Article

Neuromuscular Electrical Stimulation Combined With Rehabilitation Training Improves Rehabilitation After Spinal Cord Injury

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AIM: Spinal cord injury (SCI), particularly traumatic spinal cord injury (TSCI), is a globally prevalent neurological condition and often causes severe functional and physical disabilities. Neuromuscular electrical stimulation (NMES), when combined with rehabilitation training, has been reported to enhance functional recovery in patients with SCI. However, its specific clinical advantages and safety profile require further validation through robust empirical data. Therefore, this study aims to investigate the synergistic effects of NMES combined with rehabilitation training on improving motor function and reducing muscle atrophy in SCI patients.
METHODS: This retrospective study enrolled 856 patients with TSCI. All patients received either surgical intervention or conservative treatment based on injury severity. Among them, 472 patients received NMES combined with rehabilitation training (intervention group), while the remaining 384 patients received rehabilitation training alone (control group). Several parameters, including neurological function score, muscle mass, and quality of life (QoL) were compared pre- and post-interventions to evaluate the rehabilitation outcomes of the two groups.
RESULTS: After treatment, the patients in the intervention group showed higher motor and sensory function scores (American Spinal Injury Association [ASIA] motor and ASIA sensory scores), walking speed on the 10-Meter Walk Test (10MWT), and muscle cross-sectional area (CSA) value than those in the control group ($p < 0.05$). However, no significant differences were observed between the two groups in Spinal Cord Independence Measure III (SCIM-III) scores, muscle quality index (MQI), and World Health Organization Quality of Life–Brief Version (WHOQOL-BREF) scores ($p > 0.05$).
CONCLUSIONS: Combining NMES with rehabilitation training can enhance motor function recovery, attenuate muscle atrophy, and improve walking ability in individuals with SCI. NMES-augmented rehabilitation offers superior benefits compared to rehabilitation alone.

Keywords: neuromuscular electrical stimulation; rehabilitation training; spinal cord injury; quality of life

Introduction

Spinal cord injury (SCI) is a chronic neurological condition that leads to significant motor, sensory, and autonomic dysfunction [1]. Its complex pathophysiology involved the interaction of primary mechanical damage and secondary injury pathways and poses substantial challenges to effective rehabilitation and functional recovery [2,3]. Although acute care and timely medical management have advanced, long-term disease outcomes remain inadequate, with many patients experiencing chronic disability and reduced quality of life [4]. This highlights the urgent need for novel neurorehabilitation approaches that utilize neuroplasticity to enhance neurological restoration and improve long-term prognoses in SCI research.

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Neuromuscular electrical stimulation (NMES) is increasingly recognized as a viable adjunct in the rehabilitation of patients with SCI. By delivering controlled electrical impulses to targeted muscle groups, NMES induces muscle contractions and facilitates motor learning. Its therapeutic effects are mediated through multiple pathways, including modulation of spinal cord excitability, activation of sensory afferents, and promotion of activity-dependent neuroplasticity [5]. At the molecular level, NMES has been reported to upregulate mRNA expression of several key biological factors, such as myosin regulatory light chain interacting protein (MYLIP), vascular endothelial growth factor A (VEGFA), and Glial cell line-Derived Neurotrophic Factor (GDNF), which play crucial roles in neuronal survival, axonal regeneration, and synaptic plasticity [6]. Furthermore, NMES confers substantial musculoskeletal and cardiopulmonary benefits, including attenuation of disuse muscle atrophy via inhibition of muscle RING-finger protein-1 (MuRF-1), preservation of type II muscle fiber cross-sectional area, and enhanced cardiopulmonary function through improved venous return and cardiac preload [7].

In SCI management, NMES plays a vital role across all phases of recovery. During the acute phase (<6 weeks post-injury), it helps prevent muscle atrophy, maintain joint mobility, and reduce the risk of secondary complications such as pressure ulcers and contractures. In the subacute (6 weeks–6 months) and chronic (>6 months) phases, NMES can be incorporated into comprehensive rehabilitation programs to support motor relearning, improve gait patterns, and enhance upper limb function [8]. Functional electrical stimulation (FES) systems, which integrate NMES with orthotics devices and sensor-based feedback, have revealed advantages in improving walking speed, endurance, and balance in individuals with incomplete SCI [9].

