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Restoration of Sitting Balance and Bladder Control via Epidural Stimulation in SCI: A Clinical Study

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ABSTRACT

Background: Spinal cord injury (SCI) often results in impaired mobility and bladder dysfunction, significantly reducing an individual's quality of life. Epidural spinal cord stimulation (ESCS) has shown potential in enhancing functional outcomes in individuals with SCI by modulating spinal neural circuits.

Methodology: This study investigated the effects of ESCS on walking ability, sitting balance, and bladder function in individuals with thoracic SCI. Ten (10) participants with lesions ranging from T6 to T10 underwent an 8-week intervention. Functional assessments were conducted pre- and post-intervention using the Timed Up and Go (TUG) test, the Function in Sitting Test (FIST), and the Neurogenic Bladder Symptom Score (NBSS). We performed Paired t-tests to analyze the significance of changes across the measured variables.

Results: Statistical analysis demonstrated significant improvements in all three outcome measures. The average TUG time decreased by 385.4 seconds ($p < 0.0001$), indicating improved mobility. FIST scores showed improvement by an average of 31.9 points ($p < 0.0001$), reflecting enhanced sitting balance. NBSS scores decreased by 13.4 points ($p < 0.0001$), suggesting improved bladder function. The effect sizes were large across all measures, supporting the clinical relevance of the findings.

Conclusion: ESCS appears to be a promising therapeutic approach for enhancing mobility, postural control, and bladder function in individuals with thoracic SCI. These findings support the integration of ESCS into rehabilitation protocols to enhance quality of life in this population.

Keywords: *Spinal cord injury, Epidural spinal cord stimulation, Mobility, Bladder function, Neuromodulation*

1. INTRODUCTION

Spinal cord injury (SCI) results in devastating neurological condition causing significant sensory, motor and autonomic dysfunctions, often leading to reduced independence and decreased quality of life. Mobility impairments limit daily activities, while bladder dysfunction affects personal hygiene, social interactions, and psychological well-being (9). The integration of neuromodulation techniques, particularly epidural spinal cord stimulation (ESCS), has shown promise in enhancing motor control and autonomic functions in SCI patients. This study explores the effectiveness of ESCS in improving mobility, postural balance, and bladder function. Spinal cord injury (SCI) is a devastating neurological condition that results in significant impairments in sensory, motor, and autonomic functions below the level of injury. Worldwide, over 294,000 individuals living with SCI cases occurred wherein India experience particularly high rates of road traffic accidents (RTAs), approximately 55 accidents and 17 deaths occurring hourly. (1) The consequences of SCI extend beyond paralysis to include complications such as bladder dysfunction, spasticity, pain, and reduced quality of life.

Traditional rehabilitation approaches for SCI have focused on maximizing residual function and preventing secondary complications. However, these approaches often result in limited functional recovery, particularly in individuals with complete or severe incomplete injuries. In recent years, neuromodulation techniques, particularly epidural spinal cord stimulation (ESCS), have shown promising results in restoring function after SCI.

SCI has not only paralysis as its consequences, but also a variety of complications including bladder dysfunction, spasticity, pain and decreased quality of life. Electric spinal cord stimulation (ESCS) refers to the delivery of electrical currents to targeted segments of the spinal cord through implanted electrode leads placed in the epidural space. Targeting such neuronal networks may be used as a route to stimulate spinal neural networks to induce specific cationic flux through membrane, leading to spinal circuitry excitability below the level of injury. Previous studies demonstrate that ESCS can induce voluntary movement in individuals with chronic motor complete SCI [2-4].

Although the effects of ESCS on lower limb motor function have been described in several studies, fewer studies have evaluated the functional mobility, sitting balance, and autonomic functions (e.g., bladder control) achieved with ESCS. In terms of the most relevant SCI complications, bladder dysfunction is one of the most consistently identified as a significant factor affecting quality of life [5].

