*Review Article*

# The Effects of Neuromuscular Electrical Stimulation on Muscle Strength and Function in Patients with Spinal Cord Injury: A Systematic Review

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## ABSTRACT

A systematic review was conducted to determine effects of neuromuscular electrical stimulation on muscle strength and function in patients with SCI. The review helps in consolidating existing research, identify knowledge gaps, and provide evidence-based recommendations for integrating NMES into rehabilitation protocols. Two independent reviewers performed data extraction, and discrepancies were resolved through discussion. The extracted data were then analyzed to evaluate the effects of neuromuscular electrical stimulation on muscle strength and function in patients with SCI. A systematic review was based on 8 articles that comprised a total number of n= 279 Spinal cord injuries patients to whom electrical nerve stimulation were given to determine effects on muscle strength and function. The reviewed studies collectively demonstrate that electrical nerve stimulation (ENS), including functional electrical stimulation, EMG-ES, rTMS, and epidural electrical stimulation, plays a significant role in improving muscle strength and function in individuals with SCI. Several randomized controlled trials highlight the benefits of combining FES with conventional rehabilitation methods. The findings of this systematic review suggest that NMES is an effective intervention for improving muscle strength and functional outcomes in individuals with SCI.

**Keywords:** Neck pain, Muscle energy technique, Proprioceptive neuromuscular facilitation, Quality of life.

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## INTRODUCTION

Spinal Cord Injury (SCI) is a significant global health concern, with an estimated number of 250,000 to 500,000 reported new cases annually[1]. The primary cause of SCI is trauma caused by blunt force, with motor vehicle accidents accounting for 38.2% of cases, followed closely by falls at 32.3%[2]. The impact of SCI extends beyond physical disability, posing a substantial economic burden. Globally, over $3 billion is spent annually on managing SCI, with individual costs ranging from $380,000 to $1,160,000 in the first year alone and between $46,000 and $202,000 for each subsequent year[3-4]. Given its high prevalence, severe consequences, and financial implications, SCI remains a critical research and healthcare intervention area.

SCI is associated with a wide range of secondary complications that significantly impact the health, independence, and quality of life of affected individuals[5-6]. These complications often lead to premature mortality and include pressure ulcers, spasticity, chronic pain, urinary tract infections, depression, bowel dysfunction, cardiovascular complications, renal stones, autonomic dysreflexia, fractures, fatigue, respiratory issues, and bladder dysfunction[7-9]. Among these, paralysis or reduced mobility is the most visible consequence of SCI, contributing to further health deterioration by limiting physical activity and increasing the risk of complications such as muscle atrophy and metabolic disorders[10-12]. Managing these secondary complications is a primary goal of rehabilitation strategies, as reducing their severity can significantly improve overall well-being and social participation for individuals with SCI.

Given the significant challenges associated with SCI, neuromodulatory approaches have been explored to enhance functional recovery and mitigate secondary complications. Traditional rehabilitation methods focus on preserving residual function and preventing further complications, but they often fail to restore lost motor abilities[13-15]. In recent years, electrical stimulation techniques have emerged as promising interventions for individuals with SCI. These include epidural spinal cord stimulation (SCS), intraspinal microstimulation, functional electrical stimulation (FES), and transcutaneous spinal cord stimulation (tSCS)[16-18]. Among these, noninvasive techniques such as FES and tSCS have gained attention due to their safety, ease of application, and potential to restore motor function. tSCS, in particular, targets neural structures similar to invasive SCS while avoiding surgical risks[16]. Depending on the stimulation parameters, tSCS can be categorized into direct (tsDCS) and pulse (tsPCS), each with distinct physiological effects[19-21]. Despite the growing interest in electrical stimulation techniques, no standardized neuromodulatory treatment for SCI exists.