Rehabilitation training remains central to SCI management, encompassing a wide range of interventions aimed at optimizing functional recovery. Traditional rehabilitation modalities, including physical and occupational therapy, focus on task-oriented training, progressive resistance exercises, and compensatory strategies to improve independence in daily activities. Recent neurorehabilitation approaches incorporate advanced technologies such as body-weight-supported treadmill training (BWSTT) and robot-assisted gait training (RAGT), which apply principles of activity-dependent neuroplasticity through intensive, task-specific, and repetitive practice to promote neural adaptation and functional improvement [10,11].

Integrating NMES with rehabilitation training offers the potential for synergistic effects and enhances functional outcomes in SCI. Combining the neurophysiological effects of NMES with task-specific, motor learning-based rehabilitation can optimize the engagement of spared neural pathways, support adaptive plasticity, and promote motor function recovery. Several studies have investigated this combined strategy in SCI, reporting promising outcomes. For example, a preliminary study in individuals with SCI demonstrated that 16 weeks of home-based NMES endurance training targeting the knee extensors significantly enhanced skeletal muscle oxidative capacity [12].

While previous studies suggest that integrating NMES with rehabilitation training can enhance recovery of neurological and motor function after SCI, the current evidence remains limited by small sample sizes and short-term follow-up periods. Consequently, the efficacy and safety of this combined approach require validation in large-scale, longitudinal studies. This study aimed to evaluate whether NMES combined with rehabilitation training provides superior functional recovery and muscle preservation compared with rehabilitation alone. We hypothesized that patients receiving the combined intervention would achieve greater improvements in motor and sensory function, walking capability, and muscle cross-sectional area. The findings from this study may help optimize neurorehabilitation strategies and guide the development of evidence-based clinical guidelines for SCI management.

Methods

Study Design and Enrollment of Study Participants

This retrospective study included 856 SCI patients who were treated at the Department of Rehabilitation Medicine, The Second Affiliated Hospital of Wenzhou Medical University between January 2015 and December 2023. Inclusion criteria for patient selection were as follows: adult aged 18–75 years with a confirmed diagnosis of traumatic spinal cord injury (TSCI) supported by radiographic evidence from magnetic resonance imaging (MRI) or computed tomography (CT); American Spinal Injury Association (ASIA) Impairment Scale (AIS) grades C–D; received either surgical or conservative management; completed a minimum 12-week rehabilitation program; and had availability of complete baseline and follow-up functional assessment data. Exclusion criteria included: non-traumatic causes of SCI (neoplastic or vascular); concomitant severe traumatic brain injury or other neurological disorders; uncontrolled cardiopulmonary or metabolic diseases; contraindications to NMES (e.g., pacemakers or deep vein thrombosis); and incomplete outcome data or loss to follow-up.

Patients were divided into 2 groups based on post-treatment rehabilitation approaches: the intervention group, which underwent NMES combined with rehabilitation training (n = 472), and the control group, which received rehabilitation training alone (n = 384).

This study was approved by the Institutional Review Board of The Second Affiliated Hospital of Wenzhou Medical University (Approval No: 2024128). Due to its retrospective design, which involved recorded data from 2015 to 2023, obtaining individual informed consent from all participants was not feasible. The ethics committee granted a waiver of consent on the grounds that: (1) all data were anonymized and de-identified before analysis, ensuring patient confidentiality; (2) the investigation was conducted solely for non-commercial, public health and scientific purposes.

Intervention Protocols

Patients in the intervention group received NMES combined with rehabilitation training, whereas those in the control group received rehabilitation training alone.