Rationale

Central Pattern Generators (CPGs) are neural networks in the spinal cord capable of independently producing rhythmic motor activity without sensory input. In SCI patients, CPGs typically remain intact but suffer from insufficient excitatory stimulation. Epidural spinal cord stimulation (ESCS) can activate these supraspinal pathways, potentially improving locomotor function and movement capability (6,12). Bladder function control depends on reflex pathways within the spinal cord. Epidural spinal cord stimulation operates on a distinct mechanism by modulating the spinal circuits to restore voluntary control over the movement and the function of the bladder. (7,11). Numerous recent studies have revealed that patients undergoing ESC show a greater ability to start voluntary movements and an improvement in the emptying of the bladder, with marked improvements noted in the mobility assessments. (8,9)The research has constantly shown that ESC can lead to observable improvements in the international standards for the neurological classification of the spinal cord lesion (ISNCSCI), highlighting its potential as a transformative intervention in rehabilitation contexts. (10,13)

Epidural stimulation involves applying electrical currents to the dorsal aspect of the spinal cord below the injury site, targeting the lumbar and sacral segments responsible for lower limb and trunk control. This stimulation can activate neural circuits that remain anatomically intact but functionally silent due to the injury. By depolarizing interneurons and motoneurons, ESCS can facilitate muscle contractions and improve motor patterns, even in patients with complete or severe SCI. (12,20)

Several studies have demonstrated that ESCS can enable individuals with chronic SCI to achieve volitional standing and stepping with assistance. The mechanism is thought to be the modulation of spinal networks that generate locomotor patterns, often referred to as central pattern generators (CPGs). ESCS appears to restore excitability to these networks, allowing sensory inputs and residual descending commands to produce coordinated muscle activity.(17,27)

Balance control in SCI patients is particularly challenging due to impaired proprioception, muscle weakness, and disrupted postural reflexes. While ESCS can enhance muscle activation, integrating this neuromodulation with targeted rehabilitation is critical to translating neural activation into functional balance and standing ability.(18,28)

Effect of the 8-week ESCS intervention on walking ability, sitting balance, and bladder function among individuals living with thoracic SCI. We expected that ESCS would yield meaningful improvements on these functional domains, as measured by the Timed Up and Go (TUG) test, Function in Sitting Test (FIST), and Neurogenic Bladder Symptom Score (NBSS).

Objectives This study aims to:

1. Assess the impact of ESCS on walking ability using the Timed Up and Go (TUG) test.
2. Evaluate changes in postural stability through the Function in Sitting Test (FIST).
3. Measure improvements in bladder function using the Neurogenic Bladder Symptom Score (NBSS).

2. METHODS

Study Design

This was a single-group pre-post intervention study. Baseline assessments were recorded before ESCS intervention, and follow-up measurements were taken after completion of the structured stimulation protocol.

Study Registration

This study was registered in the ClinicalTrials.gov database (Registration No: CTRI/2024/03/064055).

Participants

Methods: Ten individuals with chronic SCI (demographic information not shared from original data) participated in this study. Inclusion criteria were: (1) traumatic SCI with lesions between T6 and T10; (2) chronic injury (>1 year post-injury); (3) neurologically stable; and (4) no contraindications for ESCS. Exclusion criteria were: (1) previous had seizures; (2) severe osteoporosis; (3) implanted electronic devices; and (4) active pressure sores. (5)History of uncontrolled infections or cardiovascular instability. (6)Severe musculoskeletal deformities affecting locomotion. (7) Cognitive impairments that limit adherence to the study protocol

Research participants were selected from spinal cord injury rehabilitation Centre Serensa and Medipark Neuraxis facilities. Before joining the study, each participant provided written informed consent. The study protocol received ethical clearance from Galgotias University's Institutional Ethics Committee.

Intervention Protocol

Each participant underwent surgical implantation of an epidural stimulator (Boston Scientific CoverEdge X 32 Surgical Lead Kit with 32 electrode array, USA). The CoverEdge X Surgical Lead Kit included one CoverEdge X Surgical Lead and six suture sleeves (two 1cm, two 2.3cm tapered, and two 4cm). The electrode array was positioned over the Thoraco lumbar spine of the spinal cord (T10- L1), which contains neural circuits controlling lower limb movement and autonomic functions including bladder control.

