



INNOVATIONS IN STROKE REHABILITATION

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ABSTRACT

Stroke rehabilitation requires a personalized and multidisciplinary approach. Stroke remains a leading cause of disability, and innovative technologies such as robotics, virtual reality, and telerehabilitation show significant potential for improving patients' motor and cognitive functions. Robotic systems provide precise, repetitive movements, while virtual reality enhances motivation through engaging and realistic environments. The combination of technologies creates a synergistic effect and leads to higher efficiency. Telerehabilitation and brain-computer interface (BCI) robots expand access to therapy and allow recovery even in severe cases. **Objective:** This article aims to analyze the role and effectiveness of these innovations in the context of modern post-stroke rehabilitation. **Materials and Methods:** A review of recent literature was conducted, including scientific publications related to the rehabilitation of ischemic or hemorrhagic stroke and the use of innovative technologies. **Conclusion:** Robotic systems, virtual reality, telerehabilitation, and BCI robots complement traditional therapies and offer new approaches to overcoming long-term disability. Clinical evidence shows significant benefits from their use, especially in the early phases after stroke.

Keywords: stroke, innovations, robotic rehabilitation, virtual reality, telerehabilitation

INTRODUCTION

Stroke is defined by the World Health Organization as an acutely occurring focal neurological deficit lasting more than 24 hours, resulting from cerebrovascular disease and documented by a head computed tomography (CT) scan. The clinical picture includes focal neurological impairment, often combined with altered levels of consciousness. Approximately 85% of strokes are ischemic (cerebral infarctions), caused by insufficient blood, oxygen, and glucose supply to the brain (1). According to the WHO, around 15 million people worldwide suffer a stroke each year, six million of whom do not survive, and about one-quarter are under the age of 65. Approximately one-third are left with permanent disability. The number of young patients is steadily increasing—10–20% of stroke cases occur in individuals between 18 and 54 years of age.

In a large proportion of patients, their activity is impaired due to residual functional, cognitive,

and psychological changes, which are essential for maintaining social, professional, and family relationships (2).

Post-stroke rehabilitation is a complex process requiring a multidisciplinary approach. Standard physiotherapy protocols are based on exercises that stimulate neuroplasticity, but the monotonous nature of kinesiotherapy routines often reduces patient motivation. Although conventional rehabilitation methods are effective, they often face limitations related to therapy intensity, patient engagement, personalization options, human resources, and access to specialized services. Innovations in stroke rehabilitation significantly transform recovery opportunities and offer solutions that overcome these limitations.

In recent decades, technological innovations have demonstrated their potential to generate and enhance classical methods. They not only provide high precision in training programs but also offer adaptive feedback, engaging gamified environments, and options for remote monitoring (3). For this reason, the use of innovative tools in rehabilitation has expanded, including robots, virtual environments (VR),

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telemedicine solutions, and neurofeedback-based systems.

The **aim** of this article is to analyze the role and effectiveness of these innovations in the context of modern post-stroke rehabilitation, to highlight competitive achievements in robotic and VR-assisted rehabilitation, and to outline the key challenges and prospects for future development. It also seeks to inform both medical professionals and patients about the best available methods and scientific advancements in contemporary rehabilitation technologies.

MATERIALS AND METHODS

This article is based on a review of contemporary literature, including up-to-date scientific publications. The sources include peer-reviewed articles from databases such as PubMed, ResearchGate, Google Scholar, arXiv, and the Cochrane Library, focusing on rehabilitation after ischemic or hemorrhagic stroke and the use of innovative technologies—robots, virtual environments, telerehabilitation, and brain-computer interface (BCI) robots.

DISCUSSION

Innovations in rehabilitation are transforming the paradigm of recovery after stroke. These technologies do not replace clinical specialists but complement them, creating conditions for more individualized, effective, and motivating therapy.

The principles of neurorehabilitation are based on scientific evidence of neuroplasticity—the brain's ability to reorganize and restore functions through new neural connections.

The key principles of neurorehabilitation include:

- Intensity and repetition: The more frequent the training, the more pronounced the neuroplasticity;
- Active patient participation: Performing movements independently enhances motor learning and motivation;
- Personalization: Programs should be adapted to the individual capabilities and progress of the patient;
- Visual/tactile feedback: Early feedback on correct performance enhances the speed of recovery (3).