During NMES protocol, patients received neuromuscular electrical stimulation using a SysStim 294 four-channel device. Five-centimeter self-adhesive hydrogel electrodes were placed bilaterally over the erector spinae muscles (parallel to T10-L2 spinous processes) and rectus abdominis (periumbilical region). The stimulation protocol had three phases: a 5-minute ramp-up phase with gradual intensity increase, a 30-minute main stimulation phase with cyclic frequency modulation (8 Hz for 8 seconds to induce tonic contraction, 2 Hz for 2 seconds as a rest interval, and 18 Hz for 10 seconds to produce phasic contraction), followed by a 5-minute ramp-down phase. Current intensity was carefully adjusted to produce visible muscle contraction ($\geq$50% of maximum voluntary contraction) while maintaining patient comfort (Visual Analogue Scale [VAS] $\leq$3). The variable-frequency paradigm was designed to prevent muscle fatigue, approximate physiological activation patterns, and enhance corticospinal tract activation through differential firing rates. Continuous impedance monitoring was applied to ensure safety, with an automatic shutdown triggered by abnormal resistance levels.

Rehabilitation training included physical therapy and exercise. Rehabilitation programs were adjusted to each patient's ASIA score and overall functional capacity, ensuring safe, progressive loading. Physical therapy focused on enhancing core muscle strength using dumbbells and resistance bands, while seated and standing balance were trained with parallel bars, walkers, and other supportive devices. Exercise training included activities of daily living (ADL) such as dressing, eating, washing, and toileting; upper- and lower-limb functional exercises (including fine motor activities and flexion–extension and rotational movements); and body-weight-supported gait training using a specialized suspension harness to partially unload body weight. This setup facilitated repetitive, standardized gait practice, activated the spinal central pattern generator, and promoted neural plasticity. Depending on patient tolerance, training sessions were conducted for 30–60 minutes per day, 5 days per week, for a 12-week total period.

Outcome Measures

Baseline Characteristics

Baseline demographic and clinical characteristics were collected from electronic medical records. Collected variables included age, sex, height, and weight, injury types, treatment approaches, and comorbidities such as atherosclerosis, spinal stenosis, neurogenic bladder, osteoporosis, diabetes mellitus, and infection.

Neurological Function Assessments

The ASIA motor score was used to evaluate bilateral upper and lower limb strength through manual muscle testing of key muscle groups (C5-T1/L2-S1 myotomes) using the 6-point Medical Research Council scale (0 = no contraction, 5 = normal strength). The total ASIA motor score (AMS) ranges from 0 to 100, with higher scores indicating greater motor strength. Sensory function was assessed using the ASIA sensory score, which evaluated light touch with a cotton wisp and pinprick sensation with a Neurotip® across 28 dermatomes (C2-S4/5). Each dermatome was scored from 0 (absent) to 2 (normal), and the light-touch and pinprick scores were summed separately and then combined to yield a total sensory score ranging from 0 to 224, with higher scores indicating better overall sensory function [13].

Functional Capacity Measures

Functional independence was evaluated using the Spinal Cord Independence Measure III (SCIM-III) [14], a 19-item clinician-rated scale comprising three domains: self-care (0–20 points), respiration and sphincter management (0–40 points), and mobility (0–40 points), with a total score range of 0 to 100. Walking ability was assessed through the 10-Meter Walk Test (10MWT), in which patients were instructed to walk at their comfortable and maximum speeds along a marked 10-meter track. The time was recorded, and walking speed was calculated in meters per second.

Musculoskeletal Imaging

Muscle morphology was assessed using B-mode ultrasonography with a 12 MHz linear transducer. The cross-sectional area (CSA) and muscle quality index (MQI) of the biceps brachii and rectus femoris were determined.

Quality of Life

Quality of life was evaluated using the World Health Organization Quality of Life–Brief Version (WHOQOL-BREF) questionnaire, containing 26 items distributed across four domains: physical health (7 items), psychological well-being (6 items), social relationships (3 items), and environment (8 items). Responses were converted to a 0–100 scale following WHO guidelines to facilitate standardized comparisons [15].

