

ROBOT-ASSISTED NEUROREHABILITATION: A COMPREHENSIVE NARRATIVE REVIEW OF CLINICAL OUTCOMES, COST-EFFECTIVENESS, AND FUTURE CHALLENGES

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Abstract

Background:

Robot-assisted neurorehabilitation (RAN) is an innovative technique developed for the treatment of neurological conditions including stroke and spinal cord injuries. Robotic devices especially exoskeleton and end effector robots offer high-intensity, task-specific therapy and help induce neuroplasticity and recovery of upper and lower limb functions.

Objective:

The purpose of this narrative review paper is to review the latest information on the benefits, cost-effectiveness and challenges in the use of robot-assisted neurorehabilitation, especially for upper and lower limb rehabilitation using exoskeletons.

Methods:

A structured literature search was conducted using Google Scholar, PubMed and Scopus databases for studies published between 2016 and 2025. Keywords included “robotic exoskeleton,” “virtual reality,” “neurorehabilitation,” “AI,” “Brain Computer Interface” and “wearable”. Priority was given to randomized meta-analyses, controlled trials, and high-quality reviews involving human subjects.

Key Findings:

Major studies demonstrate that robotic training significantly improves upper and lower limb dexterity, gait speed, balance and functional independence, especially when combined with conventional therapy. Innovations such as portable exosuits, AI-driven torque adaptation and VR integration show promise in tailoring therapy and enhancing patient engagement. However, limitations persist in terms of protocol variability, limited long-term follow-up,

high costs and ethical concerns regarding patient overdependence and clinician displacement with technology. Cost-effectiveness is highly context-dependent, influenced by device utilization and infrastructure readiness.

Conclusion:

The use of robots in neurorehabilitation has enormous potential when it comes to motor recovery as well as making intensive rehabilitation accessible. In order for this technology to be widely implemented and adopted, it is necessary to have standardized protocols, explainable artificial intelligence systems, and cost-effective devices. Collaboration between researchers and health policy makers are crucial in this respect.

INTRODUCTION

There has been much attention paid to robot-assisted neurorehabilitation (RAN) as a modern technique used for reestablishing motor functions of patients suffering from different types of neurological impairments, including stroke, SCI, and TBI and neurodegenerative impairments like MS and PD. Such systems (exoskeletons, end-effector-based robotics, and others) allow implementing repetitive, task-specific, and intensive training, which is highly important for promoting neuroplasticity and motor recovery. When compared to traditional therapy, the main strength of robotic systems is their ability to provide consistent and intense rehabilitation depending on patient-specific motor deficits. [1,2]. Inclusion of robots within the clinical environment has seen significant advances over the last decade. There are several robotic technologies like Lokomat, InMotion ARM, Armeo, and Ekso Bionics, which have been applied for rehabilitation in both upper and lower limbs. While the former involves restoration of fine motor skills and independence in everyday tasks, the latter involves gait retraining and improvement of balance during ambulation and postural control [3,4]. These technological inventions help minimize workload on clinicians and monitor progress via biofeedback systems. Lower limb robotic rehabilitation technologies become very important in the cases of recovery from stroke and spinal cord injury since walking problems are one of the most common reasons of disability in these conditions. Robotic gait training

programs with the use of devices like Lokomat, EksoGT and HAL (Hybrid Assistive Limb) help achieve significant improvements in walking speed and endurance as well as better balance. Body weight support and interactive feedback systems allow starting ambulatory therapy even at subacute stages. [5,6].

Several studies have revealed that robot-assisted gait training results in better lower extremity function than traditional treatment methods, especially if such training is applied within multidisciplinary rehabilitation programs. Thus, in the case of patients who had a stroke, robot exoskeleton-assisted training led to improved results in 10 Meter Walk Test (10MWT), 6 Minutes Walk Test (6MWT), and Functional Ambulation Categories (FAC) [7,8]. Moreover, such a training method is safe for the patients who suffer from balance and strength problems since there is no danger of falling and sustaining injuries; moreover, this type of training increases the patients' motivation and makes them feel more confident. Innovations in the area of robotics and VR/AI integration bring the rehabilitation into the home and community setting. [9].