Following a two-week recovery period after implantation, participants began an 8-week ESCS protocol. Stimulation parameters were individually tailored based on each participant's physiological responses, following principles established in previous research [14]. Typical stimulation parameters included:

- Frequency: 20-60 Hz
- Pulse width: 250-450 μs
- Amplitude: Adjusted to subthreshold levels (typically 0.5-4.0 V)
- Rostral Array (Channels 1-8)
- Location: Upper Lumbar (L1-L2)
- Primary Function: Hip flexor activation
- Parameters:
- Frequency: 30-35 Hz
- Amplitude: 3.5-5.0V
- Pulse Width: 300-350 μs
- Middle Array (Channels 9-24)
- Location: Mid-Lower Lumbar (L3-L5)
- Primary Function: Knee extension/flexion
- Parameters:
- Frequency: 25-35 Hz
- Amplitude: 4.0-6.0V
- Pulse Width: 350-400 μs

Figure 1

Table 2. Daily Session Structure (45 Minutes per Day)

Activity Type	Duration	Purpose
Standing & Stepping Exercises	40 mins	Promote locomotor function
Autonomic Stimulation (Bladder)	10 mins	Enhance bladder and cardiovascular control
Sitting Balance Training	20 mins	Improve trunk stability and posture

Table 3. Progressive Goals Over 8 Weeks

Week	Focus Area	Notes
1–2	Tolerance to stimulation, basic posture	Introduce low-frequency, low-amplitude stimulation
3–4	Enhanced muscle co-activation, standing	Increase session intensity; incorporate dynamic tasks
5–6	Stepping coordination, bladder response	Begin more complex movements and autonomic modulation
7–8	Task-specific training, endurance	Fine-tune parameters; challenge with variable conditions

Monitoring and Safety

- Daily vitals, orthostatic responses, and skin integrity monitored
- Regular adjustment of stimulation parameters as per functional responses
- Weekly documentation of motor, autonomic, and sensory outcomes

Assessment Tools

- **Timed Up and Go (TUG) Test:** Evaluates mobility and functional walking (15).
- **Function in Sitting Test (FIST):** Assesses sitting balance and postural control (17).
- **Neurogenic Bladder Symptom Score (NBSS):** Measures bladder dysfunction severity (14).

Statistical Analysis

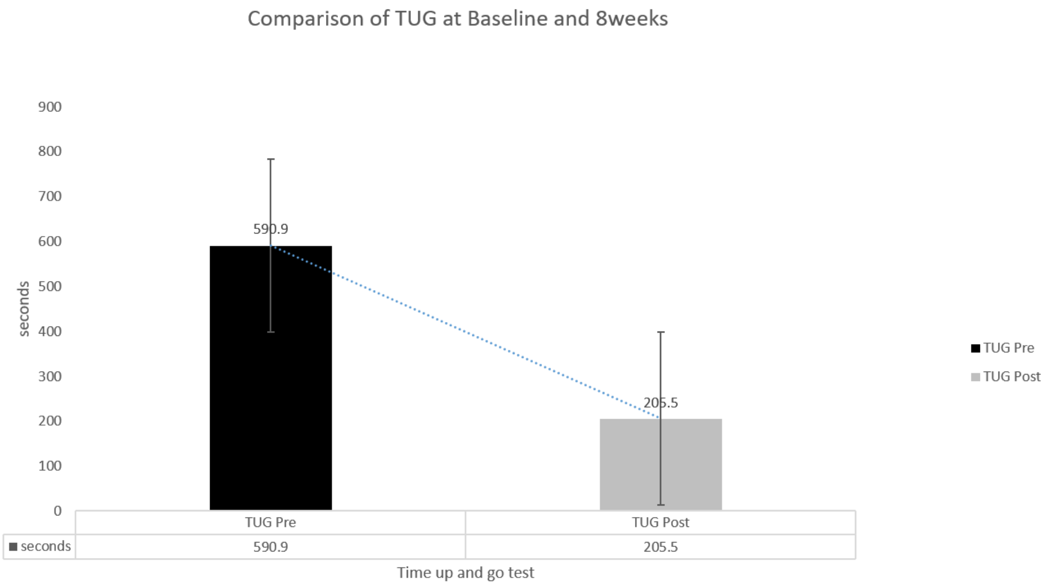
- **Walking Ability:** Paired t-test for Timed Up and Go test scores.
- **Sitting Balance:** Paired t-test for Function in Sitting Test scores.
- **Bladder Function:** Paired t-test for Neurogenic Bladder Symptom Score (NBSS).