Statistical Analysis

Statistical analyses were conducted using SPSS 26.0 (IBM Corp., Armonk, NY, USA). Normality of continuous variables was evaluated using the Shapiro-Wilk test and Q-Q plot visualization. Variables following normal distribution were presented as mean $\pm$ standard deviation, and between-group comparisons were performed using independent *t* tests, whereas non-normally distributed variables were reported as median (interquartile range) and analyzed using Mann-Whitney U tests. Categorical variables were expressed as frequencies (percentages) and compared using the chi-square or Fisher's exact tests. A two-tailed p-value < 0.05 was considered statistically significant.

Results

Comparison of Baseline Characteristics Between the Two Groups

Baseline demographic and clinical characteristics were comparable between the intervention and control groups, with no statistically significant differences observed in age, sex distribution, height, or weight. The distributions of injury mechanisms, treatment approaches (surgical vs. conservative), and antibiotic use were also similar between the two groups ($p > 0.05$). Comorbidity profiles, including

Table 1. Comparison of baseline characteristics between the two groups.

Variable	Control group (n = 384)	Intervention group (n = 472)	Test statistic	*p*-value
Age (years)	45 (32, 52)	42 (30, 50)	0.724	0.469
Gender (male)	185 (48.2)	206 (43.6)	2.274	0.125
Height (cm)	165 (161, 175)	168 (159, 174)	0.404	0.686
Weight (kg)	62.5 (52.1, 67.5)	60.8 (50.5, 67.5)	0.724	0.469
Injury types [n (%)]				
Traffic accident	60 (15.6)	87 (18.4)		
Full injury	126 (32.8)	153 (32.4)		
Machinery crush injury	5 (1.3)	12 (2.5)	0.822	0.411
Heavy object injury	14 (3.6)	23 (4.9)		
Plunge injury	68 (17.7)	58 (12.3)		
Others	111 (28.9)	139 (29.4)		
Surgical treatment [n (%)]	185 (48.2)	232 (49.2)	0.081	0.776
Antibiotic use [n (%)]	251 (65.4)	330 (69.9)	2.011	0.156
Tetraplegia (incomplete) [n (%)]	82 (21.4)	100 (21.2)	0.004	0.952
Atherosclerosis [n (%)]	82 (21.4)	81 (17.2)	2.415	0.120
Spinal stenosis [n (%)]	125 (32.6)	177 (37.5)	2.270	0.132
Infection [n (%)]	99 (25.8)	143 (30.3)	2.129	0.145
Pneumonia [n (%)]	43 (11.2)	61 (12.9)	0.591	0.442
Lumbar disc herniation [n (%)]	32 (8.3)	76 (16.1)	11.590	0.001
Hypertension [n (%)]	101 (26.3)	149 (31.6)	2.840	0.092
Deep vein thrombosis [n (%)]	46 (12.0)	58 (12.3)	0.019	0.891
Neurogenic bladder [n (%)]	92 (24.0)	107 (22.7)	0.197	0.657
Osteoporosis [n (%)]	25 (6.5)	41 (8.7)	1.409	0.235
Hyperlipidemia [n (%)]	22 (5.7)	43 (9.1)	3.449	0.063
Diabetes mellitus [n (%)]	57 (14.8)	81 (17.2)	0.841	0.359

Table 2. Comparison of neurological functions between groups.

Group	n	ASIA motor score (score)	ASIA sensory score (score)
Control group	384	22.0 (15.0, 38.0)	53.0 (31.0, 78.0)
Intervention group	472	31.0 (16.5, 59.5)	62.0 (42.5, 98.0)
Z	–	8.410	10.170
p-value	–	<0.001	<0.001

ASIA, American Spinal Injury Association.

Table 3. Comparison of functional capacity between groups.

Group	n	SCIM-III (score)	10MWT (m/s)
Control group	384	14.5 ± 4.5	0.49 ± 0.16
Intervention group	472	15.2 ± 6.1	0.52 ± 0.17
t	–	1.872	2.636
p-value	–	0.062	0.009

SCIM-III, Spinal Cord Independence Measure III; 10MWT, 10-Meter Walk Test.

tetraplegia, atherosclerosis, spinal stenosis, and infections, were comparable between the two groups. However, the intervention group had a higher proportion of patients with lumbar disc herniation ($p < 0.05$). Other comorbidities, such as hypertension, deep vein thrombosis, neurogenic bladder, osteoporosis, hyperlipidemia, and diabetes mellitus, did not differ substantially between the two groups ($p > 0.05$) (Table 1).

