TECHNOLOGICAL INNOVATIONS IN VERTICALIZATION AND POSTURAL CONTROL FOLLOWING SPINAL CORD INJURY

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ABSTRACT

Spinal injuries represent a significant public health concern, causing severe impairments in bodily functions, including disrupted postural control and the loss of the ability to maintain an upright position. These functional difficulties substantially affect patients' quality of life and their engagement in daily activities. Traditional rehabilitation approaches often demonstrate limited effectiveness in achieving functional recovery. Consequently, recent years have witnessed rapid advancements in technological innovations within the rehabilitation process for spinal injuries. The integration of robotic systems, wearable technologies, and neurostimulation, presents new opportunities for improved therapeutic outcomes. These innovations not only enhance the precision of therapy but also enable personalized approaches tailored to the specific needs of each patient. Particular emphasis is placed on technological advancements that facilitate verticalization and improve postural control, as these functions are crucial for maintaining balance and participating in everyday activities. This paper aims to present and analyze some of the technological innovations in the rehabilitation of individuals with spinal injuries, with a particular focus on verticalization and postural control. Future research should concentrate on optimizing technological solutions, developing personalized therapeutic approaches, and ensuring accessibility to maximize functional benefits for individuals with spinal injuries.

Keywords: technological innovations, verticalization, postural control, spinal cord injury
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INTRODUCTION

Spinal cord injuries (SCI) represent severe damage to the spinal cord and/or the surrounding structures that support the spine. The most common causes of SCI are traumatic incidents, including motor vehicle accidents, falls from heights, sports injuries, diving accidents, physical violence, penetrating wounds from sharp weapons, and war-related injuries (mines, explosions). Non-traumatic causes include tumors, infections (meningitis, encephalitis), sports injuries, and degenerative conditions such as disc herniation and spinal canal stenosis. The severity of these injuries ranges from mild to severe, potentially resulting in permanent disability or death. Individuals with SCI often present with complete or incomplete injuries at various levels of the spinal cord, leading to sensory and motor impairments, limitations in physical activities, and reduced participation in family and community life. SCI can be classified using various criteria, with the most common being the *American Spinal Injury Association* (ASIA) Impairment Scale, which ranges from A (complete injury) to E (normal neurological function) (Table 1) (1).

Table 1. *Spinal Cord Injury Assessment Scale**

Grade	Type of Injury	Description of Injury
A	Complete	No sensory or motor function is preserved in sacral segments S4-S5, no sacral sparing
B	Sensory Incomplete	Sensory but not motor function is preserved below the neurological level and includes sacral segments S4-S5, AND No motor function is preserved more than three levels below the motor level on either side of the body
C	Motor Incomplete	Motor function is preserved below the neurological level AND More than half of the key muscle functions below the neurological level of injury has a muscle grade of less than 3 (Grades 0-2)
D	Motor Incomplete	Motor function is preserved below the neurological level AND At least half (half or more) of the key muscle functions below the neurological level of injury has a muscle grade of≥ 3
E	Normal	If sensation and motor function are graded as normal in all segments AND the patient had prior SCI-related deficits *Individuals without a spinal cord injury do not receive an AIS Grade

* According to the Spinal Cord Injury Association of America (*American Spinal Injury Association)*

Depending on the level and extent of neurological impairment, injuries are categorized as tetraplegia/tetraparesis (cervical region) or paraplegia/paraparesis (thoracic and lumbar regions) (1,2). Spinal injuries profoundly impact patients' physical functionality, leading to a loss of independence, including the ability to maintain an upright position and postural control. Verticalization (movement and ambulation) and body stability are among the top five functional recovery priorities for individuals with SCI, regardless of the severity or level of injury. Consequently, postural control and achieving an upright body position are essential to physiotherapeutic interventions in SCI rehabilitation. In recent years, technology has increasingly been integrated into physiotherapy through the development of novel devices and methods designed to facilitate the rehabilitation process. These advancements include robotic systems, smart and wearable technologies, advanced sensors, and electrical stimulators that assist patients in restoring functionality, maintaining balance, and preventing complications such as respiratory conditions, changes in muscle tone, osteoporosis, and pressure ulcers (3,4). Although many of these technologies are still in the developmental and implementation phases, their application in routine SCI rehabilitation promises significant improvements in patients' quality of life. Moreover, future technological advancements are expected to offer even greater opportunities for innovation in SCI rehabilitation.