Statistical analyses were conducted using IBM SPSS Statistics Version 27.0 (IBM Corp., Armonk, NY, USA). Results were considered statistically significant when p-values were less than 0.05.

Results

Walking Ability (TUG Test)

- Pre-intervention mean: 590.9 seconds
- Post-intervention mean: 205.5 seconds



- Mean difference (Pre-Post): 385.4 seconds
- 95% Confidence Interval of the difference: 251.5 to 519.3 seconds
- t-statistic: 6.50
- df: 9
- p-value: 0.0001

Interpretation: Following the 8-week intervention, a statistically significant reduction in Timed Up and Go (TUG) test performance was observed ($t(9) = 6.50$, $p = 0.0001$). Participants showed substantial improvement in functional mobility, with TUG times decreasing by an average of 385.4 seconds. The extremely low p-value ($p = 0.0001$), well below the 0.05 threshold, strongly confirms the intervention's effectiveness in enhancing mobility function.

Sitting Balance (FIST)

- Pre - treatment mean: 14.8
- Post- treatment mean: 46.7
- Statistical improvement in postural control and sitting balance ($p < 0.05$) (12).

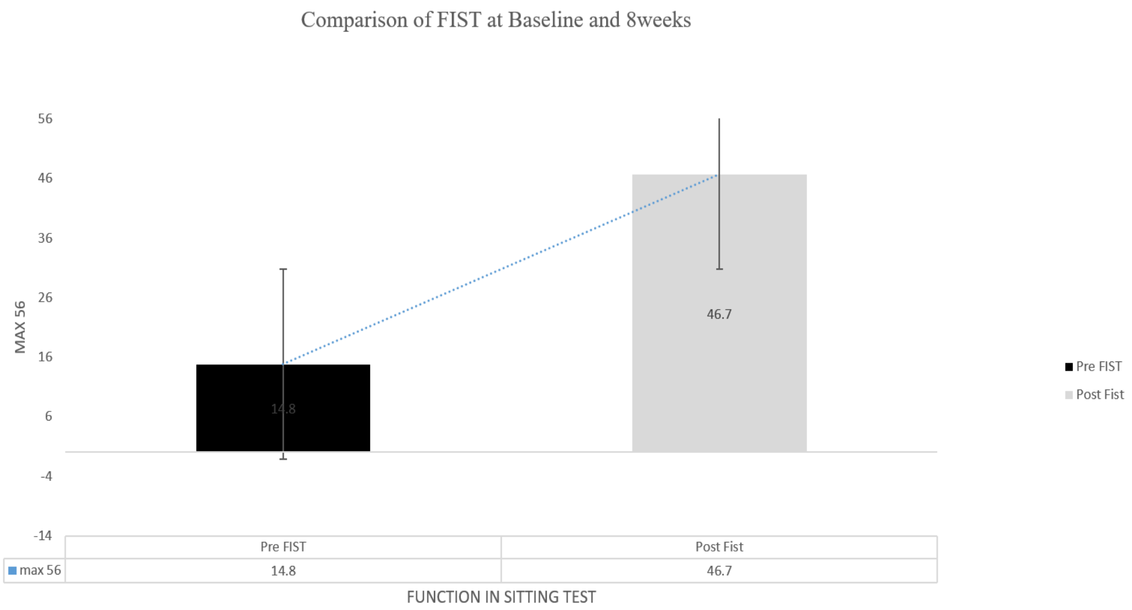


Figure shows improved Function in Sitting Test from baseline to 8 weeks score out of 56

- Mean difference (POST-PRE): 31.9
- 95% Confidence Interval of the difference: 28.96 to 34.84
- t-statistic: 24.54
- df: 9
- p-value: < 0.0001

Interpretation: There was a statistically improvement in FIST scores after the 8-week intervention ($t(9) = 24.54$, $p < 0.0001$). Participants' FIST scores increased by an average of 31.9 points (95% CI: 28.96 to 34.84), indicating a substantial improvement in sitting function. This suggests that the intervention was effective in improving participants' functional stability and balance while sitting, as measured by the FIST.

