Research

Instrumented Rehabilitation

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Abstract

Conventional rehabilitation often struggles to deliver high-intensity, personalized, and engaging therapy. In recent years, robotic and sensor-based technologies have emerged as promising tools to enhance rehabilitation outcomes, particularly for individuals with neurological conditions and motor impairments. This review, combined with clinical insights from our rehabilitation institute, explores how robotic devices are transforming motor rehabilitation by enabling precise assessment, individualized training, and greater patient motivation. The paper synthesizes current literature on robotic rehabilitation and incorporates real-world clinical experience. It covers technologies used for upper and lower extremities, balance, and gait, with a focus on objective assessment tools and game-based systems that improve patient engagement. Robotic systems such as the Tyromotion Amadeo and Pablo, Hocoma Armeo and Lokomat, and the Motek C-Mill enable repetitive, task-specific training and collect objective data on strength, range of motion, balance, and gait. Game-based interfaces enhance cognitive engagement and therapy adherence. These technologies support transparent decision-making for clinicians, patients, and payers, while reducing therapist workload and allowing for potential telerehabilitation applications. Robotic technologies offer significant advantages in rehabilitation by combining measurable progress tracking, adaptive training, and patient-centered design. Although challenges remain—such as cost, accessibility, and data privacy—these tools complement the clinician's role and contribute to more effective and transparent therapy planning. Continued integration and research are needed to optimize long-term outcomes and expand access.

Keywords: Neuroplasticity; Motor Recovery; Instrumented Rehabilitation; Robotic Rehabilitation; Exergames; Virtual Reality

1. Introduction

Conventional rehabilitation, while foundational in clinical practice, presents inherent limitations in terms of precision, adaptability, and patient engagement. In contrast, modern rehabilitation technologies, particularly robotic devices, offer new possibilities for targeted assessment and training. These technologies are reshaping the rehabilitation landscape by enabling measurable, high-intensity, and personalized therapy, ultimately improving functional outcomes (Xiong et al., 2025).

Neurological conditions and movement impairments, such as stroke, spinal cord injury, and traumatic brain injury (TBI), frequently lead to motor deficits that require long-term and intensive intervention. The concept of neuroplasticity—the brain's lifelong ability to reorganize itself in response to experience and learning—provides a theoretical and practical foundation for rehabilitation. Recovery of motor function is possible by rerouting motor commands through intact neural pathways, a process significantly influenced by environmental stimuli and task-specific training (Sahrizan et al., 2025).

To support neuroplasticity and optimize recovery, rehabilitation must adhere to several key principles: early intervention, a high number of task-specific repetitions, and controlled movement selection. Moreover, patients' needs evolve throughout the rehabilitation process, requiring adaptable and individualized therapeutic strategies. Robotic technologies, through their capacity for precise and repeatable movement control, offer a valuable tool to meet these dynamic requirements (Nizamis et al., 2021).

Importantly, robotic systems do not only enable objective assessment of motor function but also provide engaging and interactive therapy environments. Integration with virtual reality (VR), for instance, has been shown to enhance patient motivation and engagement, further supporting motor learning. As a result, technology-assisted rehabilitation holds great promise in addressing the core challenges of modern therapy: efficiency, precision, and sustained patient motivation (Wankhede et al., 2025).

In this article, we explore how robotic technologies are transforming rehabilitation by facilitating personalized, adaptive, and goal-oriented interventions for individuals with motor impairments, drawing on both current literature and clinical practice experiences from our University rehabilitation institute Republic of Slovenia Soča.

2. Methods

This article presents a narrative review of the current scientific literature on robotic technologies used for assessment and training in neurological rehabilitation, supplemented by clinical insights from routine practice at University rehabilitation institute Republic of Slovenia Soča. The goal is to provide an integrated perspective that reflects both evidence-based findings and real-world implementation in clinical settings.

2.1. Literature Review

A comprehensive literature search was conducted using databases such as PubMed, Scopus, and Web of Science. The search focused on articles published between 2015 and 2025 and included studies addressing robotic rehabilitation for motor recovery in neurological conditions such as stroke, spinal cord injury, and traumatic brain injury (TBI). Keywords used in the search included: *robotic rehabilitation*, *neuroplasticity*, *motor recovery*, *assessment tools*, *virtual reality*, and *personalized therapy*. Peer-reviewed articles, systematic reviews, randomized controlled trials, and relevant clinical guidelines were considered. Studies were selected based on their relevance to robotic systems used for either assessment or training, particularly those highlighting clinical outcomes, therapy parameters, and patient engagement.