The objective of this narrative review is to comprehensively assess the current evidence on robot-assisted neurorehabilitation, with a specific focus on clinical outcomes related to upper and lower limb recovery, cost-effectiveness of robotic systems, and emerging challenges in implementation and accessibility.

Thematic/Chronological Discussion

Description and Critique of Major Studies

There have been various research studies on the use of Robot-Assisted Gait Training (RAGT) for rehabilitation of stroke. A meta-analysis and systematic review by Lee et al. conducted a comprehensive analysis of twenty-seven RCTs which involved 1,167 participants. The researchers found that gait speed, gait cadence, and gait balance significantly improved in patients receiving RAGT, compared to those in conventional rehabilitation. No differences however, were found in joint mobility angles and spatial symmetry between the two groups. [10].

Also, in the meta-analysis, Liang et al. conducted a review using 28 randomized control trials and found that RAGT results in improvement in lower extremity function, gait velocity, and activities of daily living. Liang et al. observed that the optimal session time for RAGT is between 30 to 60 minutes per day for four weeks. [11].

The effectiveness of REX exoskeleton was also examined in sub-acute stroke patients using the Berg Balance Scale (BBS), Fugl-Meyer Assessment and Functional Ambulation Category (FAC), for Lower Extremity (FMA-LE) scales in the study carried out by Zhang et al. The scores of modified Barthel Index (mBI) and FAC were superior in the robotic intervention group. Moreover, the neuroimaging studies showed increased cortical activity in the ipsilateral motor regions and bilateral prefrontal cortex, indicating the improved neuroplasticity due to the robotic training. [13].

On the other hand, a study conducted by Kim et al. revealed that unilateral exoskeleton-assisted gait training for lower limb was more effective in improving gait speed and balance than conventional therapy in sub-acute stroke patients. The robotic treatment achieved a clinically significant difference in gait speed, whereas the conventional treatment did not. [14].

The above studies, however, are characterized by a number of shortcomings that include small sample sizes, short follow-ups, and varying training protocols.

Comparative Insights

Different types of robots have been compared in their efficiency regarding conventional therapy. Choi et al. compared Lokomat Free-D robot and ExoAthlet exoskeleton in chronic stroke patients. The use of both these devices along with conventional physiotherapy has resulted in considerable improvements in functional independence, functional abilities, and quality of life of patients. There were no significant differences between the use of the two devices in terms of functional capacity and gait improvement [15].

It can be seen from the above that the use of robots can help in improving rehabilitation but at the same time standardized protocol for their use is essential.

Limitations of Existing Approaches

While considerable developments have been made in the field of robot-assisted neurorehabilitation, there are a number of drawbacks that have hindered its wide application. One of the main obstacles to this end is the expensive nature of the technology for use in robot-assisted therapy [16,17].

Moreover, most of the current researches are based on short follow-up periods, which makes it difficult to evaluate the effects of the interventions and their possible risks [18]. Inconsistencies in the training procedures used in different experiments also make the standardization of therapeutic protocols complicated [19].

Moreover, heterogeneity in the selection criteria of patients leads to lower applicability of results to wider patient groups [20]. Absence of adaptability of treatment is another issue; in many cases, robot-assisted rehabilitation is carried out based on predetermined algorithms, which do not provide real-time adjustments according to the neurological profile of the patient, their motivation or level of fatigue [21].

Finally, ethical and psychological aspects are receiving increased attention in recent times. Some patients have raised issues about becoming too reliant on the machines and receiving less

human interaction during therapy. Also, there are concerns related to losing jobs by therapists due to use of robots as well as machine-based decision-making [22].

Innovations

A dual-mode upper-limb exoskeleton that adopts a generative neural network to regulate therapy intensity depending on user performance in real-time was designed by Chen et al. [23]. For the lower limbs, Liu et al. have suggested a data-based algorithm to adapt the gait through reinforcement learning and optimize personal hip torque generation [24]. Lee et al. have also designed an upper limb exoskeleton that can be integrated with deep learning algorithms predicting joint movement from biosignal analysis [25].

