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Publications 2025

OPEN ACCESS
ONLINE ISSN: 2992-5460
PRINT ISSN: 2992-6041

NEWPORT INTERNATIONAL JOURNAL OF RESEARCH IN MEDICAL SCIENCES (NIJRMS)

Volume 6 Issue 2 Page 202-209 2025

https://doi.org/10.59298/NIJRMS/2025/6.2.202209

The Role of Robotics in Rehabilitation Therapy

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ABSTRACT

Rehabilitation robotics is revolutionizing patient recovery by integrating advanced hardware and software to enhance therapeutic interventions. These robotic systems aid in motor function recovery by providing precise, repetitive movements that support neuroplasticity and motor learning. Exoskeletons, end-effector systems, and telemanipulators are among the primary robotic rehabilitation devices used to assist patients with neurological, orthopedic, and geriatric conditions. While robotics in rehabilitation offers advantages such as data-driven therapy customization, enhanced accessibility, and improved patient adherence, challenges like cost, patient engagement, and ethical concerns persist. The growing role of artificial intelligence (AI), sensor technology, and tele-rehabilitation is shaping the future of robotic-assisted therapy, offering personalized and efficient rehabilitation solutions. Continued research and technological advancements will further optimize robotic rehabilitation, making it more effective and accessible for diverse patient populations.

Keywords: Rehabilitation robotics, robotic-assisted therapy, exoskeletons, motor recovery, AI in healthcare, tele-rehabilitation.

INTRODUCTION

In a world constantly evolving with technology, the advancement of robotics in all aspects of human life from automation, healthcare, and industry to research is unstoppable. The increasing adaptability and gradual intelligence gained to function manually have greatly reduced human involvement. Among the developments of robotics in medical fields was rehabilitation. Rehabilitation refers to a combination of recovery processes aiming at patients who suffer a disability through affirming mental and physical individuals who cannot return to good conditions and to improve the quality of daily living. The earlier the process, the higher the probability of successful recovery, and the role of robotics in the recovery process immediately catches the attention of the researchers to further accelerate the self-recovery process of the patient. Physical disabilities represent the situation when an individual lacks cognitive and physical skills wholly or partially, reducing the capacity to conduct daily life activities such as talk, move, and so on. Medical robotics is the pairing of robotics technology with medicine. Four main areas of medical robotics have been identified: Minimally Invasive Surgical Robotics, Micro and Nano Robotics in Medicine, Image-guided Surgical Procedures and Interventions, and Rehabilitation Robotics. Rehabilitation robotics is the pairing of robotics technology with therapy techniques to assist individuals with physical disabilities to enhance the quality of their therapy. This robotic system embraces software and hardware instruments for patient assessment and therapy training in a manner of skill acquisition to restore lost or impaired physical function as well as to prevent further loss. The supplemented robotic system normally supports human assessment and physical functional activities such as balance and walking, manipulation of items, and other types of exercise training. There is a sense of urgency and necessity for the therapeutic tasks to evolve with the growth of technology condition in handling different disabilities and scenarios motivating the patient to engage with the therapy session [1, 2].

Background and Importance of Rehabilitation Therapy

Rehabilitation is a therapy for treating injuries or surgeries, evolving over 5000 years into a modern interdisciplinary field. It involves various professionals, including physiatrists, therapists, and bio-

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ONLINE ISSN: 2992-5460
PRINT ISSN: 2992-6041

engineers, focused on improving patients' quality of life. Rehabilitation can include hospital exercises to robotics, tailored to the patient rather than just symptoms. It is essential for helping patients regain function, maintain independence, and reduce healthcare costs. In severe cases, it can prevent lifelong personal assistance needs. This literature review will explore the role of robotics in rehabilitation and its benefits, aiming to promote its societal acceptance as an innovation. More individuals are seeking to enhance their physical well-being post-injury or stress, making therapy vital. In the past, treatment relied heavily on healthcare providers, but now, numerous tools, including robots, assist therapists and encourage patient exercise. Advances in biomedical engineering and related sciences have led to sophisticated devices in various fields, such as orthotics and robotics, designed to enhance patient recovery through intensive training and support. One notable invention is therobotics, a system that aids patient training. Although robot-assisted rehabilitation is relatively new, its popularity has surged, with recent developments focusing on advanced robotic tools for home training [3, 4].