Verticalization and Postural Stability

Verticalization is how a patient transitions from lying to an upright position. It represents a critical function that many patients with spinal cord injuries either completely lose or experience a significant reduction in. This ability is a physical challenge and carries multiple health implications. For individuals with SCI, verticalization is essential for improving circulation, preventing pressure ulcers, reducing the risk of osteoporosis, and avoiding other complications associated with inactivity (5,6). Given its importance in rehabilitation, the development and application of technologies that enable safer and more effective verticalization have become fundamental in the physiotherapy of individuals with partial or significant motor impairments. The development of robotic devices, such as exoskeletons, allows patients with lower limb paralysis or severe spinal column injuries to achieve an upright position and/or walk. These systems are typically based on mechanical frameworks equipped with motors and sensors. Postural control involves the ability to maintain balance and body position in space and is essential for independence (7,8). Among individuals with spinal cord injuries, loss of muscle strength, altered sensation, the presence of spasms, and other pathological changes can severely impair balance and postural control, not only while standing but also while sitting. These difficulties prevent patients from performing basic daily activities such as dressing, eating, personal hygiene, and transfers. Consequently, rehabilitation interventions aimed at improving balance in either a sitting or standing position are crucial for achieving essential functional goals in individuals with SCI (9,10). Technological advancements, such as sensor systems capable of detailed body movement analysis, enable precise real-time monitoring of patient posture. This capability is particularly valuable in physiotherapeutic interventions, where therapists can identify and correct unconscious compensatory movement patterns in patients. Additionally, technological devices such as muscle stimulators, through the application of electrical stimulation, promote the activation of paralyzed muscles, thereby enhancing body stability and improving balance (11). Innovative approaches and technologies not only facilitate the restoration of physical abilities but also improve the psychological well-being of patients by restoring a sense of control over their bodies, thereby enabling greater independence and autonomy.

ROBOTIC TECHNOLOGY

In recent decades, robotic technologies have been developed to provide more effective support to clinicians during the rehabilitation process of individuals with spinal cord injuries (SCI). Technologies that facilitate verticalization and postural stability for SCI patients are based on various technological innovations. In practical applications, these technologies refer to any mechatronic device with a certain capacity to assess sensorimotor functions and train the human brain through physical intervention aimed at improving patients' quality of life (12). Robotics remains in a developmental and innovative phase, with ongoing efforts to create robotic systems that play specific roles in physiotherapeutic interventions during SCI rehabilitation. Currently, the most well-known technologies include various robotic and/or wearable devices (exoskeletons) and smart wearable technologies that integrate electrical stimulation. These systems enable patients to position their bodies upright, even when paralyzed or suffering from severe spinal injuries. A wide range of robotic devices is currently in use, each designed with the primary goal of enhancing functional capabilities. These devices are broadly categorized into two main groups. The first group consists of simpler robots that control only a single limb or a part thereof. The second group comprises exoskeletons, which are more complex as they control entire limbs and are designed with multiple joints, motors, and sensors. The fundamental objective of both categories is to enable the active participation of patients in performing movements and tasks essential to daily living activities (11,12,13). Technological support for verticalization and postural stability has a significant impact on rehabilitation outcomes for individuals with SCI. The development and application of various wearable devices, electrical stimulation, and robotic systems offer patients the possibility of achieving a level of physical functioning and independence that was previously unimaginable. Although certain challenges remain, the future of technology aimed at improving verticalization and postural stability for SCI patients promises advanced solutions that will enhance patients' quality of life and enable better integration into personal and broader social environments (14,15).