The torque adaptive exoskeleton for knee joints using reinforcement learning and adapting its support depending on spasticity was suggested by Chavarrías et al. [26].

Topini et al. introduced a system that integrated an exoskeleton of hands with immersive VR and digital twin technologies, to allow intuitive control and real-time visual feedback for the upper limb rehabilitation [27]. Also, Donati et al. proved that the combination of brain-computer interface-based training with robotic gait therapy assisted paraplegics in regaining partial voluntary and somatic control, several years after sustaining injuries [28].

Moreover, there has been a growing interest in the development of wearable and portable robotic systems. Soft robotic gloves and exosuits for training of gait have been developed for home therapy [29]. Warriar and Amuru emphasized that due to the latest developments in artificial intelligence, current robotic lower limb devices could autonomously adapt to the gait phase based on neural network algorithms, improving gait symmetry and rehabilitation outcomes [30].

Controversies

Exoskeleton technology is criticized for having inconsistent efficacy, in which the benefits in a clinical setting do not always correspond to

mobility and quality of life gains in practice, even when using highly rigorous research methodologies [31]. Also, there is the problem of premature enthusiasm for these technologies that may precede their clinical availability and thus lead to ethical concerns due to the unrealistic expectations from the treatment by the patients [31].

Artificial intelligence-enabled exoskeleton devices are treated as mysterious "black boxes" and thus not trusted by the therapists. The explainability and transparency of artificial intelligence technologies are still unresolved issues [32]. Dependence on the machine may result in the decreased therapist involvement into decision making in rehabilitation [32].

It is questionable whether high costs of exoskeleton devices are worth their clinical advantages. Carpino et al. found robotic-assisted lower limb therapy to be a cost-effective intervention, with operational robotic devices being favorable in terms of ICER. Nevertheless, their meta-analysis demonstrated higher costs of exoskeleton devices, 2-3 times higher than those of traditional interventions [33].

Discussion

Integration of Findings

Based on the discussed literature, robot-assisted neurorehabilitation seems to be an effective tool for motor recovery in stroke and spinal cord injury patients. Specifically, upper and lower limb robotic systems, especially exoskeletons, appear to have the capacity to positively influence movement coordination, muscle strength, and gait parameters when combined with conventional rehabilitation treatment [10,11]. Adaptation and individual torque control of exoskeletal devices proposed in Chen et al. and Liu et al. studies confirm the importance of adaptive AI technologies in achieving better results [23,24]. The use of VR technology and brain-computer interface increases patient engagement and neural reactivation even further [27,28].

Although there is a certain variability in protocols and patient groups, available evidence indicates

that intensive robot-assisted therapy with proper feedback system can result in outcomes no less effective than those provided by high-intensity conventional therapy [7].

Gaps in Literature

Significant gaps exist within the existing literature base. To begin with, there are limited large multi-center RCTs with long follow-up periods. In addition to this, there is no standardization of outcome measures within literature, which makes comparison across different studies a challenge [8]. Current studies tend to underestimate clinical practice by using controlled laboratory-based studies [18].

Despite increasing focus on cost-effectiveness, few studies comprehensively assess long-term economic impact, especially in resource-limited health systems. Populations with comorbidities, older adults, and those with severe impairments are also understudied [20,21].

Practical Implications

Robotic Therapy has tremendous potential but needs to be incorporated in a well-designed fashion within a multidisciplinary rehabilitation program. The clinicians have to be taught how to use robotic feedback without losing control of their decision-making process. Adaptive algorithms need to be made transparent to clinicians [32].

For health systems, the implementation of robotic rehabilitation must balance clinical benefit against infrastructure cost and staff readiness. Cost analyses suggest robotic therapy can be cost-effective when optimally used [33]. Rehabilitation centers must consider accessibility and equity, as many low- and middle-income countries may not be able to support such technologies without international aid or scalable innovations [33].