Comparison of Neurological Function Between the Two Groups

As shown in Table 2, both ASIA motor and ASIA sensory scores differed substantially between the two groups ($p < 0.05$), suggesting that the intervention improved both motor and sensory neurological functions compared to the control group.

Comparison of Functional Capacity Between the Two Groups

Between-group comparison revealed no significant difference in SCIM-III scores ($p > 0.05$). However, patients in the intervention group showed a statistically significant improvement in 10MWT performance compared to the control group ($p < 0.05$, Table 3).

Comparison of CSA and MQI Between the Two Groups

Significant between-group differences were found in the CSA of both the biceps brachii and rectus femoris ($p < 0.05$), with greater values in the intervention group. Conversely, the MQI of the biceps brachii and rectus femoris showed no significant between-group difference ($p > 0.05$, Table 4).

Table 4. Comparison of CSA and MQI between groups.

Group	n	Biceps brachii		Rectus femoris	
		CSA (cm^2)	MQI	CSA (cm^2)	MQI
Control group	384	3.19 ± 0.46	0.038 ± 0.016	4.11 ± 0.55	0.035 ± 0.015
Intervention group	472	3.32 ± 0.59	0.040 ± 0.015	4.33 ± 0.62	0.036 ± 0.017
t	–	2.717	1.883	4.936	0.902
p-value	–	0.007	0.060	<0.001	0.367

CSA, cross-sectional area; MQI, muscle quality index.

Comparison of Quality of Life Between the Two Groups

No statistically significant difference was found in WHOQOL-BREF quality of life scores between the two groups (control group vs. intervention group: 62.5 ± 17.3 vs. 63.8 ± 20.6, $t = 0.986$, $p = 0.325$).

Discussion

NMES has been extensively investigated in various clinical settings, with numerous studies demonstrating its role in improving motor function, reducing spasticity, and enhancing quality of life in individuals with SCI [16]. A key application of NMES is the restoration of upper limb function, particularly in individuals with tetraplegia, where stimulation of key muscles such as the biceps brachii, triceps brachii, and wrist extensors facilitates the performance of activities of daily living [17,18]. NMES is also used to prevent and manage secondary complications, such as pressure ulcers and deep vein thrombosis (DVT), by promoting muscle contractions, improving blood flow, and supporting skin integrity in individuals with limited mobility [19,20]. However, the effectiveness of NMES is not uniformly consistent across all protocols and patient cohorts. A recent study assessing the superimposing patellar tendon vibration during wide-pulse, moderate-intensity NMES in individuals with SCI reported heterogeneous responses: while some individuals showed increased total knee extensor impulse, the overall results did not reveal statistically significant improvements [21]. These results suggest that although high-intensity, wide-pulse NMES remains a potential approach for strengthening paralyzed muscles, the addition of tendon vibration does not consistently enhance performance or delay fatigue. Further research is needed to elucidate individual variability and optimize stimulation parameters for optimal therapeutic benefit.

In addition to its use as a standalone approach, NMES has been successfully integrated into multimodal rehabilitation programs for individuals with SCI. Rehabilitation training remains a crucial component of injury management after injury, with a range of techniques developed to promote neuroplasticity, improve motor control, and maximize residual functional capacity. Task-specific training is a core approach that prioritizes repetitive practice of functionally relevant movement.

The efficacy of rehabilitation training in patients with SCI has been extensively investigated, with promising outcomes reported. Particularly, locomotor training is commonly used to enhance ambulation through repetitive, task-oriented gait practice. Harkema *et al*. [22] conducted a study involving individuals with chronic motor-incomplete SCI, assessing the effects of locomotor training on walking speed and distance. Participants underwent up to 60 sessions of locomotor training, with each session lasting 1–2 hours. The training protocol included body weight-supported treadmill walking, overground gait practice, and functional electrical stimulation when appropriate. The participants demonstrated significant improvements, with an average increase of 0.12 m/s on the 10MWT and 27.9 m on the 6MWT. These findings underscore the potential of targeted, high-intensity rehabilitation to improve walking ability in chronic SCI.