While research suggests that neuromuscular electrical stimulation (NMES) may enhance muscle strength and function, the extent of its effectiveness remains unclear[22]. A comprehensive synthesis of available evidence is necessary to determine the clinical significance of NMES in SCI rehabilitation. Therefore, a systematic review is needed to evaluate the effects of neuromuscular electrical stimulation on muscle strength and function in patients with SCI. This review will help consolidate existing research, identify knowledge gaps, and provide evidence-based recommendations for integrating NMES into rehabilitation protocols.

## METHODOLOGY

### Study Design

A systematic review was conducted following PRISMA guidelines[23] to evaluate the effects of NMES on muscle strength and function in patients with SCI. A comprehensive literature search was performed across PubMed, Scopus, and Web of Science databases, including randomized controlled trials and observational studies.

### Search Strategy

Studies published in the last 10 years were searched using a combination of Medical Subject Headings (MeSH) and free-text terms related to "SCI," "neuromuscular electrical stimulation," "muscle strength," and "functional recovery."

### Selection of Studies

Full-text articles published in English within the last 10 years were included. Studies focusing on the effects of NMES on muscle strength and function in patients with SCI were considered. Randomized controlled trials (RCTs) and observational studies were included, while review articles, conference abstracts, and animal studies were excluded. Two independent reviewers screened titles and abstracts, followed by a full-text review to ensure eligibility. Discrepancies were resolved through discussion or consultation with a third reviewer.

### Data Extraction

Relevant data were extracted from the selected studies, including study design, sample size, participant characteristics, intervention details, outcome measures, and key findings. Initially, 115 studies were identified through database searches. After removing 20 duplicate records, 95 studies were screened based on titles and abstracts. Following this, 30 full-text articles were assessed for eligibility, of which 22 were excluded due to not meeting the inclusion criteria. Ultimately, eight studies were included in the systematic review.

Two independent reviewers performed data extraction, and any discrepancies were resolved through discussion. The extracted data were then analyzed to evaluate the effects of NMES on muscle strength and function in patients with SCI (Figure-1).