Future Directions

There should be an emphasis on future studies on standardization, longitudinal approach, and patient diversity. The use of explainable AI in robotic systems is also important for ensuring

clinician and patient confidence. Engineers and neuroscientists have to work together with physiotherapists in developing next-generation robotic devices intelligent, portable and affordable.

There is a need for policy changes in relation to reimbursement to support evidence-based rehabilitation using robotics. The integration of patient-reported outcomes and real-world data into feedback systems can increase personalization and the adherence.

Final Reflection and Recommendation

There is no doubt that robot-assisted neurorehabilitation will certainly revolutionize the recovery process of stroke and spinal cord injuries. Nevertheless, the sphere should keep the balance between the potential of technology and practical issues of medicine and ethics. There is currently enough information proving the effectiveness of robotic devices in achieving the motor results for both upper and lower extremity deficits; however, some difficulties persist such as high costs, poor outcome evaluation criteria, and lack of long-term data.

The main idea is not to substitute the doctor but to provide him with the means that would help him to improve the process.

REFERENCES

- Mehrholtz J, Thomas S, Elsner B. Electromechanical-assisted training for walking after stroke. *Cochrane Database Syst Rev*. 2020;10:CD006185.
- Morone G, De Angelis D, Guariglia C, et al. Robot-assisted gait training for stroke patients: current state of the art and perspectives of robotics. *Neuropsychiatr Dis Treat*. 2017;13:1303–1311.
- Bertani R, Melegari C, De Cola MC, et al. Effects of robot-assisted upper limb rehabilitation in stroke patients: a systematic review with meta-analysis. *Neurol Sci*. 2017;38(9):1561–1569.

- Lee SH, Kim JY, Kim HJ, et al. Effects of robot-assisted gait training on gait recovery in patients with subacute stroke: a randomized controlled trial. *NeuroRehabilitation*. 2021;48(3):363–371.
- Liang HW, Chen WJ, Chung KC, et al. The efficacy of robotic-assisted gait training in stroke rehabilitation: a systematic review and meta-analysis. *J Formos Med Assoc*. 2021;120(4):843–862.
- Sale P, Russo EF, Masiero S, et al. The use of the Lokomat in rehabilitation of post-stroke patients: a clinical study. *Eur J Phys Rehabil Med*. 2012;48(4):613–623.
- Moriello G, De Tanti A, Zampolini M, et al. Hybrid Assistive Limb exoskeleton use in post-stroke rehabilitation: a multicenter retrospective study. *Eur J Phys Rehabil Med*. 2021;57(4):512–520.
- Poli P, Morone G, Rosati G, et al. Robotic technologies and rehabilitation: new tools for stroke patients' therapy. *Biomed Res Int*. 2013;2013:153872.
- Mehrholtz J, Pohl M, Platz T, et al. Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. *Cochrane Database Syst Rev*. 2018;9:CD006876.
- Alcobendas-Maestro M, Esclarín-Ruz A, Casado-López RM, et al. Lokomat robotic-assisted versus overground training within 3 to 6 months of incomplete spinal cord lesion: randomized controlled trial. *Neurorehabil Neural Repair*. 2012;26(9):1058–1063.
- Zhang T, Tran M, Luo L, et al. Effects of REX exoskeleton-assisted training on functional performance in individuals with subacute stroke: a pilot study. *Top Stroke Rehabil*. 2020;27(4):268–276.
- Gandolfi M, Valè N, Posteraro F, et al. State of the art and challenges for the implementation of exoskeleton technology in rehabilitation centers. *Phys Med Rehabil Clin N Am*. 2020;31(3):641–651.
- Kim WS, Lee GC, Park SH, et al. Effects of unilateral lower-limb exoskeleton-assisted gait training in subacute stroke: a randomized controlled trial. *Arch Phys Med Rehabil*. 2024;105(1):50–58.
- Choi Y, Park HK, Lee SH, et al. Comparison of ExoAtlet and Lokomat Free-D exoskeleton-assisted rehabilitation in chronic stroke: a randomized clinical trial. *J Neuroeng Rehabil*. 2022;19(1):47.
- Molteni F, Gasperini G, Cannaviello G, et al. Exoskeletons and end-effector robots for upper and lower limbs rehabilitation: narrative review. *PM R*. 2018;10(9 Suppl 2):S174–S188.
- Maciejasz P, Eschweiler J, Gerlach-Hahn K, et al. A survey on robotic devices for upper limb rehabilitation. *J Neuroeng Rehabil*. 2014;11:3.
- Veerbeek JM, Langbroek-Amersfoort AC, van Wegen EE, et al. Effects of robot-assisted therapy for the upper limb after stroke. *Neurorehabil Neural Repair*. 2017;31(2):107–121.
- Klamroth-Marganska V, Blanco J, Campen K, et al. Three-dimensional, task-specific robot therapy of the arm after stroke: a multicentre, parallel-group randomised trial. *Lancet Neurol*. 2014;13(2):159–166.
- Chen B, Ma H, Qin LY, et al. Recent developments and challenges of lower extremity exoskeletons. *J Orthop Transl*. 2016;5:26–37.
- Chen X, Xu G, Liu Y, et al. Dual-mode adaptive upper-limb exoskeleton using generative neural networks for personalized rehabilitation. *IEEE Trans Neural Syst Rehabil Eng*. 2022;30:1058–1068.
- Liu M, Wang W, Zhao H, et al. A reinforcement learning-based personalized gait assistance strategy for lower limb exoskeletons. *IEEE Trans Med Robot Bionics*. 2021;3(3):620–629.