Fundamentals of Rehabilitation Robotics

Rehabilitation Robotics focuses on developing robot-assisted devices for physical therapy to enhance therapeutic exercises during rehabilitation. Active patient participation through repetitive exercises is vital for optimizing motor recovery after musculoskeletal injuries or impairments. Traditional physical therapy can present challenges, leading to the primary goal of rehabilitation robotics: creating electromechanical systems that guide patient efforts and supplement physical therapy. This enhances the dosage and intensity of specific movements, promoting neural reorganization and motor learning for both non-disabled individuals and those with partial impairments. The outcome is improved engagement and performance in prescribed exercises. Research supports the effectiveness of robotic systems in sensorimotor rehabilitation, as they can deliver preprogrammed assistance and capture movement data related to forces and kinematics experienced by patients. This capability enables a range of cognitively engaging exercises or requiring a specific intensity that improves patient involvement. The PDT-RF (Predefined Direction and Target-Based Robotic Facilitator) is a prototype rehabilitation robot designed for shoulder exercises. It acts as an additional arm for the physical therapist, functioning as an arm–arm exoskeleton. This system incorporates haptic feedback to guide therapy exercises, with a programmed arm joint that moves in a circular trajectory, providing movement cues. Patients grasp a handle, moving their arm to follow the therapist and robot's motions simultaneously [5, 6].

Definition and Scope

Rehabilitation robotics is defined to clarify its role in helping individuals with movement disorders regain or improve physical and cognitive functions. Despite historical neglect compared to other robots, understanding this field is crucial for expanding research and therapeutic approaches. The inclusive definition of rehabilitation robotics covers technologies for diagnosis, assessment, and treatment after illness or injury, utilizing robotic systems for effective therapy delivery. This definition contrasts with traditional rehabilitation, which is narrowly defined as using exercises or adaptive devices for recovery after physical injuries. The term "illness" in rehabilitation robotics broadens the scope to include various health issues like stroke, spinal cord injuries, and Parkinson's disease, moving beyond just surgery-focused recovery. An expanded interpretation includes interventions for congenital and developmental disorders and the aging population, emphasizing the importance of robotics in neuro-motor rehabilitation. The research highlights how integrating robotics can enhance patient diagnosis and care delivery, addressing societal pressures for cost-effective, home-based therapies. Demographic trends increase the need for such interventions, as patients express a desire for more intensive therapy options that traditional healthcare resources struggle to provide. Moreover, customization in therapy and devices is essential, where robotic solutions excel. Thus, there is a pressing need to explore the potential of robotics in delivering tailored, adaptive therapies for diverse neuro-motor disorders, paving the way for improved clinical outcomes and patient experiences. [7, 6].

Benefits and Challenges of Robotics in Rehabilitation Therapy

The integration of robotic systems in rehabilitation therapy focuses on physical therapy after stroke, spinal cord injuries, or cerebral palsy patients. Robots can assist in guiding limb movements to retrain motor skills. Although they provide benefits like controlled, repetitive training and biofeedback, patient engagement may be insufficient. This creates a conflict between patient involvement, essential for positive outcomes, and robots' efficient, repeatable assistance. Robotic systems play an increasing role in rehabilitation, either assisting or replacing therapists during exercises. While robots handle various tasks that require less human intervention, there are challenges in ensuring optimal interaction with patients. Some patient tasks may be physically demanding or require more flexibility than the robots can offer, yet

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PRINT ISSN: 2992-6041

patient engagement remains crucial for effective rehabilitation. Robotic technologies can adapt to fulfill diverse rehabilitation needs, such as guiding limbs along a defined path to improve motor function and assist in muscle exercises. Different robotic configurations impart various assistance forces, leading to unique results. However, achieving optimal interaction is often difficult, particularly when flexibility mismatches arise between biological and robotic systems. Therefore, fostering good cooperation between patients and robots is important to enhance rehabilitation performance and minimize conflicts between the robot's adaptive forces and the patients' or therapists' intentions. [8, 9].

