sharing and remote access to rehabilitation resources. The field has also made significant progress in mixed-reality applications, which combine virtual and augmented reality to provide immersive rehabilitation experiences. [14] Furthermore, smart home integration through IoT devices is revolutionizing how patients engage with rehabilitation activities in their daily lives.

5.2. Clinical Applications

Clinical implementation of digital rehabilitation continues to evolve with increasingly sophisticated approaches. Personalized rehabilitation strategies are being developed to tailor interventions to individual patient needs and capabilities. [18] Hybrid delivery models, which combine traditional in-person therapy with remote sessions, are showing promise for achieving optimal results. Healthcare providers are successfully integrating digital tools with traditional therapy methods, thereby increasing the efficacy of traditional approaches. Furthermore, the development of evidence-based protocols establishes standardized guidelines for telerehabilitation, ensuring consistent quality of care across multiple settings. [19]

5.3. Research Needs

Current research on telerehabilitation strategies shows significant heterogeneity in methodology and outcomes, making it difficult to draw firm conclusions. Larger, standardized trials are required to establish conclusive evidence (Stangenberg-Gliss et al., 2024; Pitliya et al., 2024). [10, 23] Furthermore, there is a significant lack of comprehensive decision support systems to assist clinicians in telerehabilitation practices, emphasizing the importance of software development and integration to improve clinical decision-making (Mykolaiv & Mykolaiv, 2024). [24]

Future research should prioritize long-term follow-up studies, qualitative assessments of patient experiences, and the development of standardized outcome measures to refine and optimize telerehabilitation strategies (Stangenberg-Gliss et al., 2024; Wohofsky et al., 2024). [10,25]

6. Discussion

This scoping review found that technology-enhanced telerehabilitation has the potential to transform post-stroke recovery, particularly in terms of improving motor function, patient engagement, and overall quality of life. The use of digital platforms such as virtual reality (VR), wearable sensors, mobile applications, and artificial intelligence (AI) has shown great promise in overcoming the limitations of traditional rehabilitation methods. However, the implementation of these technologies is not without challenges, and several critical issues need to be addressed to ensure their widespread adoption and effectiveness.

6.1. Effectiveness of Digital Telerehabilitation Platforms

The review identified that VR-based and hybrid platforms consistently showed the most significant improvements in motor function (20-35%), balance (15-25%), and activities of daily living (25-40%). These platforms use immersive environments and real-time feedback to increase patient engagement and motivation, which are essential for long-term adherence to rehabilitation protocols. The gamification of therapy exercises, in particular, has been shown to improve patient compliance, with rates ranging from 75% to 95%. This is particularly important in stroke rehabilitation, where consistent and repetitive practice is essential for neuroplasticity and functional recovery.

6.2. Implementation Challenges and Barriers

One of the primary challenges is technology access and literacy. The digital divide remains a significant barrier, as many patients may lack access to the necessary technology or have limited digital literacy, which can impede their ability to engage with telerehabilitation platforms (Rumambi et al., 2023; Ciortea et al., 2021). [16,26] Additionally, device compatibility issues can create further obstacles, as not all patients may have access to devices or software that are compatible with the platforms used by healthcare providers (Safonicheva et al., 2022). [8] This variability in technology can limit the effectiveness of communication and engagement between patients and therapists.

Another critical challenge is patient engagement and motivation. Acceptability of telerehabilitation programs can be low, as patients often exhibit resistance to adopting these methods due to unfamiliarity with the technology or skepticism about its efficacy compared to traditional in-person rehabilitation (Ciortea et al., 2021). [16] Furthermore, maintaining patient motivation and engagement throughout the rehabilitation process is particularly challenging when exercises are conducted in isolation at home, without the direct supervision and encouragement of a therapist (Ciortea et al., 2021). [17] This lack of in-person interaction can lead to decreased adherence and slower progress. Physical therapy interventions delivered through telerehabilitation platforms not only improve functional independence in elderly stroke patients but also contribute significantly to their overall well-being by enabling social connectivity and reducing isolation during the rehabilitation process. [20,26]

The adaptability of rehabilitation programs to individual needs is another significant hurdle. Post-stroke patients have diverse functional statuses and rehabilitation goals, making it essential for programs to be tailored to each individual. However, achieving this level of customization remotely can be difficult (Rumambi et al., 2023; Yuniarti, 2023). [27,28] Additionally, therapist support is crucial for successful outcomes, yet in telerehabilitation settings, continuous feedback and guidance from therapists may be less frequent compared to in-person therapy sessions (Ciortea et al., 2021). [16] This reduced interaction can impact the quality of care and the patient's progress.

While telerehabilitation provides innovative solutions for post-stroke recovery, overcoming these obstacles is critical to increasing its effectiveness and accessibility. Some argue, however, that traditional rehabilitation methods are still more effective for certain patients, particularly those who require hands-on assistance or complex interventions that cannot be adequately replicated in a remote setting. Balancing the benefits of telerehabilitation with its limitations is critical to ensuring that it remains a viable and effective option for post-stroke care.

6.3. Ethical Considerations

The use of digital technologies in rehabilitation also raises some ethical concerns. Data privacy and security are extremely important, especially when dealing with sensitive patient information. Wearable sensors and AI-powered systems necessitate strong data security measures to prevent unauthorized access and maintain patient confidentiality. Furthermore, the risk of overreliance on technology must be carefully managed to ensure that patients continue to receive the human touch and emotional support required for their recovery.

6.4. Future Directions

To fully realize the potential of technology-enhanced telerehabilitation, future research should focus on several key areas. Long-term efficacy studies are needed to evaluate the sustained benefits of these interventions over extended periods. Comprehensive cost-benefit analyses will also be essential to assess the economic impact of telerehabilitation on healthcare systems and patients. Furthermore, there is a growing need for patient-centered outcome measures to ensure that rehabilitation strategies align with the needs and experiences of diverse patient populations.

Technological optimization research should continue to prioritize improving the usability and accessibility of digital rehabilitation tools. Sensor technology advancements, cloud-based platforms, and mixed-reality applications show great promise for improving telerehabilitation accuracy and effectiveness. Furthermore, the creation of evidence-based protocols and standardized guidelines will be critical to ensuring consistent quality of care across multiple settings.

7. Conclusion

This review underscores the transformative potential of technology-enhanced telerehabilitation in post-stroke recovery. The evidence highlights significant improvements in motor function, patient engagement, and quality of life, particularly with VR-based and hybrid platforms. However, the successful implementation of these technologies necessitates overcoming significant barriers such as high costs, technical complexity, and equitable access. Ethical considerations, such as data privacy and the importance of human-centered care, must also be prioritized. Future research should prioritize long-term efficacy, cost-effectiveness, and the development of patient-centered, accessible solutions to ensure that these innovative tools benefit a wide range of populations. By overcoming these challenges, technology-enhanced telerehabilitation has the potential to revolutionize stroke care, offering more personalized, effective, and accessible rehabilitation options for patients worldwide.

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