The mechanisms underlying the combined effects of NMES and rehabilitation training are multifaceted. NMES induces muscle contractions and enhances local blood flow, thereby promoting the delivery of oxygen and nutrients essential for muscle maintenance, repair, and adaptation. It also activates peripheral sensory receptors, increasing afferent input to the spinal cord and brain, thereby supporting neuroplasticity and the reorganization of neural pathways. When NMES is combined with task-specific training, such as gait or cycling training, it enhances the specificity and intensity of sensory and motor inputs, leading to greater functional improvements. Moreover, NMES helps prevent disuse muscle atrophy and maintain muscle mass in individuals with SCI with limited voluntary activation. This preservation of muscle mass is crucial for optimizing functional recovery and reducing the risk of secondary complications, including pressure ulcers and cardiometabolic dysfunction. By stimulating muscle contractions and promoting muscle hypertrophy, NMES counteracts the adverse effects of immobilization and prolonged inactivity.

In this retrospective study involving 856 patients with SCI, we evaluated the therapeutic effectiveness of NMES combined with rehabilitation training compared with rehabilitation training alone. Patients in the NMES group demonstrated significantly greater neurological recovery, indicated by higher ASIA motor and sensory scores, superior 10MWT performance, and increased muscle CSA ($p < 0.05$). These findings indicate that combining NMES with rehabilitation enhances muscle morphology and neuromotor function, thereby supporting the restoration of physical function.

Our results align with previous reports. For instance, Alashram *et al*. [23] reported that combining NMES with other rehabilitative techniques, particularly for $\geq$8 weeks, yields optimal improvements in muscle strength and functional outcomes. Similarly, this combined approach has achieved significant improvements in gait and lower-limb motor function comparable to those observed with robotic gait training in individuals with incomplete SCI [24]. Collectively, these findings highlight the potential of incorporating NMES into rehabilitation programs to optimize functional recovery after SCI.

However, no significant between-group differences were observed in SCIM-III scores, MQI, or WHOQOL-BREF quality of life scores ($p > 0.05$). This lack of statistical significance may be partially attributed to the relatively short follow-up duration and to slower progression in functional independence and psychosocial adaptation compared with neurological and muscular recovery. Moreover, functional and quality-of-life assessments may require longer rehabilitation duration or more sensitive measures to capture clinically meaningful changes. Therefore, the present findings should not be interpreted as definitive evidence of equivalence. Further rigorous randomized controlled trials with larger cohorts, extended follow-up, and refined assessment tools are warranted to validate these findings and define optimal NMES-integrated rehabilitation strategies for specific SCI subpopulations.

Despite the promising evidence supporting the integration of NMES and rehabilitation training, several challenges and limitations remain. Optimal stimulation parameters, standardized training protocols, and precise patient selection criteria are yet to be fully established. The heterogeneity of SCI, including differences in injury level and completeness, necessitates individualized therapeutic approaches. Moreover, the long-term sustainability of treatment effects and the extent of prolonged neuroplastic adaptations remain unclear. Longitudinal studies with extended follow-up periods are required to assess the maintenance of functional improvements and the need for ongoing or booster interventions.

Additionally, there was a statistically significant difference in the incidence of lumbar disc herniation between the two groups at baseline. Although this difference is relatively small compared to the overall sample size and is unlikely to have a substantial impact on the primary neurological and functional outcomes, its potential effect on joint mobility, exercise tolerance, or training intensity cannot be entirely excluded. We therefore acknowledge it as a possible confounding factor that may have affected the study outcomes.

Conclusions

In conclusion, combining NMES with rehabilitation training represents a promising strategy for promoting functional recovery in individuals with SCI. This integrated approach leverages the neuroplastic mechanisms within the central nervous system, leading to improved muscle strength, motor control, and functional performance. While challenges remain in optimizing stimulation parameters, refining treatment protocols, and individualizing interventions, the growing body of evidence supports the efficacy and potential of this NMES-augmented rehabilitation. Ongoing research and careful clinical implementation of NMES-augmented rehabilitation may help reshape recovery trajectories, improve long-term outcomes, and foster better community reintegration and quality of life for those living with SCI.