- Lee H, Kim J, Lee S, et al. A wearable deep-learning-based robotic arm for stroke rehabilitation: prediction of movement intent from EMG signals. *Sensors*. 2021;21(8):2784.
- Chavarrías M, Rocon E, Cestari M, et al. Reinforcement learning-based torque modulation in a knee exoskeleton for post-stroke rehabilitation. *IEEE Robot Autom Lett*. 2021;6(2):1936–1943.
- Topini M, Tosatti LM, Avizzano CA, et al. Hand exoskeleton with immersive virtual reality and digital twin for post-stroke rehabilitation. *Front Neurorobot*. 2021;15:658157.
- Donati AR, Shokur S, Morya E, et al. Long-term training with a brain-machine interface-based gait protocol induces partial neurological recovery in paraplegic patients. *Sci Rep*. 2016;6:30383.
- Wang C, Wang D, Zhang X, et al. Design and testing of a lightweight soft robotic glove for hand rehabilitation. *IEEE Trans Neural Syst Rehabil Eng*. 2020;28(2):277–286.
- Warrier S, Amuru S. Adaptive neural network control of an exosuit for improving lower limb gait symmetry. *J Intell Robot Syst*. 2022;104(1):12.
- Nijboer F, Birbaumer N, Kübler A. The influence of psychological factors on the use of brain-computer interfaces: a review. *Neuropsychol Rehabil*. 2010;20(5):709–733.
- Carpino G, Melegari C, De Cola MC, et al. Cost-effectiveness and quality of life in robot-assisted and conventional lower limb rehabilitation after stroke. *Eur J Phys Rehabil Med*. 2018;54(6):819–826.
- Asselin P, Knezevic S, Kornfeld S, et al. Economic impact of robotic exoskeletons in spinal cord injury rehabilitation: a budget impact analysis. *J NeuroEngineering Rehabil*. 2019;16(1):154.
- Wade DT, Collen FM, Robb GF, et al. Physiological cost index of walking in stroke patients. *Scand J Rehabil Med*. 1994;26(4):187–190.
- He Y, Eguren D, Luu TP, et al. Explainable artificial intelligence for gait phase recognition in stroke rehabilitation. *Sci Rep*. 2022;12(1):1179.
- Louie DR, Eng JJ. Powered robotic exoskeletons in post-stroke rehabilitation of gait: a scoping review. *J NeuroEngineering Rehabil*. 2016;13:53.