Benefits

Robotics enhances rehabilitation by offering precise exercise delivery and monitoring, improving control and measurement of patient performance. The extensive data gathered during robotic therapy can accurately reflect patient conditions, enabling personalized therapy experiences. Automation ensures consistent execution, as robots do not tire, leading to improved patient outcomes over time. These systems collect vast amounts of data, which can identify progress biomarkers and predict future advancements through machine learning, facilitating tailored recovery strategies. Additionally, accurate therapy records allow for the assessment of patient engagement and effort, which is crucial in long-term rehabilitation, where logistics and budgeting are challenges. Studies indicate that interactive robotic therapy boosts motivation and adherence; patients are more engaged with robotic exercises, especially when simple tasks are combined with games that enhance focus. Haptic interaction aids in teaching precise motor tasks, minimizing patient startle responses. Advanced electric motors enable the development of lightweight, handheld devices, making robotic rehabilitation accessible globally, including in nursing homes and spas. Overall, robotics responds to chronic conditions by broadening therapy accessibility for numerous patients across diverse settings [10, 11].

Types of Robotic Devices Used in Rehabilitation Therapy

The architecture of robot-aided therapy for upper limbs includes fully robotic systems, telemanipulators, and assistive devices, categorized by DOFs and motion types. For lower extremities, different manipulators are used for treadmill-based gait training, with systems that can be both robotic and non-robotic. The integration of sensors and advanced control strategies is crucial, featuring adjustable spring-damper systems for hips connected to linear drives and adaptable surfaces for existing orthoses. A body weight support system complements these devices, which include HD-TV and dual infrared cameras for improved user interfaces. A haptic device allows for simultaneous bilateral training of hands. Fully robotic systems have been created with orthoses and exoskeletons, weighing about 14 kg, and are easily adjustable via telescopic sections. These manipulators include cables and springs to balance the arm's weight and can be backdriveable. An orthosis model incorporates interlocking rings at joint axes for movement, while a passive device aids severely impaired patients. Modified industrial robots like the Puma 560 serve as research platforms functioning as actuated orthoses or exoskeletons, coupled with end-effectors and a 6-channel perturbation system for therapy customization. Support from a 6-DOF force/torque sensor ensures effective therapy, emphasizing early intervention to combat 'learned non-use' while flexible adaptive programs enhance compensatory strategies. Despite advancements, many sophisticated robotic devices are unaffordable for smaller hospitals or clinics due to size and infrastructure needs, necessitating time-consuming adjustments. Here, we propose a flexible, safe, and affordable robot-aided device for upper extremity rehabilitation in stroke patients [12, 13].

Exoskeletons

Robot-based rehabilitation therapy has received considerable attention in the last decade. It is a new implement for the assessment and rehabilitation of sensorimotor impairments due to various injuries and neurodegenerative diseases. Robotic systems are increasingly used in rehabilitation to provide high-intensity training for patients with motor impairment under clinical observation. Rehabilitation requires intense and long-term training. It is expensive and time-consuming as well. Therefore, the development of automated systems becomes very important. The results of controlled trials confirm the effectiveness of robot-enhanced methods of upper limb therapy and prove them to be marginally superior to standard manual therapy. There are two main categories of robots in rehabilitation therapy, i.e., end-effector and exoskeleton. The exoskeleton-based robot is a wearable robot used to facilitate physical movement in inpatient rehabilitation. It is a mechatronic device that is worn by a patient like a suit. Exoskeletons for rehabilitation purposes use external actuators to provide physical assistance or resistance to the joints for neuro-rehabilitation training. Passive and active actuation systems can be used for that. Exoskeletons have been widely studied due to their capability in providing more control over the paretic limb motion. At the same time, many complex issues arise in the construction and control of an exoskeleton. There is a