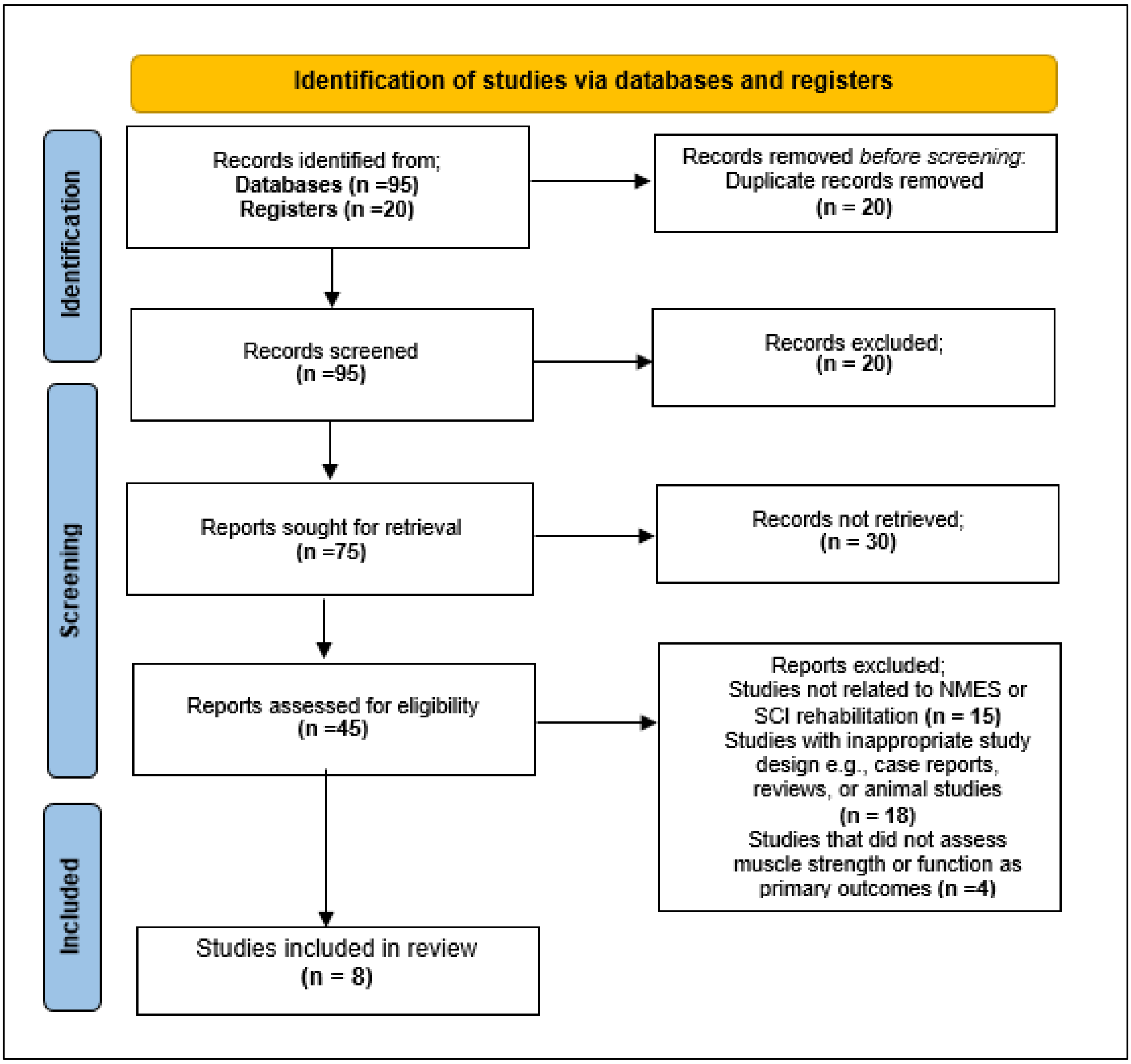


*Fig.1 PRISMA Flow Diagram*

## RESULTS

A systematic review was based on eight articles comprising a total of n= 279 Spinal cord injury patients to whom electrical nerve stimulation was given to determine effects on muscle strength and function. A detailed description of the studies included in the review is given in Table-1.

**Table-1 Description of Studies Included in the Systematic Review**

| Author | Type of Study | Sample Size | Intervention Methodology | Findings |
|---|---|---|---|---|
| **Rosley et al. 2022**[24] | Randomized Controlled Trial | n=28 (n=23 completed the study) | Combined Progressive Resistance Training (PRT) and Functional Electrical Stimulation-Evoked Leg Cycling Exercise (FES-LCE) vs. FES-LCE alone, conducted over 12 weeks | PRT + FES-LCE showed significantly greater improvements in lower limb muscle strength and volume compared to FES-LCE alone |