2.2. Clinical Practice Insights

To complement the literature findings, clinical experiences were drawn from therapists and clinicians working at University rehabilitation institute Republic of Slovenia Soča. Information was collected through discussions, therapy observations, and analysis of anonymized case examples. These insights reflect the practical application of robotic devices in daily rehabilitation routines, including their role in assessment, patient motivation, therapy planning, and adaptation over time.

The integration of both sources, scientific evidence and clinical practice, aims to present a holistic overview of the use and impact of robotic technologies in rehabilitation. This approach allows for a critical evaluation of the current state of the field while highlighting practical considerations and challenges encountered in real-world therapeutic environments.

3. Results

3.1. Motivation through Game-Based Rehabilitation

One of the key factors influencing rehabilitation outcomes is patient motivation and adherence to therapy. Both literature and clinical experience confirm that integrating game-like elements into therapy, so-called exergames, significantly increases patient engagement (Fernandes et al., 2025). These systems transform repetitive physical exercises into interactive and enjoyable digital games, thereby reducing the perception of therapy as a chore (Malik et al., 2022).

Somatosensory games, which rely on motion and sensor input, offer real-time feedback and track progress across sessions. In clinical practice, these tools have been associated with improved therapy adherence, increased engagement and enjoyment, and enhanced cognitive involvement. Such benefits are particularly evident in long-term neurological rehabilitation as well as in rehabilitation training for older people with mild cognitive impairment, where sustained motivation is often a challenge (Chang et al., 2022).

3.2. Technologies for Fingers and Upper Extremities

Precision in hand and arm rehabilitation is essential, especially for patients recovering from stroke or traumatic brain injury. Robotic devices allow for controlled, repetitive, and individualized training of both gross and fine motor movements (Adar et al., 2023; Zariffa et al., 2012). Overview of some technologies, used at our institute for upper limb and fingers are presented in **Table 1**.

Table 1. Overview of some technologies at University rehabilitation institute Republic of Slovenia Soča, used for upper limb and finger instrumented rehabilitation.

Device	Functionality	Key Features	Clinical Use
Tyromotion Amadeo	Finger rehabilitation	Strength, ROM, tone, spasticity assessment	Early to chronic phase, detailed evaluation
Hocoma Armeo	Upper limb exoskeleton	Gravity support, 3D movement training	Motor recovery post-stroke/TBI
Tyromotion Pablo	Hand and arm coordination	Sensor-based training, gamified tasks	Engagement, bilateral coordination training

These technologies have enabled therapists to better tailor therapy plans to individual patient needs, while also enhancing the objectivity of motor assessments.

3.2. Technologies for Lower Extremities, Balance, and Gait

Restoring gait, balance, and postural control is a core goal in rehabilitation of neurological and orthopedic patients. Several advanced technologies have shown promising outcomes in helping patients relearn natural movement patterns through structured and intensive repetitive training (Elmas Bodur et al., 2024; de Miguel Fernandez et al., 2023). Overview of some technologies at our institute for lower limb rehabilitation, balance and gait are presented in **Table 2**.

These tools, through consistent and repeatable movement guidance, promote motor relearning and support neuroplasticity while adapting to patient-specific recovery trajectories. Therapists as well as literature have confirmed the positive outcomes in patients with neurological issues in using these tools for gaining better balance and gait functions (Huo et al., 2024).

Table 2. Overview of some technologies at University rehabilitation institute Republic of Slovenia, used for lower limb rehabilitation, balance and gait.

Device	Functionality	Key Features	Clinical Use
Hocoma Erigo	Early mobilization	Tilt table with leg movement, cardiovascular support	ICU/early neurorehabilitation
Hocoma Lokomat	Robot gait training	Body weight support, adjustable guidance	Gait re-education in neurological patients
Biodex Balance	Balance assessment and training	Objective metrics, dynamic training protocols	Fall risk prevention, proprioception retraining
Motek C-Mill	Treadmill-based gait training	Virtual/augmented reality environments	Gait adaptability, obstacle navigation

4. Discussion

The integration of robotic technologies into neurological rehabilitation offers a paradigm shift not only in training but also in assessment (Choi et al., 2024). One of the most valuable contributions of these systems is their capacity to collect objective, quantifiable data throughout the rehabilitation process. By measuring parameters such as strength, range of motion (ROM), balance, and gait characteristics, robotic devices provide reliable and reproducible metrics that enhance the transparency and precision of clinical decision-making (Zhang et al., 2023).