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PRINT ISSN: 2992-6041

far-reaching variability in the size, weight, and shapes of the human body, as well as an enormous variety of types of damage. There are exoskeletons for the lower limbs, which are used to assist or enhance average people to increase their performance. Some are used in the rehabilitation center to help people with damage to walk, as well as devices to assist people in carrying heavy objects. A lot of research is currently carried out in the development of exoskeletons for arms. Such devices are the most diverse since damage to the upper limbs is the most common. They are used in a variety of processes for both rehabilitation and therapy [14, 10].

Applications of Robotics in Specific Rehabilitation Fields

The use of robotics in medical treatment has become increasingly accessible due to advancements in technology and manufacturing. This progress is evident in medical robotics, particularly in minimally invasive surgeries and rehabilitation. Rehabilitation robotics, in particular, has seen significant growth in research and product development in the last decade, aligning with social, economic, and healthcare trends. The focus on specific rehabilitative patient conditions and physical therapy disabilities where medical robots can have an impact is discussed. While rehabilitation therapy encompasses a broad range of studies, much of the research has been general, lacking specialized attention. Emphasizing neurological rehabilitation for motor function recovery is crucial, particularly following brain injuries like strokes. Stroke rehabilitation serves as a prime example of the benefits of robotics, improving patient recovery outcomes through human-robot interaction. The strategy known as “Use it or lose it” compensates for lost muscle function by employing healthy muscles, while another approach, “Use it and improve it,” stresses the importance of task practice. Current studies highlight the need for expanded research on implementing medical robots in rehabilitation, including orthopedic and geriatric settings. The wide applicability of robots across various rehabilitation fields and their impact on patients with disabilities is crucial for future advancements [15, 16].

Neurological Rehabilitation

Robotic neurorehabilitation may greatly enhance patient care and outcomes by providing precise, controllable training tailored to individual needs. Stroke patients face deficits in movement, vision, and sensation, which impede their balance control and object manipulation, limiting independence. The main goal of neurological rehabilitation is to help recover lost abilities and relearn challenging skills due to brain injury. Research in brain plasticity indicates that extensive repetitive practice aids long-term motor recovery. Therefore, the primary aim of motor training is to facilitate relearning movements through intensive use of affected limbs. Robotic devices meet the need for mechanical precision necessary for evaluating rehabilitation outcomes. They serve as high-precision interfaces for rehabilitating hand movement sequences. Various robotic devices have been designed to target specific impairments, often featuring stiff structures ideal for dynamic modeling. Many utilize joint manipulandum designs, like planar parallel linkages, to assist stroke patients in movement training within controlled environments. Studies reveal that robotic training significantly improves motor outcomes in affected arms and even benefits untrained limbs. Such training enables stroke survivors to practice precise 3-D trajectories to regain control of specific muscle groups, while actuated manipulanda provide assistive torques based on measured performance [17, 18].