| | | | | |
|---|---|---|---|---|
| **Krogh et al. 2022[25]** | Randomized Sham-Controlled Clinical Trial | N=20 (REAL = 11, SHAM = 9) | rTMS (20 Hz, 1800 pulses/session) or sham stimulation delivered over leg M1, five times per week for 4 weeks before resistance training/physical therapy. Lower limb strength and gait function assessed pre- and post-intervention | rTMS may enhance long-term lower limb muscle strength recovery in SCI patients. LEMS improved significantly for rTMS but not for sham. No short-term recovery benefits or gait function improvements were observed |
| **Sun et al. 2023[26]** | Prospective, Randomized Controlled Trial | N=20 (10 per group) | Patients with SCI receiving epidural electrical stimulation randomized into two groups: (1) Control (conventional rehab), (2) EMG-induced rehab (target muscle therapy based on conventional rehab). Follow-up at 2 weeks, 1, 3, and 6 months. Primary outcome: Manual Muscle Testing (MMT) grading. Secondary outcomes: Barthel Index, EMG values, VAS, Spinal Cord Independence Measure, and Ashworth scale. Safety assessed by adverse events | Study aims to assess EMG-induced rehabilitation's effectiveness in improving muscle strength, quality of life, and functional outcomes in SCI patients after epidural stimulation. Findings will inform future rehabilitation methods. |
| **Bayraktaret al. 2024[27]** | Randomized Controlled Trial | N=34 (Experimental: 17, Control: 17) | Experimental group received electromyography-triggered electrical stimulation (EMG-ES) to abdominal muscles for 4 weeks, 3 times per week, alongside routine rehabilitation. Control group received isometric abdominal exercises instead of EMG-ES. Primary outcomes: modified functional reach test (mFRT) and trunk control test (TCT). Secondary outcomes: pulmonary function test (PFT) and abdominal muscle thickness (via ultrasonography). | Experimental group showed significantly greater improvements in sitting balance (mFRT: +242.8 cm², TCT: +5.0 points, $P < 0.001$) and abdominal muscle thickness ($P < 0.001$). No significant differences in pulmonary function ($P > 0.05$). EMG-ES may enhance sitting balance and abdominal muscle thickness in complete thoracic SCI patients. |
| **Moritz et al. 2024[28]** | Prospective, single-arm, multicenter, open-label, non-significant risk trial | N= 60 (Chronic Cervical SCI) | ARCEX Therapy: Non-invasive electrical stimulation over the cervical spinal cord combined with structured rehabilitation. Primary endpoints: safety and efficacy. Outcomes measured: strength, functional performance, fingertip pinch force, hand prehension, upper extremity motor/sensory abilities, and quality of life | 72% of participants showed clinically meaningful improvements in both strength and function. Secondary outcomes included increased fingertip pinch force, improved hand prehension and strength, enhanced upper limb motor and sensory abilities, and better self-reported quality of life. No serious adverse events were reported |
| **Zulbaran-Rojas t al. 2022[29]** | Phase I double-blinded randomized controlled trial | N=16 (COVID-19 ICU patients, 32 lower extremities) | Daily 1-hour electrical stimulation (E-Stim) on both gastrocnemius muscles for up to 14 days. Control group received non-functional E-Stim. Primary outcomes: ankle strength (Ankles) via ankle dynamometer, gastrocnemius endurance (GNMe) via surface electromyography (sEMG) | At 3 days, intervention group showed moderate improvements in ankle strength and muscle endurance ($p = 0.06$). At 9 days, GNMe was significantly higher ($p = 0.04$) with a 6.3% improvement from baseline ($p = 0.029$). No adverse effects reported. No impact on vital signs or ICU procedures. |
| **Anderson et al. 2022[30]** | Multi-center, single-blind randomized controlled trial | N=51 (FES = 27, Conventional Therapy = 24) | 40 sessions of FES using the MyndMove stimulator vs. conventional therapy targeting upper extremities over 14 weeks. Outcomes measured at baseline, mid-treatment (20th session), post-treatment (40th session/14 weeks), and follow-up (24 weeks). Primary outcome: SCIM III-SC score | Both groups showed a clinically meaningful 2-point increase in SCIM III-SC, but no statistically significant difference between FES and conventional therapy. COVID-19 interruptions affected sample size and protocol adherence in one-third of participants |

| | | | | |
|---|---|---|---|---|
| **Tefertiller et al. 2022[31]** | Prospective case series | N=50 (13 motor complete, 37 motor incomplete SCI) | Patient UE training program (60 min/session, 5x/week, avg. 72 sessions) using functional task-specific practice (FTP) combined with wide-pulse/high-frequency functional electrical stimulation (WPHF-FES). Primary outcome: Capabilities of Upper Extremity Test (CUE-T). Secondary outcomes: UE motor score (UEMS) and modified functional reach (MFR) | Significant improvements in CUE-T (+14.1, p < .0001), UEMS (+4.6, p < .0001), and MFR (+13.6 cm, p < .0001). Demonstrated improved UE strength, function, and trunk stability. Future studies needed for comparative effectiveness |

