Noninvasive neuromodulation as an adjunct rehabilitation strategy for respiratory dysfunction in individuals with low-level spinal cord injury

Neuromodulación no invasiva como estrategia de rehabilitación complementaria para la disfunción respiratoria en individuos con lesión medular de bajo nivel

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Abstract

Introduction. For individuals suffering from mild spinal cord injuries (SCIs), respiratory problems continue to be a leading source of disability, mainly due to impaired ventilatory muscle performance. Conventional respiratory rehabilitation improves pulmonary function to some extent, but additional strategies are needed to optimize recovery. Noninvasive neuromodulation has recently gained attention as a promising adjunctive therapy to increase respiratory complications in cases with SCI.
Aim: This study sought to assess the impact of noninvasive neuromodulation, in addition to standard respiratory rehabilitation, on pulmonary function parameters in cases with low-level SCI compared with standard rehabilitation alone.
Methods: Forty patients with incomplete or complete SCI at or below T6 in chronic stage were arbitrarily partitioned into 2 equal groups. Both groups A and B received a standardized respiratory rehabilitation program while Group A received additional noninvasive neuromodulation therapy, sessions were conducted 3 times/week for 8 consecutive weeks, Pulmonary function parameters, including forced expiratory volume in the first second (FEV_1), forced vital capacity (FVC), and the FEV_1/FVC ratio were evaluated pre- and post-intervention.
Results: Both populations exhibited significant intra-group enhancements in FEV_1 and FVC post-treatment ($P < 0.001$). However, the neuromodulation group (Group A) exhibited significantly greater post-treatment values matched to the control group ($P \leq 0.001$ for both FEV_1 and FVC). The FEV_1/FVC ratio showed no statistically significant changes within or among groups.
Conclusion: Noninvasive neuromodulation, when added to standard respiratory rehabilitation, provides significant improvements in pulmonary function (FEV_1 and FVC) among patients with low-level spinal cord injury. This approach may represent a valuable, and noninvasive adjunct to conventional rehabilitation strategies.

Keywords

Noninvasive neuromodulation; pulmonary function; respiratory rehabilitation; spinal cord injury; transcutaneous spinal cord stimulation.

Resumen

Introducción. Para las personas que padecen lesiones leves de la médula espinal(LME), los problemas respiratorios continúan siendo una fuente principal de discapacidad, principalmente debido al deterioro del rendimiento muscular ventilatorio. La rehabilitación respiratoria convencional mejora la función pulmonar hasta cierto punto, pero se necesitan estrategias adicionales para optimizar la recuperación. La neuromodulación no invasiva ha ganado atención recientemente como una terapia complementaria prometedora para aumentar las complicaciones respiratorias en casos con LME.
Objetivo: Este estudio buscó evaluar el impacto de la no invasiva de la neuromodulación, además de la rehabilitación respiratoria, en los parámetros de la función pulmonar en los casos con bajo nivel de SCI comparación con el estándar de rehabilitación.
Métodos: Cuarenta pacientes con LME incompleta o completa en o por debajo de T6 en estadio crónico se dividieron arbitrariamente en 2 grupos iguales. Ambos grupos A y B recibieron un programa estandarizado de rehabilitación respiratoria, mientras que el Grupo A recibió terapia de neuromodulación no invasiva adicional, se realizaron sesiones 3 veces por semana durante 8 semanas consecutivas, se evaluaron los parámetros de la función pulmonar, incluido el volumen espiratorio forzado en el primer segundo (FEV1), la capacidad vital forzada (FVC) y la relación FEV1/FVC antes y después de la intervención.
Resultados: Ambas poblaciones exhibieron mejoras significativas intragrupo en FEV1 y FVC después del tratamiento ($P < 0,001$). Sin embargo, el grupo de neuromodulación (Grupo A)exhibió valores postratamiento significativamente mayores coincidentes con el grupo de control ($P \leq 0,001$ tanto para FEV1 como para FVC). La relación FEV1/FVC no mostró cambios estadísticamente significativos dentro o entre los grupos.
Conclusión: La neuromodulación no invasiva, cuando se agrega a la rehabilitación respiratoria estándar, proporciona mejoras significativas en la función pulmonar (FEV_1 y FVC) entre los pacientes con lesión medular de bajo nivel. Este enfoque puede representar un complemento valioso y no invasivo de las estrategias de rehabilitación convencionales.

Palabras clave

Neuromodulación no invasiva; función pulmonar; rehabilitación respiratoria; lesión de la médula espinal; estimulación transcutánea de la médula espinal.

