JOURNAL OF ARTIFICIAL INTELLIGENCE AND ROBOTICS
Jan-Mar 2025, VOL. 2, ISSUE 1, pp. 15-17
https://doi.org/10.61577/jaiar.2025.100005

RESEAPRO JOURNALS

SHORT COMMUNICATION

OPEN ACCESS

Robotics and spinal stimulation: A synergistic approach to restoring movement in paralysis

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ABSTRACT

Paralysis, often resulting from spinal cord injury (SCI), severely impairs voluntary motor control and functional independence. Despite advances in rehabilitation, regaining substantial locomotor ability remains a challenge for many individuals with SCI. Emerging technologies such as robotic exoskeletons and epidural electrical stimulation (EES) of the spinal cord have shown promise independently, but recent interdisciplinary innovations are revealing that their integration could offer transformative solutions. Robotic-assisted gait training has been instrumental in enabling repetitive, task-specific movement patterns, which promote neuroplasticity. Concurrently, targeted spinal cord stimulation has been demonstrated to modulate the excitability of spinal circuits below the injury site, facilitating voluntary control and enhancing residual neural activity. Recent clinical and preclinical studies have explored the synergistic impact of combining robotic systems with spinal stimulation to restore complex motor functions, particularly walking. These hybrid neurotechnologies leverage the mechanical support and feedback from robotics with the physiological modulation of neural circuits provided by EES. Evidence from trials in both animal models and human subjects indicates significant improvements in voluntary movement, trunk stability, and gait coordination when both systems are employed simultaneously. This communication provides an overview of themechanistic basis, technological advancements, and clinical outcomes associated with the integration of robotics and spinal stimulation for movement restoration. It also discusses recent breakthroughs including AI-enabled adaptive stimulation, real-time biomechanical feedback loops, and implantable brain-machine-spine interfaces. Ethical, accessibility, and regulatory challenges surrounding these therapies are also considered. While challenges remain in scaling and personalizing these approaches, the confluence of robotics and neuromodulation is poised to redefine the rehabilitation paradigm for individuals with paralysis. Ultimately, this integrated approach not only revives dormant pathways but also offers renewed hope for independence and improved quality of life.

KEYWORDS

Spinal cord stimulation; Robotic exoskeletons; Neurorehabilitation; Paralysis recovery; Brain machine interface

ARTICLE HISTORY

Received 17 February 2025; Revised 10 March 2025; Accepted 17 March 2025

Introduction

Spinal cord injury (SCI) continues to be one of the most devastating neurological conditions, leading to permanent or partial loss of motor, sensory, and autonomic functions below the level of injury [1]. The global incidence of SCI is estimated at 40 to 80 cases per million population per year, with millions living with its long-term consequences. Traditionally, rehabilitation has relied on physical therapy and assistive devices, aiming to maximize residual function and compensate for loss [2]. However, recent technological progress has begun to challenge the assumption that functional recovery is limited to compensation alone.

Two of the most promising and rapidly advancing modalities in this space are robotic assistive devices and spinal cord stimulation. Robotic technologies, particularly wearable exoskeletons, have allowed individuals with complete and incomplete SCI to stand and walk under supervised conditions [3]. Separately, epidural electrical stimulation (EES) has reawakened spinal neural circuits, enabling voluntary movement even in individuals previously thought to have complete paralysis. Recent breakthroughs lie in the integration of these technologies—combining the precision and adaptability of robotics with the neuromodulatory effects of spinal stimulation to create a closed-loop system for locomotor restoration.

This communication outlines recent developments in this hybrid therapeutic approach, supported by clinical studies, animal model research, and cutting-edge engineering innovations. We discuss how robotics and spinal stimulation work synergistically to promote motor recovery, their mechanisms of action, and the future directions of this field. This holistic synthesis reflects the emerging reality that robotics and spinal stimulation are not merely parallel interventions but mutually reinforcing components of a new neurotechnological frontier.

Mechanisms of Spinal Stimulation in Motor Restoration

Spinal stimulation, especially EES, works by modulating the

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excitability of spinal circuits below the lesion [4]. These circuits, known as central pattern generators (CPGs), are capable of producing rhythmic motor outputs such as walking even in the absence of supraspinal input [5]. In individuals with SCI, although descending commands from the brain may be impaired or interrupted, the intrinsic circuitry in the lumbosacral spinal cord often remains intact but dormant. EES delivers continuous or patterned electrical pulses through implanted electrodes over specific spinal segments, reactivating these latent circuits.

Stimulation does not directly cause muscle contractions; rather, it increases the responsiveness of the spinal cord to residual signals from the brain or afferent input from the limbs [6]. This neuromodulation creates a state of "electrical permissiveness" that enables voluntary control, particularly when synchronized with external sensory feedback. Furthermore, recent work has shown that spatiotemporal modulation of stimulation, tailored to gait phases, enhances coordination and motor output.

Beyond EES, transcutaneous spinal stimulation (TSS), a non-invasive modality, has also been investigated. Though it offers lower precision, it holds potential for broader accessibility and initial screening for implant suitability. Both EES and TSS have demonstrated neuroplasticity-promoting effects when combined with locomotor training, creating long-term improvements in motor control [7].

Robotics in Neurorehabilitation

Robotic exoskeletons have transformed rehabilitation by enabling repetitive, task-specific, and intensive training, which are crucial for motor recovery. These devices, such as ReWalk, EksoGT, and HAL (Hybrid Assistive Limb), provide mechanical support to facilitate movements like standing, stepping, and sitting, guided by pre-set or adaptive control algorithms [8]. These systems also serve as a platform for collecting kinematic, kinetic, and neuromuscular data, which can inform real-time adjustments and progress tracking. By reducing therapist burden and allowing high-volume training, robotic gait devices improve patient engagement and training intensity. Importantly, robotics contribute to errorless learning environments, minimizing compensatory movements that could hinder true recovery [9].