## Effects of Electric Nerve Stimulation on Muscle Strength and Function

The reviewed studies collectively demonstrate that ENS, including FES, EMG-ES, repetitive transcranial magnetic stimulation (rTMS), and epidural electrical stimulation, significantly improve muscle strength and function in individuals with SCI. Several randomized controlled trials (RCTs) highlight the benefits of combining FES with conventional rehabilitation methods. Tefertiller et al. reported significant improvements in upper extremity (UE) function, strength, and dynamic trunk stability following a training program incorporating wide-pulse/high-frequency FES (WPHF-FES), with notable gains in Capabilities of Upper Extremity Test (CUE-T), UE motor score (UEMS), and modified functional reach (MFR)31. Similarly, Anderson et al.[30] found that FES therapy led to clinically meaningful, though not statistically significant, improvements in self-care abilities, as measured by the Spinal Cord Independence Measure (SCIM III-SC).

In lower extremity rehabilitation, Rosley et al.[24] demonstrated that combining progressive resistance training (PRT) with FES-evoked leg cycling exercise (FES-LCE) resulted in significantly more significant improvements in lower limb muscle strength and volume compared to FES-LCE alone. Krogh et al.[25] showed that high-frequency rTMS applied to the leg motor cortex before resistance training improved lower extremity motor strength (LEMS), though it had no immediate effect on gait function. Additionally, Sun et al.[26] investigated the impact of electromyography (EMG)-induced rehabilitation following epidural electrical stimulation, revealing enhanced muscle strength and functional recovery, though long-term data are pending.

For trunk and abdominal muscle function, Bayraktar et al.[27] demonstrated that EMG-triggered electrical stimulation (EMG-ES) applied to the abdominal muscles significantly improved sitting balance and abdominal muscle thickness in individuals with complete thoracic SCI. Moritz et al.[28] further reinforced these findings, reporting that ARCEX Therapy, a combination of non-invasive cervical spinal cord stimulation and structured rehabilitation, led to meaningful improvements in upper limb motor strength, hand prehension, and sensory function, with no serious adverse events. Additionally, Zulbaran-Rojas et al.[29] proved that daily electrical stimulation of the gastrocnemius muscle in ICU patients improved ankle strength and endurance over time, indicating its potential benefits in early SCI rehabilitation.

### Estimation of Risk of Bias

The estimation of risk of bias was performed based on randomization, blinding, allocation concealment, attrition bias and reporting bias based on the author's judgement (Table-3).

### Random Sequence Generation

(Selection Bias)[24]

The selection bias random sequence generation was found low in all included studies.

### Allocation Concealment

(Selection Bias)

Allocation concealment was also found low in all included studies.

### Blinding of Outcome Assessment

(Detection Bias)

Detection bias was low in all included studies.

### Reporting Bias

Anderson et al.[30] was found to have a moderate risk of bias in reporting bias estimation, Bayraktar et al.27 were considered unknown reporting bias as per the author's judgement.

**Blinding of Participants & Personnel**
(Performance Bias)
Two studies that were Moritz et al.[28] and Anderson et al.[30] were considered to have a moderate risk of bias.

## DISCUSSION

The findings of this systematic review indicate that NMES plays a significant role in enhancing muscle strength and functional outcomes in individuals with SCI. The reviewed studies consistently demonstrate that NMES, whether applied as FES, EMG-ES, rTMS, or epidural electrical stimulation, provides substantial benefits in upper and lower limb rehabilitation, trunk stability, and overall functional recovery.

### Effects on Muscle Strength and Functional Recovery

The results suggest that NMES when combined with conventional rehabilitation strategies, enhances muscle strength and function more effectively than traditional rehabilitation alone.