Upper Extremity Robotics

One of the earliest robots designed for the control of distal segments of the upper extremities is the MIT Manus, which has been in operation since 1994 and belongs to the category of segmental robots for the rehabilitation of impaired upper extremities. This system enables active, passive, and active-assisted movements in the shoulder, elbow, and hand joints. Using its integrated 6-degree-of-freedom force sensor provides physiotherapists with the ability to monitor the direction of movements and the amount of force exerted by the patient during specific tasks while ensuring postural control in a seated position and minimizing compensatory movements (16). A significant limitation of this type of robot is its ability to perform movements only in two dimensions, whereas everyday activities typically require three-dimensional movement patterns. Furthermore, the hand remains in a flexed finger pattern throughout the therapy, which can lead to contractures and weakening of the muscles responsible for hand opening (17). Other systems, such as ARMin III, IntelliArm, Braccio di Ferro, and In Motion WRIST, share similar limitations as they only control the distal segment of the body without managing the entire kinematic chain (14,18). In recent years, more complex and sophisticated exoskeletons for the upper extremities have been developed, capable of detecting and analyzing the patient's intention to move using surface electromyography (sEMG) and electroencephalography (EEG) (19,20,21). One notable example is WristBot, developed in 2019 at the Laboratory for Motor Learning, Assistive, and Rehabilitation Robotics of the Italian Institute of Technology (IIT). This end-effector device was designed to rehabilitate patients with neurological and/or orthopedic impairments of the wrist and elbow joints. WristBot enables movement in three dimensions, offering a range of motion closest to the physiological movement typical of human subjects. Additionally, it allows for the application of auxiliary oscillatory forces that automatically adapt to the patient's performance. The integrated graphical interface enables physiotherapists to select desired exercises and continuously adjust the activities based on the patient's personalized needs. The system's integration with a virtual environment further provides patients with visual feedback on the effectiveness of assigned activities (17). This feature also supports applications in everyday life activities, ensuring postural control during task execution.

Wearable Robotic Devices and Smart Systems

Robots and exoskeletons (wearable robotic devices) represent one of the most significant innovations in rehabilitating spinal cord injuries (SCI). Wearable devices equipped with advanced sensors can analyze specific patient body movements, including standing, posture, walking, and movements of both upper and lower extremities. These data provide biomechanical movement analysis for patients undergoing SCI rehabilitation and help identify abnormalities or compensatory mechanisms during activities. This allows physiotherapists to correct patient errors, ultimately reducing the risk of recurrent injuries. This technology represents an exceptionally important and rapidly growing field in SCI applications, offering greater mobility and independence. Furthermore, wearable devices such as clothing-integrated sensors and/or smart wristbands utilize biometric data to monitor key physiological parameters in patients, including blood pressure, respiration, heart rate, body temperature, muscle activity, and movement. This enables physiotherapists to analyze real-time data, recognize signs of fatigue or poor postural alignment, and make timely adjustments to physiotherapy interventions during patient activities. These devices can be applied to the patient's body in the form of exoskeletons, sensors, orthoses, and other similar technologies, allowing individuals with SCI to regain lost functions caused by spinal cord damage (22, 23). Wearable devices that assist with verticalization and body stability in spinal cord injuries encompass various technologies that enable individuals with SCI to stand upright, walk, and maintain stability and balance with the support of external devices. Some of the most commonly used examples specifically designed to improve verticalization and postural stability include exoskeletons equipped with external frames, motors, sensors, and computer systems. These devices enable SCI patients to stand independently, walk, and perform other essential movements with external support. The term "exoskeleton" originates from the Greek words *exo* (meaning external) and *skeleton* (meaning skeleton). In the context of assistive technology, an exoskeleton serves as a body armor that provides support to the limbs during movement. When attached to a patient's body, it allows them to stand, walk, and even perform basic movements (24, 25). These devices often utilize electric motors to generate movement in the legs and other body parts, enabling patients to stand upright, walk, and even use stairs, thereby significantly enhancing their quality of life. In addition to facilitating verticalization, exoskeletons contribute to more active rehabilitation through movement, which helps reduce the risk of muscle atrophy and stimulates better circulation (26).

In a study by Tarnacka et al. (2023), conducted at the Research Institute for Innovative Rehabilitation Methods for Patients with Spinal Cord Injuries in Poland, exoskeleton devices such as the *EKSO-GT* model *EKSO 1* and the *Lokomat-pro* model *LO2018* were used. A physiotherapy program administered by a "blinded researcher" physiotherapist demonstrated the superior benefits of these technological devices compared to traditional movement-based interventions, particularly for patients with incomplete SCI (optimal candidates being patients with ASIA-C classification) in contrast to those with complete SCI (27).