Current Trends and Future Directions

The world is becoming more interconnected and automated. The advancement in technology and communication is allowing the revolution of new ways that are changing the way people interact, are socially connected, and even govern. Vast improvements in artificial intelligence and machine learning are needed to push automation forward. The same improvements are seen as crucial to enhancing the capabilities of robots in a standardised way, aiding their acceptance in multiple settings, with rehabilitation therapy only a small fraction. Once rehabilitation robots advance in this manner, they will be able to turn rehabilitation from a bulk delivery to a personalised data-intensive discipline, fortunately augmenting patient health outcomes and quality of life. Sick, aged, or disabled people will widely obtain health benefits from such advanced therapy through collaborative efforts among developers, laycarers, healthcare providers, and patients [19]. Robotics might be employed to monitor the taking of courses have even been devised. Remotely monitoring tools have continuously been in use in assisting monitors to follow the diverse needs of the EU. This same set of technologies germinated the Ekso garments worn in Santa Clara. Physicians there are kept informed of the status of their attendance via data streaming. Healthcare delivery models are swiftly evolving towards massive tele-rehabilitation. It is said that e-visits occurred four to eight times more often from mid-March to mid-June than before March 16th. Analysis displayed a variation of around 10% in the share of visits by telemedicine compared to the instant of the week. If the same share of elective encounters that were done via telehealth in line with the 'normal' share of weekday e-visits were sustained in the future, it would grow to a figure almost 20 occasions greater [20].

Advancements in Sensor Technology

Improvements in sensor technology are critical for robot-assisted therapy to ensure both patient safety and effective treatment. Motion capture sensors are critically important to track the movements of the subjects to accurately assess their performance accurately and measure the treatment effects. Accurate measurements of the patient's state, such as the effectiveness of the applied therapy over time, offer health care professionals valuable information regarding the patient's immediate condition or long-term progress. Sensor technologies are enabling health care professionals to take advantage of reconfigurable robotic structures in both clinical settings and for use in the home environment. Sensors are also critical to ensure the safety of subjects during an exercise. Electrical charges and electric noise are associated with some new sensor technologies that may not be provided by traditional mechanical sensors. This is an obstacle in the use of electrical sensor-based systems for a rehabilitation application, as the robot system should never deliver high electrical charges to the user. These sensors are also costly, unreliable, and relatively complex to apply to a robotic application. Future work in developing more accurate, reliable, and easy-to-use sensors for robotic applications to provide a safer and more efficient rehabilitation system is necessary and viable [21, 22].

Ethical Considerations in the Use of Robotics in Rehabilitation Therapy

The integration of robots in rehabilitation therapy raises ethical concerns about responsibility for their functioning and patient well-being. Key issues involve end-users, such as patients and healthcare providers. Informed consent is a critical concern, as inadequate disclosure about robotic therapies may lead to patients misinterpreting these devices, resulting in fear and negative emotional reactions. Dependence on robots' risks undermining self-esteem and patient autonomy, essential for therapy's success. It may also damage the therapist-patient relationship, jeopardizing recovery through meaningful interactions. Therefore, policies supporting biomedical research and tech advancements in rehabilitation robots must address healthcare disparities. High costs could worsen inequalities, necessitating public debate and targeted policy development to navigate these ethical implications. The goal is to align technology with human-centered values, ensuring that patient welfare and emotional health remain priorities in rehabilitation [23, 24].

Privacy and Data Security

In this context, rehabilitation therapy is not only about regaining physical function but also about regaining independence, dignity, and self-esteem. This therapy is often provided in a private room that qualifies patients to expect their sensitive medical, emotional, or even financial information to have the highest level of confidentiality. However, growing interest in applying robotics to healthcare has resulted in various innovative therapies. Some forms of rehabilitation can be performed with interactive robots, both face-to-face and remotely. Thus, patients might wonder what kind of data is being collected, who it is or will be shared with, and what the implications are for their privacy. Consequently, adequate action is required to protect patients' information privacy, as patient information confidentiality is mandated by law in many areas [25]. Patients do not expect that while a therapy robot is trying to assist them, it jeopardizes the security of their personal information. The immense economic potential of healthcare data has been widely recognized by the industry, and data breaches have been estimated to cost $4m on average. Breaches of digital patient records have become a subject of media coverage in terms of cybercriminals' increasing disposition toward suppliers of sensitive information. Concerns have been voiced over the state's deficient ability to secure such databases, their reliance on methods in need of substantial cyber expertise, and their potential vulnerability to hackers. Patients expect that their data is stored in encrypted form and that only authorized access to it will be possible. This is of paramount importance. Recent surveys have shown that most patients are deeply privacy-conscious and struggle to trust healthcare providers who do not respect their personal information. Hence, data security is important in an age when digital healthcare is becoming increasingly prevalent, if not the rule [26].