**Table-3 Risk of Bias Analysis**

| Studies | Random Sequence Generation | Allocation Concealment | Blinding of Participants & Personnel | Blinding of Outcome Assessment | Reporting Bias |
|---|---|---|---|---|---|
| Rosley et al. 2022[24] | + | + | + | + | + |
| Krigh et al. 2022[25] | + | + | + | + | + |
| Sun et al. 2023[26] | + | + | + | + | + |
| Bayraktar et al. 2024[27] | + | + | + | + | ? |
| Moritz et al. 2024[28] | + | + | - | + | + |
| Zulbaran-Rojas et al. 2022[29] | + | + | + | + | + |
| Anderson et al. 2022[30] | + | + | - | + | - |
| Tefertiller et al. 2022[31] | + | + | + | + | + |

+ low risk of bias
- moderate risk of bias
? unknown risk of bias

Rosley et al.[24] found that combining progressive resistance training (PRT) with FES-evoked leg cycling exercise (FES-LCE) led to more significant improvements in lower limb muscle strength and volume compared to FES-LCE alone. Similarly, Krigh et al.[25] reported that applying high-frequency rTMS to the leg motor cortex before resistance training significantly improved lower extremity motor strength (LEMS). However, improvements in gait function were not observed in the short term.

The effectiveness of NMES in strengthening upper extremities was evident in studies such as Anderson et al.[30] and Tefertiller et al.[31], both of which demonstrated notable improvements in self-care abilities, upper limb strength and functional capabilities when FES was incorporated into rehabilitation protocols. The findings from Moritz et al.[28] further reinforced this by showing clinically meaningful gains in hand prehension, motor abilities, and quality of life following non-invasive cervical spinal cord stimulation combined with structured rehabilitation.

### Impact on Trunk Stability and Abdominal Muscle Function

The role of NMES in improving trunk stability and abdominal muscle function was highlighted in studies such as Bayraktar et al.[27], which demonstrated that EMG-ES applied to abdominal muscles significantly improved sitting balance and muscle thickness in individuals with complete thoracic SCI. This suggests that NMES may enhance core stability and reduce postural control deficits in SCI patients.

### Short- and Long-Term Benefits of NMES

The studies included in this review suggest that NMES has both immediate and long-term benefits. Sun et al.[26] indicated that electromyography-induced rehabilitation following epidural electrical stimulation showed promising results in improving muscle strength and functional outcomes. However, longer-term data are needed to confirm sustained benefits. Additionally, Zulbaran-Rojas et al.[29] demonstrated that daily NMES application in ICU patients improved ankle strength and muscle endurance, highlighting its potential role in preventing muscle atrophy during prolonged immobilization.

### Clinical Implications and Future Directions

Despite the promising findings, several challenges remain in integrating NMES into standard SCI rehabilitation protocols. One major limitation is the variability in stimulation parameters, such as frequency, intensity, and duration, across studies, which makes direct comparisons difficult. Standardizing NMES protocols is essential to ensure consistent clinical outcomes and facilitate broader implementation in rehabilitation settings.

Another consideration is the accessibility of NMES technologies. While non-invasive modalities such as tSCS and EMG-ES offer safer and more accessible alternatives to invasive epidural stimulation, their availability and cost-effectiveness need further evaluation. Future research should optimize NMES parameters, explore long-term effects, and conduct larger, multi-centre trials to validate findings across diverse SCI populations.

## CONCLUSION

The findings of this systematic review suggest that neuromuscular electrical stimulation NMES is an effective intervention for improving muscle strength and functional outcomes in individuals with SCI. The included studies demonstrated significant muscle activation, endurance, and functional mobility improvements, particularly when NMES was combined with conventional rehabilitation strategies. While NMES showed positive effects across various SCI populations, variability in stimulation protocols, intervention duration, and outcome measures highlights the need for standardized approaches to optimize clinical applications.

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None.

**Author Contributions**
**Fahmida** and **Alia Niaz** were responsible for conceptualizing the study, designing the methodology, and overseeing the research process. **Muhammad Asad Ullah** and **Zaib-un-Nisa** conducted the literature search, data extraction, and analysis. **Saima Tariq** contributed to data interpretation and manuscript drafting, while **Muhammad Riaz** provided critical revisions and final approval of the manuscript. All authors have read and approved the final version of the manuscript.

**Ethical Approval**
Not Applicable.

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None.

**Conflict of Interests**
None.

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