Despite these advantages, exoskeletons alone have limited efficacy in promoting neuroplastic changes when used without neuromodulatory inputs [10]. Their role, therefore, is evolving from mere mechanical facilitators to components of integrated neuromodulatory systems.

The Synergistic Integration of Robotics and Spinal Stimulation

The integration of robotics and spinal stimulation represents a convergence of engineering and neuroscience aimed at restoring function rather than compensating for loss [11]. When combined, these systems create a feedback loop where robotic-assisted movement provides proprioceptive input to the spinal cord, while spinal stimulation amplifies the spinal cord's responsiveness to that input [12]. This synergy allows for partial voluntary control to emerge even in individuals previously considered "motor complete." Groundbreaking studies have demonstrated the power of this approach. A 2022 Nature Medicine study by Courtine and colleagues highlighted three individuals with complete paralysis who regained the ability to walk with assistance after receiving spatiotemporally patterned spinal cord stimulation paired with robotic support. This combination also facilitates more precise targeting and calibration of stimulation protocols, guided by biomechanical data from robotic systems. Such real-time data can inform adaptive algorithms that personalize therapy to each individual's motor capabilities, maximizing efficacy.

Brain-Machine-Spinal Interfaces: A New Frontier

A transformative advancement in this field is the development of brain-machine-spinal interfaces (BMSIs), which decode motor intentions from cortical activity and relay them to the spinal cord via stimulation [13]. This approach bypasses the lesion site entirely, using brain signals to directly control spinal circuits responsible for locomotion.

In a recent clinical breakthrough reported in 2023, researchers successfully implemented a wireless BMSI in a human subject with chronic tetraplegia. The interface decoded movement intentions from a subdural cortical implant and transmitted them to a spinal pulse generator, enabling volitional movement of paralyzed limbs [14]. The patient achieved improved walking stability and voluntary control, a result unattainable with stimulation or robotics alone. BMSIs offer unprecedented potential to reintegrate cognitive intention with motor output, restoring the sense of agency in movement. While still experimental, these systems represent the next stage of neuromodulatory robotics.

fMRI-Based Deep Learning Models for Lie Detection

fMRI provides high spatial resolution imaging of brain activity, making it a valuable tool for identifying deception-related neural activation patterns [15]. Deep learning techniques have been applied to analyze fMRI data, extracting relevant features for deception classification.

Clinical Outcomes and Rehabilitation Protocols

Clinical protocols integrating robotics and spinal stimulation typically involve intensive, multi-week sessions focused on standing, stepping, and walking. Patients undergo initial mapping of motor responses to determine optimal stimulation sites and parameters. Robotic systems then guide movement while stimulation is applied, with progressive increases in voluntary effort encouraged.

Outcomes from such protocols include improved gait symmetry, enhanced trunk stability, and increased lower limb strength. Functional Independence Measures (FIM), 10-Meter Walk Test (10MWT), and electromyographic recordings show sustained improvements over baseline [16]. Importantly, many participants retain some motor gains even after stimulation sessions cease, suggesting underlying neuroplasticity. However, these outcomes vary significantly depending on injury level, chronicity, and patient-specific factors, underscoring the need for personalized approaches. Current research is focused on optimizing these protocols for broader applicability and long-term benefit.

https://doi.org/10.61577/jaiar.2025.100005

Challenges and Limitations

Despite promising results, several challenges remain. Spinal stimulation requires surgical implantation, posing risks and limiting its adoption. Device costs and the need for multidisciplinary teams constrain scalability. Additionally, not all patients respond equally, and mechanisms behind differential outcomes are not fully understood. From a technical perspective, synchronizing robotic movement with stimulation in real-time demands high precision. Latency in signal transmission or mismatched timing can reduce therapeutic benefit. Moreover, the psychological burden on patients adapting to complex assistive technologies must be considered. Ethical concerns also arise regarding autonomy, consent, and access. These technologies raise questions about identity, enhancement versus restoration, and long-term dependency on external devices. Ensuring equitable access is essential to prevent widening health disparities.

Future Directions

The future of robotic and spinal stimulation integration lies in adaptive, intelligent systems that learn from patient responses and adjust stimulation patterns and robotic assistance accordingly. Artificial intelligence (AI) and machine learning are increasingly employed to enhance personalization, predict outcomes, and optimize training intensity.

Advances in biomaterials and electrode miniaturization may enable less invasive stimulation techniques. Wireless systems are under development to reduce hardware burden. Meanwhile, closed-loop BMSIs integrating visual, vestibular, and proprioceptive feedback are pushing the boundaries of what's possible. Collaboration across neuroscience, engineering, and rehabilitation medicine will be vital to translate these innovations into scalable, effective therapies. Regulatory frameworks must evolve to support rapid yet safe adoption, and funding models must adapt to accommodate high-cost, high-reward interventions.

Conclusions

The integration of robotics and spinal stimulation represents a paradigm shift in the treatment of paralysis, transforming previously passive patients into active participants in their own recovery. These hybrid systems go beyond compensation to foster true neurological recovery by reengaging dormant circuits, enhancing sensory-motor feedback loops, and, in some cases, restoring volitional control. While hurdles remain in terms of accessibility, affordability, and scalability, the pace of advancement is accelerating, driven by interdisciplinary innovation and patient-centered design. Continued investment in this field will not only expand therapeutic options but also redefine what is considered possible for individuals living with paralysis. As these technologies mature, they hold the promise of restoring movement, independence, and dignity to millions worldwide.

Disclosure statement

No potential conflict of interest was reported by the authors.

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https://doi.org/10.61577/jaiar.2025.100005