Robotic rehabilitation is becoming an increasingly popular method in

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neurorehabilitation, especially for patients with partial or complete loss of motor control. It involves the use of devices that assist or guide the movement of the upper and lower limbs. Robots enable multiple, precisely dosed repetitions that are crucial for stimulating neuroplasticity.

Exoskeletons wrap around joints and provide greater stability of movement—they are more expensive but allow for the training of complex functional activities in earlier phases of rehabilitation. Robotic therapy using exoskeletons improves movement quality, reduces muscle tone, and ensures a level of repetition that is difficult to achieve with manual therapy (7).

Rajashekar et al. (2024) emphasize that robotic systems improve motor skills through active patient engagement (4). According to Macaluso et al. (2024), a hip exoskeleton led to significant gait improvements in stroke patients during the outpatient phase (5).

Other studies, such as Park et al. (2019), demonstrate that a portable hand robot controlled by the patient enables the recovery of fine motor functions and increases autonomy in daily activities (6).

Virtual Reality (VR) in rehabilitation is a modern approach where the patient is placed in a computer-generated environment, wearing a VR headset or using a screen with cameras, and performs therapeutic exercises through interaction. Movements are trained in realistic scenarios via gamified or functional tasks—for example: grasping objects, balancing on an imaginary platform, or repeating arm, leg, or body movements.

This leads to higher motivation and enables personalized feedback.

A meta-analysis by Laver et al. (2017) shows that VR has comparable or even superior effectiveness to traditional therapy in improving upper limb motor function (8). VR rehabilitation plays an important role in increasing engagement, motivation, and adherence to therapeutic programs (9). Furthermore, it has a positive effect on mental health and quality of life in stroke patients (10). The combination of robotic systems and virtual reality produces a synergistic effect. Alashram (2024), in a systematic review, finds that

combined robot and VR therapy leads to better upper limb recovery outcomes and outperforms conventional approaches (11).

Chheang et al. (2023) describe a system that uses VR and robotics to train elbow joint movements, allowing personalized training in an immersive environment (12). Lee et al. (2023) present a social robot that encourages patients at home and monitors their progress through AI-based feedback (13).

Telerehabilitation is increasingly entering healthcare. It enables remote therapy delivery, which is especially important for patients with limited access to healthcare services. VR-based telerehabilitation systems offer two-way communication, automated monitoring, and adaptive rehabilitation programs based on recovery progress. Successful telerehabilitation depends on good interface design, safety, and maintaining patient engagement (14). It is effective and sustainable long-term when based on clear protocols (15).

Brain-Computer Interface (BCI) robots are an innovative form of neurotechnology in which brain activity directly controls robotic devices. In rehabilitation, especially after stroke, these technologies are used to restore motor function by strengthening the connection between the brain and limbs.

Electroencephalography or other non-invasive sensors placed on the head are used to record electrical activity from the cerebral cortex. Special software analyzes brain waves and recognizes the “intention to move” (e.g., “I want to lift my hand”), even if the movement cannot actually be performed. This signal is sent to a robot (e.g., an exoskeleton or stationary device), which performs the movement on behalf of the patient.

Although still experimental and costly, this technology creates opportunities for motor recovery even in patients with severe deficits. Liu et al. (2025) analyze the potential of BCI to restore neural connections by linking brain activity with external devices, thus stimulating neuroplasticity (16). The authors summarize data from multiple systematic reviews and conclude that BCI supports motor recovery, especially when combined with visual and sensorimotor stimulation (16).

Despite the proven benefits, several barriers hinder the application of innovative treatment methods. These include:

- High initial equipment costs;
- Lack of adequately trained specialists;
- Insufficiently standardized protocols;
- Need for long-term studies with large sample sizes.

The future of rehabilitation will involve the development of hybrid therapies that combine technologies tailored to the individual needs of each patient.

CONCLUSION

Innovations in post-stroke rehabilitation open up new opportunities for a personalized, engaging, and effective recovery process. Robotic systems, virtual reality, tele-rehabilitation, and brain-computer interface robots complement traditional therapies and offer new ways to overcome long-term disability. Clinical evidence shows significant benefits from their use, especially in the early phases after a stroke.

Implementing these technologies in daily practice can significantly improve treatment outcomes and the quality of life for patients.

Innovative methods do not replace humans; they complement them. They make rehabilitation more effective, humane, and inspiring. Rehabilitation after a stroke, based on science combined with technology and a humane approach, leads to better results and a better quality of life.

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