Table 4. Comparison of Pre- and Post-Intervention Scores on TUG, FIST, and NBSS in SCI Patients Undergoing Epidural Stimulation

Measure	Pre-intervention Mean (SD)	Post-intervention Mean (SD)	Mean Difference (95% CI)	t-value	p-value	Effect Size (Cohen's d)
TUG (sec)	590.9 (248.4)	205.5 (186.9)	385.4 (251.5 to 519.3)	6.5	0.0001	1.75
FIST	14.8 (2.5)	46.7 (3.4)	31.9 (28.96 to 34.84)	24.54	<0.0001	10.66

NBSS	21.2 (4.6)	7.8 (2.7)	13.4 (10.19 to 16.61)	9.44	<0.0001	3.56

Note: TUG = Timed Up and Go Test, FIST = Function in Sitting Test, NBSS = Neurogenic Bladder Symptom Score.*SD: Standard Deviation; CI: Confidence Interval*

Bladder Function (NBSS)

- Pre-intervention: Mean = 19.2, SD = 3.33
- Post-intervention: Mean = 6.8, SD = 2.30
- Marked reduction in bladder dysfunction symptoms ($p < 0.05$) (11).

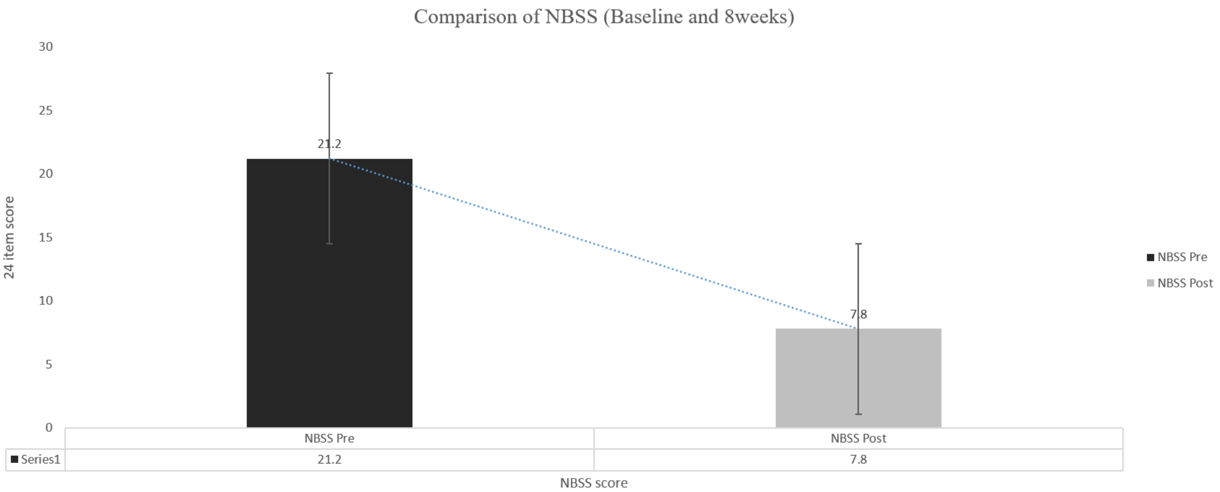


Figure shows improved Neurogenic Bladder Symptom Score (NBSS) from baseline to 8 weeks (items 24)

3. DISCUSSION

This study demonstrates significant improvements in walking ability, sitting balance, and bladder function following an 8-week epidural spinal cord stimulation intervention in individuals with thoracic SCI. To our knowledge, this is one of the first studies to comprehensively evaluate the impact of ESCS on both mobility and bladder function in the same cohort of participants