Availability of Data and Materials

The data used and analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

FH and MMZ conceived and designed the study. RZ, FFS, YHH and ZHZ analyzed data and interpreted the results. FH wrote the original draft, and the other authors conducted a thorough review and contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was performed according to the Declaration of Helsinki, and the study protocol was approved by the Institutional Review Board of The Second Affiliated Hospital of Wenzhou Medical University (Approval No: 2024128). Due to its retrospective design, which involved recorded data from 2015 to 2023, obtaining individual informed consent from all participants was not feasible. The ethics committee granted a waiver of consent because: (1) all data were anonymized and de-identified before analysis, ensuring patient confidentiality; (2) the investigation was conducted solely for non-commercial, public health and scientific purposes.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] Wu G, Chen J, Wang L, Meng F. Clinical Effectiveness of Minimally Invasive Surgery on Spinal Trauma. Annali Italiani Di Chirurgia. 2024; 95: 552–560. https://doi.org/10.62713/aic.3546.

[2] Hu X, Xu W, Ren Y, Wang Z, He X, Huang R, *et al*. Spinal cord injury: molecular mechanisms and therapeutic interventions. Signal Transduction and Targeted Therapy. 2023; 8: 245. https://doi.org/10.1038/s41392-023-01477-6.

[3] Zhao H, Li Z. Analgesic Mechanism of Dexmedetomidine and Esketamine in Rats with Spinal Cord Injury. Discovery Medicine. 2024; 36: 714–720. https://doi.org/10.24976/Discov.Med.202436183.67.

[4] Kirshblum S, Snider B, Eren F, Guest J. Characterizing Natural Recovery after Traumatic Spinal Cord Injury. Journal of Neurotrauma. 2021; 38: 1267–1284. https://doi.org/10.1089/neu.2020.7473.

[5] Bickel CS, Lein DH, Jr, Yuen HK. Optimal neuromuscular electrical stimulation parameters after spinal cord injury. The Journal of Spinal Cord Medicine. 2024; 47: 968–976. https://doi.org/10.1080/10790268.2023.2231674.

[6] Ackermann PW, Juthberg R, Flodin J. Unlocking the potential of neuromuscular electrical stimulation: achieving physical activity benefits for all abilities. Frontiers in Sports and Active Living. 2024; 6: 1507402. https://doi.org/10.3389/fspor.2024.1507402.

[7] Gorgey AS, Goldsmith JA, Khalil RE, Liu XH, Pan J, Cardozo C, *et al*. Predictors of muscle hypertrophy responsiveness to electrically evoked resistance training after spinal cord injury. European Journal of Applied Physiology. 2023; 123: 479–493. https://doi.org/10.1007/s00421-022-05069-0.

[8] Dolbow DR, Bersch I, Gorgey AS, Davis GM. The Clinical Management of Electrical Stimulation Therapies in the Rehabilitation of Individuals with Spinal Cord Injuries. Journal of Clinical Medicine. 2024; 13: 2995. https://doi.org/10.3390/jcm13102995.

[9] Ho CH, Triolo RJ, Elias AL, Kilgore KL, DiMarco AF, Bogie K, *et al*. Functional electrical stimulation and spinal cord injury. Physical Medicine and Rehabilitation Clinics of North America. 2014; 25: 631–654, ix. https://doi.org/10.1016/j.pmr.2014.05.001.

[10] Yang FA, Chen SC, Chiu JF, Shih YC, Liou TH, Escorpizo R, *et al*. Body weight-supported gait training for patients with spinal cord injury: a network meta-analysis of randomised controlled trials. Scientific Reports. 2022; 12: 19262. https://doi.org/10.1038/s41598-022-23873-8.

[11] Alashram AR, Annino G, Padua E. Robot-assisted gait training in individuals with spinal cord injury: A systematic review for the clinical effectiveness of Lokomat. Journal of Clinical Neuroscience. 2021; 91: 260–269. https://doi.org/10.1016/j.jocn.2021.07.019.