The EksoGT exoskeleton enables users to stand and/or walk. It is designed for individuals with spinal cord injuries (paraplegia and tetraplegia), providing substantial stability during walking while promoting natural leg movements (22,23). In contrast to the EksoGT exoskeleton, although not a fully wearable device, Lokomat is a robotic system that utilizes robotic legs to facilitate gait training for patients with spinal cord injuries. It provides support for body stability and balance, assisting in verticalization and relearning walking movements in a therapeutic setting (28, 29, 30). Similar findings have been confirmed in other studies that examined the use of another well-known exoskeleton device, ReWalk, among participants with chronic SCI who were wheelchair users (31-33). This device employs motorized and mechanical systems to support the lower extremities, granting patients greater autonomy not only in walking but also in ensuring safer transfers (34-36).

In addition to robotic devices designed for walking, some devices enable spinal cord injury (SCI) patients to maintain an upright position. These devices are often lighter than exoskeletons and are designed with supportive braces, belts, and/or frames equipped with motors and sensors for body guidance and stabilization. They incorporate technology that monitors balance and stability, automatically adjusting the patient's body position. In some cases, these devices can also stimulate muscles to enhance movement control and maintain an upright posture. One such device is the THERA-Trainer balo, which features a unique support frame designed to ensure patient safety in an upright position. It is equipped with a patented balance unit that enables both static and dynamic standing, allowing for controlled weight shifting and targeted postural control training for SCI patients who are unable to stand independently. Additionally, thanks to its integrated electric lift system, patients can be easily and safely transitioned to an upright position directly from a wheelchair (37,38,39). Smart systems refer to innovative technologies that integrate smart sensors and other advanced technologies to monitor patients during rehabilitation. These systems can track an individual's physical condition, analyze mobility data, muscle activity, and postural changes, and provide real-time feedback. Additionally, they can be connected to computer systems and/or mobile applications, allowing both patients to monitor their progress and physiotherapists to adjust rehabilitation interventions according to individualized goals (40,41). Smart systems can assist individuals with tetraplegia or paraplegia in performing daily activities such as sitting, dressing, transferring from a bed to a wheelchair, and returning to bed. They also enable early detection of issues related to postural changes, muscle tone, and circulation, thereby reducing the risk of further complications associated with SCI (42). Biometric sensors, such as electromyography (EMG) devices, provide insights into the electrical activity of muscles, allowing for the assessment of muscle activation during physiotherapy interventions and daily activities. This tracking of muscle activity helps in identifying weakness or discomfort, enabling physiotherapists to tailor rehabilitation strategies to the patient's specific needs. Furthermore, biometric sensors, such as electroencephalography (EEG) devices, can monitor brain waves, offering insights into brain activity in neurologically impaired patients, including those with spinal cord injuries. This data can help both patients and physiotherapists understand how the brain responds to certain activities, guiding a more optimized and effective rehabilitation plan (43,44).

Systems for Electrostimulation and Muscle Activation

Electrostimulation is becoming increasingly important in the rehabilitation of spinal injuries because it enables the activation of paralyzed muscles. By using electrical impulses that stimulate the nerves in the muscles, it is possible to restore a certain degree of function in paralyzed limbs. When electrical stimulation is used in conjunction with robotic devices, it can help patients achieve a greater degree of mobility and independence during verticalization, allowing them to stabilize the body and maintain a vertical position for longer periods. To achieve better balance in the upright position and postural control of the trunk in the sitting position, various electrostimulation modalities are also applied. The goal of electrostimulation systems is to activate individual muscles or entire neural networks in the area of injury. The purpose is to achieve better postural adaptation and control over body stability (45). It allows people with SCI to remain upright by working on muscle tone, balance, and coordination. One example is the functional neuromuscular stimulation (FES) device, which is used to activate the muscles of the lower extremities, thereby enabling control over maintaining a vertical position, stabilizing the body, and/or walking (46,47,48).