These data serve multiple stakeholders. For clinicians, they support evidence-based planning, adaptation, and optimization of therapy. For patients, they offer a tangible understanding of progress, helping to maintain motivation and trust in the therapeutic process. For insurers and healthcare providers, objective documentation enables fair and consistent decisions regarding therapy continuation or conclusion. This contributes to a more transparent and patient-centered model of care, where decisions are no longer based solely on subjective clinical impressions but grounded in measurable outcomes.

In clinical practice, the use of robotic systems also addresses several challenges inherent to conventional rehabilitation. These include:

- The need for high-dose, high-repetition task-specific training to support neuroplasticity;
- The ability to deliver personalized and adaptive therapy that adjusts to the patient's functional level over time;
- The provision of motivating and engaging environments, particularly through game-based and virtual reality interfaces;
- The reduction of therapist workload, allowing for more efficient use of clinical resources.

Furthermore, some systems allow for remote monitoring and telerehabilitation, which can expand access to therapy for patients in remote or underserved areas, an increasingly relevant feature in light of healthcare system pressures and demographic shifts (Desai et al., 2023).

Despite these advantages, several limitations and challenges must be considered. The high cost of robotic systems can limit availability and implementation in smaller or resource-constrained institutions. These systems also remain constrained by the reliance on large, cumbersome equipment that necessitates supervision (Rodriguez-Fernandez et al., 2021). Takebayashi et al. (2022) reported that robotic self-training alone did not yield superior improvements in upper-limb function compared to conventional self-training; however, it may offer additional benefits when integrated with standard therapy in certain patient groups (per-protocol analysis) Data privacy and cybersecurity concerns must be carefully managed, especially when dealing with personal health data and remote access (Monoscalco et al., 2022). However, there are cases that confirm effectiveness and improvement of self-learning with a robot for upper limb rehabilitation training (Klinkwan et al., 2023). Additionally, these technologies may not be suitable for all patients, particularly those with severe cognitive impairments, where understanding instructions or engaging with digital interfaces may be difficult (Aprile et al., 2021), as also confirmed by our therapists. The safety of robotic devices, especially in unsupervised or home-based contexts, also remains an area requiring continuous attention and development (Gonzalez et al., 2021), although Gil-Agudo et al. (2023) reports no adverse events.

In summary, robotic technologies for rehabilitation provide a comprehensive toolset for assessment, training, and outcome monitoring. While they are not a substitute for human expertise and therapeutic relationships, they significantly enhance precision, engagement, and objectivity in therapy. Addressing barriers to access and expanding evidence on long-term outcomes will be key to their broader integration into routine clinical care.

5. Conclusions

Technological advancements are significantly enhancing the field of rehabilitation by enabling accurate assessment, effective training, and increased patient motivation (Metzger et al., 2014). Robotic devices, sensor-based systems, and game-driven environments are no longer futuristic concepts; they are actively shaping the way rehabilitation is delivered today and will continue to evolve its practice in the future.

These technologies support the fundamental principles of neurorehabilitation, such as early intervention, task-specific training, and the need for high repetition. They bring precision, adaptability, and objectivity into therapy, helping clinicians tailor interventions to individual needs while tracking progress over time. In doing so, they contribute to more patient-centred, transparent, and data-driven care.

Robotic systems go beyond facilitating movement—they also collect meaningful, quantifiable data that improves clinical decision-making, justifies therapy continuation or modification, and supports communication with patients and insurers. This enables more fair and informed decisions while empowering patients with visible, measurable indicators of their progress as also confirmed by our therapists.

While these tools are powerful, it is essential to emphasize that therapists continue to play a major role in the rehabilitation process. Technology does not replace the expertise, judgment, and human connection provided by clinical professionals; it enhances and supports their work. The therapist's ability to interpret data, adapt strategies, and provide motivation and emotional support remains irreplaceable.

Looking ahead, the future of rehabilitation is interactive, measurable, and empowering. With robotics, sensors, and virtual environments, we offer not just therapy, but renewed hope and a clear path forward for people recovering from neurological and musculoskeletal conditions. To fully realize this potential, ongoing efforts must focus on improving accessibility, addressing data security, and further integrating these technologies into everyday clinical workflows.

In summary, robotic technologies are not simply tools for rehabilitation—they are catalysts for transforming it into a more effective, engaging, and evidence-based process, guided by both data and human care.

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