Introduction

Spinal cord injury (SCI) can affect and destroy respiratory motor control it also significantly impact the individual's health and quality of life. Patients frequently exhibit diminished respiratory rates, lung capacity, airway clearance, and coughing efficacy, which hinder everyday activities and elevate morbidity. Restoring respiratory function in these individuals enhances health and quality of life. (Abraham et al., 2023; Flett et al., 2022; Gharedah, 2025; Khanzada et al., 2024; Laskin et al., 2022).

As a result of the fact that respiratory problems are one of the primary reasons of morbidity and death in this group, they are a substantial reason for worry following spinal cord injuries. (Lucky, 2025). These effects often appear soon after the SCI and may endure. Neurological impairment at or above the cervical spinal cord results in respiratory muscle weakness or paralysis, inadequate airway clearance, and diminished lung compliance during the acute phase, which persists for days to weeks post-injury. (Auld et al., 2024; Linn et al., 2000).

This stage increases the danger of atelectasis, pneumonia, and respiratory failure so, requiring severe medical treatment. (Endo et al., 2024). Respiratory dysfunction causes decreased vital capacity, persistent hypoventilation, and inefficient coughing in the subacute and chronic stages, exposing people to repeated infections and lower quality of life. (Richards & Schwartzstein, 2024; Tharu et al., 2024).

These consequences vary in timing and severity based on SCI level and completeness. Cervical injuries, especially those affecting segments C3–C5, impede the phrenic nerve, which supplies the diaphragm, the main respiratory muscle. Upper thoracic injuries impair intercostals and abdominal muscles, reducing breathing efficiency. Without targeted treatment, these issues become chronic, underlining the need for pulmonary function-supporting medications during recovery. (Randelman et al., 2021; Tharu et al., 2024).

Spinal cord stimulation (SCS), initially created for chronic pain, is being studied for SCI functional rehabilitation. Electrical impulses affect spinal neuronal networks. (Wang et al., 2026). Transcutaneous SCS (tSCS) activates spinal circuitry without surgery using surface electrodes (Teragiwa et al., 2025). In numerous neurological diseases, tSCS modifies spinal interneuronal activity, improving functional recovery. (García-Alén et al., 2023; Moritz et al., 2024). The stimulation of afferent fibers in the dorsal roots is believed to be the mechanism behind this behavior. This stimulation leads to an increase in the excitability of spinal networks, but it does not directly generate action potentials in the body. (García-Alén et al., 2023; Hofstoetter et al., 2021; Moritz et al., 2024).

Despite the demonstrated benefits of noninvasive neuromodulation techniques, such as transcutaneous spinal cord stimulation and transcutaneous diaphragmatic stimulation, on respiratory function in patients with cervical spinal cord injury, there is a lack of evidence concerning their effectiveness in individuals with low-level (thoracic and lumbar) spinal cord injury. Most available studies focus on cervical populations, and systematic reviews emphasize the heterogeneity of methods and the limited number of controlled trials addressing lower-level injuries.

Given the limited evidence on noninvasive neuromodulation for respiratory complications in low-level SCI, and the persistent burden of pulmonary dysfunction in this population despite conventional rehabilitation, it is rational to explore whether neuromodulation can provide an additional therapeutic benefit.

The objective of this study was to evaluate whether adding noninvasive neuralmodulation to standard respiratory therapy provides superior improvements in pulmonary function metrics (FEV1, FVC, and FEV1/FVC ratio) compared with standard respiratory therapy alone in patients with low-level spinal cord injury.

Method

Study design

Through the use of a prospective randomized controlled trial and CONSORT guidelines was followed. Also, the study was conducted in accordance with the Declaration of Helsinki, and was permitted by

scientific study ethics committee, Faculty of Physical Therapy, Al-Salam University No: SREC.PT.SUE(20)1125 27\11\2025

Participants

This study was conducted on male participants because they constitute the majority of the spinal cord injury population and to minimize variability related to sex-specific physiological differences in respiratory function.

A total of 40 patients participated in this study, as determined by a sample size calculation using G*Power software, with a significance level of 0.05 and a statistical power of 80%.

Forty male aged 18 years and older with either partial or total spinal cord injury at or below the T6 level were included in this study, they were all in chronic stage, at least six months after injury as the respiratory complications had become clinically evident.

Inclusion criteria: 40 male participant were aged between 18–50 years and documented as a cases of traumatic SCI at or below T6 level, they were all 6 month or more post injury, at chronic stage and were clinically stable and had the ability to perform spirometry training.

Exclusion criteria: any patient with pre-existing chronic pulmonary disease (e.g., COPD, asthma), recent respiratory tract infection within the last 4 weeks were excluded from this study, in addition to patients required mechanical ventilation at the time of recruitment, and patients contraindicated to electrical stimulation. Also, smokers and patients had comorbidities such as diabetes or chronic respiratory diseases that could influence pulmonary outcomes were excluded.