Spinal cord stimulation is a treatment method in which the spinal cord is exposed to electrical stimulation using a non-invasive method (transcutaneous stimulation tSCS) or invasive (epidural stimulation eSCS). In the epidural, pulse generators, stimulation leads, and a cable to connect the lead to the generator are implemented, while surface electrodes are used in transcutaneous stimulation. Based on the theory of pain control, the first such device was designed in 1968 (49-51). The results of studies conducted in patients with SCI, undergoing epidural stimulation surgery indicate significant improvements in motor and autonomic functions (52,53). A systematic review (Denac, 2023), in which 75 papers were analyzed, indicates that both transcutaneous spinal stimulation and epidural spinal stimulation in SCI are used for the stated purpose. Most of the conducted studies were focused on the recovery of the function of the upper limbs and trunk after injury with observed positive results in terms of postural stability and control of the trunk. However, emphasis was placed on a very small number of participants, suggesting that further research with larger samples is necessary to optimize performance in individuals with SCI (54). Likewise, for the use of electrostimulation modalities, it is very important to know the level of injury. For example, people with cervical spine injury have more pronounced problems in maintaining verticalization and postural stability due to reduced hand function compared to people with lower levels of SCI (55).

CONCLUSION

The use of innovative technology aimed at verticalization and postural control provides numerous advantages, both in the physical and psychological recovery of patients with SCI. Returning to an upright position and the ability to stand and/or walk increases the patient's motivation and sense of self-confidence by achieving a greater level of independence in activities of daily living, as well as a greater degree of independence. Given that their technological characteristics promote neuroplasticity (a process in which the brain creates new neural connections), their stimulation and repetition of movements can help activate the nerve pathways responsible for muscle movement. Likewise, they reduce the physical effort that the patient has to exert to perform basic movements, which allows patients to perform exercises for a longer period without excessive fatigue, thus reducing the physical effort of the physiotherapist and improving the quality of physiotherapy. Although technological innovations provide significant benefits in SCI rehabilitation, there are also certain challenges.

The high production and maintenance costs are still too high for widespread use, which may limit their availability, especially in less developed countries and/or in smaller healthcare facilities. Although in terms of use, many systems have become simpler today, their installation and adaptation for use require specific knowledge and education of physiotherapists. Furthermore, their adaptation to the patient's physical needs can also be very challenging, as some patients may feel discomfort during use due to the strength and/or weight of the devices themselves. Work on improving the aforementioned components and adaptability is a key challenge for the wider application of these technologies, especially for patients with various SCI, which will contribute to their independence, and mobility, as well as reduce the need for constant assistance and enable them to integrate more easily into social activities.

GENERATIVE AI STATEMENT

Artificial Intelligence (AI) tools were not used in the preparation of this manuscript. The authors remain responsible for the content's integrity and originality.

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TEHNOLOŠKE INOVACIJE U VERTIKALIZACIJI I POSTURALNOJ KONTROLI NAKON SPINALNE OZLJEDE

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SAŽETAK

Spinalne ozljede predstavljaju značajan javnozdravstveni problem uzrokujući ozbiljna oštećenja tjelesnih funkcija, uključujući i narušenu posturalnu kontrolu i gubitak sposobnosti održavanja okomitog položaja. Ove funkcionalne poteškoće značajno utječu na kvalitetu života pacijenata i njihov angažman u aktivnostima svakodnevnog života. Tradicionalni pristupi u rehabilitaciji često imaju ograničenu učinkovitost u postizanju funkcionalnog oporavka, stoga posljednjih godina svjedočimo brzom razvoju tehnoloških inovacija u rehabilitacijskom procesu spinalnih ozljeda. Primjena robotskih sustava, nosivih tehnologija i neurostimulacije otvaraju nove mogućnosti u postizanju boljih terapijskih ishoda. Ne samo da osiguravaju precizniju terapiju, već omogućuju i personalizirane pristupe koji uzimaju u obzir specifične potrebe svakoga pacijenata. Posebna važnost pridaje se tehnološkim inovacijama koje omogućuju vertikalizaciju i poboljšanje posturalne kontrole, jer su te funkcije ključne za održavanje ravnoteže i sudjelovanje u svakodnevnim aktivnostima. Cilj ovog rada je predstaviti i analizirati neke od tehnoloških inovacija u rehabilitaciji osoba sa spinalnim ozljedama, s naglaskom na vertikalizaciju i posturalnu kontrolu. Daljnja istraživanja trebala bi se fokusirati na optimalizaciju tehnoloških rješenja, personalizirani terapijski pristup kao i dostupnost kako bi se postigla maksimalna funkcionalna korist za osobe sa spinalnom ozljedom.

Ključne riječi: tehnološke inovacije, vertikalizacija, posturalna kontrola, spinalna ozljeda

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