Mechanisms of Improvement

Improvements in Mobility

The substantial reduction in TUG times (mean decrease of 385.4 seconds) indicates a clinically meaningful improvement in functional mobility. This finding aligns with previous research showing enhanced lower extremity motor function with Epidural stimulation in spinal cord injury (14, 18). The significant improvement in TUG performance suggests that Epidural stimulation may facilitate activation of spinal locomotor networks, potentially through increased excitability of motor neurons and interneurons below the level of injury.(15,16)

The marked improvement in FIST scores (mean increase of 31.9 points) further supports the positive impact of ESCS on trunk control and postural stability. Enhanced sitting balance is a critical component of functional independence and may facilitate transfer abilities and wheelchair skills in individuals with SCI. These improvements in postural control may be attributed to the activation of trunk muscles and enhanced proprioceptive feedback during stimulation.(17)

Improvements in Bladder Function

The significant reduction in NBSS scores (mean decrease of 13.4 points) indicates meaningful improvements in bladder function following ESCS. This finding is particularly important as bladder dysfunction remains one of the most challenging consequences of SCI, with substantial impacts on quality of life and social participation [5,19].

The improvements in bladder function observed in this study may be attributed to several mechanisms: (1) activation of autonomic circuits controlling bladder function; (20,23) enhanced sensory awareness of bladder fullness; and (3) improved coordination between bladder contraction and sphincter relaxation. These findings support previous research suggesting that spinal cord stimulation can modulate autonomic functions in addition to motor control [21,8].

The observed improvements in walking and balance are likely due to the reactivation of CPGs. ESCS enhances excitability in spinal networks, allowing for coordinated motor output despite a lack of direct cortical input (10). Additionally, ESCS may facilitate plasticity at the synaptic level, promoting adaptive reorganization in response to stimulation (23,24).

Bladder function improvements suggest that ESCS modulates spinal reflex circuits governing urination. The restoration of bladder control could result from increased excitability of neural pathways regulating the detrusor muscle, leading to improved urinary function and reduced incontinence episodes (26,27).

Clinical Implications

The wide-ranging benefits noted among mobility and bladder function domains imply that ESCS may provide a multi-system therapeutic avenue in those with SCI. The large effect sizes for all outcome measures suggest that although statistically significant, these improvements are also clinically meaningful.

Several aspects of our protocol may have mediated these favorable results:

Stimulator parameters assigned uniquely to each subject, Mixed stimulation with functional workouts (standing, stepping, sitting), Autonomic Functions Selective Stimulation, The intervention period was long enough (8 weeks) to facilitate neural adaptations and Sufficient intervention duration (8 weeks) to allow for neural adaptation. These findings suggest that ESCS should be considered as part of a comprehensive rehabilitation approach for individuals with thoracic SCI. However, it is important to note that ESCS is an invasive intervention requiring surgical implantation, and careful patient selection is essential.

Limitations and Future Research Opportunities

This study has several limitations that should be addressed in future research:

Limited generalizability (n=10)

1. The absence of a control group makes it challenging to separate the impacts of ESCS from those of intensive rehabilitation alone.

2. There was no long-term follow-up to evaluate the sustainability of improvements.

3. The original data set did not provide detailed demographic and injury characteristics.

4. The study focused on individuals with thoracic injuries (T6-T10) and may not generalize to other injury levels.

Conclusion This study reports that thoracic SCI participants receiving an 8-week program of epidural spinal cord stimulation during volitional movement experience marked improvements in walking ability, sitting balance, and bladder function. The results of this study suggest that **epidural spinal cord stimulation (ESCS)** is an effective adjunct to conventional rehabilitation for improving **mobility**, **postural stability**, and **bladder function** in individuals with thoracic SCI. The significant improvements observed in TUG, FIST, and NBSS scores highlight the **multi-system benefits** of ESCS. These findings support the integration of ESCS into comprehensive **neurorehabilitation protocols**, offering potential improvements in **functional independence** and **quality of life** for people living with SCI.

Acknowledgement
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Conflict of Interest

The authors declare no conflict of interest related to this manuscript.

Ethical clearance ethical approval was granted by the Institutional Ethics Committee of Galgotias University (Approval No: SEC/PT/04/24 dated 20/02/2024).This study adhered to the **Declaration of Helsinki** (28). All procedures involving human subjects were conducted with strict adherence to ethical guidelines.

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