[12] Erickson ML, Ryan TE, Backus D, McCully KK. Endurance neuromuscular electrical stimulation training improves skeletal muscle oxidative capacity in individuals with motor-complete spinal cord injury. Muscle & Nerve. 2017; 55: 669–675. https://doi.org/10.1002/mus.25393.

[13] Kirshblum SC, Burns SP, Biering-Sorensen F, Donovan W, Graves DE, Jha A, *et al*. International standards for neurological classification of spinal cord injury (revised 2011). The Journal of Spinal Cord Medicine. 2011; 34: 535–546. https://doi.org/10.1179/204577211X13207446293695.

[14] Unai K, Uemura O, Takemura R, Kawakami M, Liu M. Association Between SCIM III Total Scores and Individual Item Scores to Predict Independence With ADLs in Persons With Spinal Cord Injury. Archives of Rehabilitation Research and Clinical Translation. 2019; 1: 100029. https://doi.org/10.1016/j.arrct.2019.100029.

[15] Development of the World Health Organization WHOQOL-BREF quality of life assessment. The WHOQOL Group. Psychological Medicine. 1998; 28: 551–558. https://doi.org/10.1017/s0033291798006667.

[16] Doucet BM, Lam A, Griffin L. Neuromuscular electrical stimulation for skeletal muscle function. The Yale Journal of Biology and Medicine. 2012; 85: 201–215.

[17] Rinaldin CDP, Cabral LPA, Krueger E, Nogueira-Neto GN, Nohama P, Scheeren EM. Fatigue in complete spinal cord injury and implications on total delay. Artificial Organs. 2020; 44: 305–313. https://doi.org/10.1111/aor.13573.

[18] Gorgey AS, Khalil RE, Sutor TW, Goldsmith JA, Cifu DX. Employment of Neuromuscular Electrical Stimulation to Examine Muscle and Bone Qualities after Spinal Cord Injury. Journal of Clinical Medicine. 2022; 11: 6681. https://doi.org/10.3390/jcm11226681.

[19] Broderick BJ, O'Connell S, Moloney S, O'Halloran K, Sheehan J, Quondamatteo F, *et al*. Comparative lower limb hemodynamics using neuromuscular electrical stimulation (NMES) versus intermittent pneumatic compression (IPC). Physiological Measurement. 2014; 35: 1849–1859. https://doi.org/10.1088/0967-3334/35/9/1849.

[20] Bogie KM, Wang X, Triolo RJ. Long-term prevention of pressure ulcers in high-risk patients: a single case study of the use of gluteal neuromuscular electric stimulation. Archives of Physical Medicine and Rehabilitation. 2006; 87: 585–591. https://doi.org/10.1016/j.apmr.2005.11.020.

[21] Bochkezanian V, Newton RU, Trajano GS, Vieira A, Pulverenti TS, Blazevich AJ. Effect of tendon vibration during wide-pulse neuromuscular electrical stimulation (NMES) on muscle force production in people with spinal cord injury (SCI). BMC Neurology. 2018; 18: 17. https://doi.org/10.1186/s12883-018-1020-9.

[22] Harkema S, Angeli C, Gerasimenko Y. Historical development and contemporary use of neuromodulation in human spinal cord injury. Current Opinion in Neurology. 2022; 35: 536–543. https://doi.org/10.1097/WCO.0000000000001080.

[23] Alashram AR. Letter to the Editor on "Effects of Electrical Stimulation Training on Body Composition Parameters After Spinal Cord Injury: A Systematic Review". Archives of Physical Medicine and Rehabilitation. 2023; 104: 514. https://doi.org/10.1016/j.apmr.2022.11.013.

[24] Kamgar P, Agarwal A, Chao T, Askari S, Tan M, Honor R, *et al*. Step trajectory analysis of spinal cord injured rats trained with neuromuscular electrical stimulation coordinated with robotic treadmill training. Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference. 2012; 2012: 1864–1867. https://doi.org/10.1109/EMBC.2012.6346315.