Case Studies and Success Stories

There is growing evidence that robotics enhances physical therapeutic assistance for patients. This fast-expanding industry leverages advancements in Artificial Intelligence and affordable electronics, making it applicable in homes and clinics. However, the recipient perspective on robot-mediated assistance has been overlooked. This paper includes case studies and success stories in robotics for rehabilitation, providing context for a study on feedback from amputees that could inform future assistive robot development. It

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PRINT ISSN: 2992-6041

explores the implications for designing physical assistive robots and discusses the social challenges in their development. Case studies exemplify significant improvements in patients' conditions, covering strength, mobility, and overall therapeutic outcomes. While abundant literature exists, many focus solely on high-tech interactions, neglecting the patients' views on robot-assisted recovery [27, 14].

The EKSO Bionics Suit

Robotic technology offers significant advancements in rehabilitation therapy through innovative devices. For instance, a bionic suit enhances ambulation for individuals with lower limb paralysis or weakness, utilizing a specialized algorithm to adapt to gait patterns, promoting a more natural walking experience. This technology is especially beneficial for stroke patients, as walking ability is a major quality of life predictor post-stroke. The suit features eight high-density electromyography sensors positioned on key muscles, allowing for real-time responsiveness to the user's movements, crucial for initiating steps. Insurance coverage for the device is becoming more common, as research demonstrates reduced rehabilitation times and enhanced at-home exercise quality. Case studies show effectiveness across various severity levels, with notable improvements in walking distance, speed, and symmetry after just a few sessions. Patients often achieve greater independence in daily activities with reduced support. The technology enhances rehabilitation by promoting timing, coordination, and duration of lower limb movements, aligning with the focus on high-intensity, task-specific gait training. Treatment aims should include steadily increasing the number and quality of steps taken. Therapists require extensive experience to optimize patient training and maximize device benefits. Pre-session tasks, like material selection and alignment measurement, can be streamlined to save time. Patients should wear specialized clothing before device application, and individualized goals should be developed to enhance the understanding of therapy processes. Initial training sessions should be limited to 30 minutes to prevent fatigue that impacts gait. Exercises may be conducted on each leg separately, with at least two therapists present for safety and software operation. Careful adjustment of the device is necessary to avoid muscle cramps and maintain exercise confidence. Exercises should gradually progress in difficulty to encourage neurological improvement while preventing pressure sores, especially on critical points. The complexity of the device demands high spatial awareness from the therapist to adapt to patient movements. To combat the fear of falling, therapists should acclimatize patients to longer strides while considering environmental factors that can affect device use. Overall, the device serves as a versatile tool for simulating real-world scenarios and challenges in rehabilitation [28, 29].

CONCLUSION

Robotics is playing a transformative role in rehabilitation therapy by enhancing recovery for patients with physical impairments. The integration of automation, AI, and sensor-based technology is improving rehabilitation outcomes through personalized, data-driven approaches. While cost, accessibility, and ethical considerations remain challenges, ongoing research and technological advancements are addressing these barriers. The expansion of tele-rehabilitation and remote monitoring is making robotic-assisted therapy more accessible, ensuring consistent and effective patient care. As innovation continues, rehabilitation robotics will become a fundamental component of modern healthcare, significantly improving the quality of life for individuals requiring physical and neurological rehabilitation.

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CITE AS: Tugonza Akiro F. (2025). The Role of Robotics in Rehabilitation Therapy. Newport International Journal of Research in Medical Sciences, 6(2):202-209
https://doi.org/10.59298/NIJRMS/2025/6.2.202209