Randomization and grouping

Before enrollment, all participants were told of the study's goals, methods, benefits, and risks and gave signed informed permission. The 40 participants were randomly allocated to two groups of 20 cases each by using block randomization technique. Group A received noninvasive neuromodulation in addition to standard respiratory rehabilitation, while Group B received standard respiratory rehabilitation alone and served as the control group. Baseline demographic and anthropometric characteristics (Age and BMI) did not differ significantly among groups.

Intervention Protocol

Tow equal groups of patients were randomly assigned (n = 20 each). Both groups received standard respiratory rehabilitation as the following:

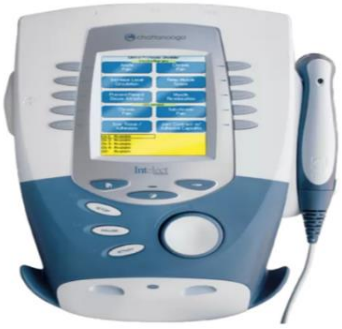
Standard respiratory rehabilitation was given to both groups three a week for eight weeks. Duration per session was around 30-40 minutes. This included inspiratory as well as expiratory muscle exercise through resistive breathing exercises, performed in sets of 2-3 with 10-15 repetitions with appropriate resting periods among them. Assisted coughing maneuvers were also given as required to improve pulmonary drainage. Abdominal as well as diaphragmatic breathing exercises were performed for around 5-10 minutes, followed by abdominal muscle exercise. Correct positioning principles were followed during all sessions to facilitate effective lung expansion and prevent any respiratory complications, as per standard respiratory rehabilitation protocols followed in spinal cord injury patients (Patwa & Gunjal, 2024).

In addition to standard rehabilitation given to both groups, Group A received a noninvasive neuromodulation therapy along with respiratory muscle training as the following:

Interventions

Transcutaneous electrical nerve stimulation (TENS), a noninvasive neuromodulation technique, was utilized by the Intlect Chattanooga Group Electrical Stimulation 2 Channels Device, USA. The Hixon (TN) 37343 model equipment (Fig. 1).

Figure 1. TENS device used



Procedure

TENS stimulation was applied by using 2 channels with 4 surface electrodes, 1st channel electrodes were placed para-spinal at the level of dorsal spine and other channel was placed at posterolateral aspect of the abdomen to stimulate expiratory muscles.

The neuromodulation therapy was performed three times a week for eight weeks. Each treatment session lasted for around 30 minutes. The intensity of the TENS was gradually raised during the treatment to the maximum limit of 25-120 mA, which did not cause any pain or other side effects. The parameters for stimulation, which included the pulse width of 1 ms and the frequency of 5 kHz, were maintained constant for all sessions.

Pulmonary function measures were done by well-trained evaluator, including forced expiratory volume in the first second (FEV_1), forced vital capacity (FVC), and the FEV_1/FVC ratio, were evaluated for both groups before to and during the intervention period utilizing a calibrated Spirolab Spirometer (Medical International Research, Italy) (Fig.2).

Figure 2. Spirolab Spirometer

Spirometry testing was conducted according to standardized procedures to ensure measurement reliability. At least three technically acceptable trials were obtained for each participant, and the highest reproducible value was used for analysis. All measurements met established acceptability and repeatability criteria, with sufficient time having been allowed to rest between trials to minimize fatigue-related variability.

Outcome measures

The primary outcome measures were pulmonary function parameters obtained by spirometry (FEV1, FVC, and FEV1/FVC ratio). Calculations were performed at baseline (pre-intervention) and after completion of the intervention period (post-intervention) for both groups.

Statistical analysis

SPSS version 26 (IBM Inc., Chicago, IL, USA) was used to collect, arrange, and analyze data. Quantitative parametric variables were provided as mean and SD, with unpaired Student's t-tests for intergroup comparisons and paired t-tests for intragroup comparisons. The Chi-square test was used to assess qualitative variable associations when relevant. Two-tailed P values < 0.05 were significant, shapero test of normality.

Results

No statistically significant differences were seen in age and BMI among the groups investigated. As demonstrated in Table 1.

Pre- and post-treatment FEV1 (Liter) comparison

Within group comparison

Group A

The mean ± SD (FEV1 (Liter)) pre-treatment was 3.077±0.169 while post-treatment was 3.43±0.152. Post-treatment showed a substantial increase matched to pre-treatment (P≤0.001*).

Group B:

The mean ± SD (FEV1 (Liter)) pre-treatment was 3.077±0.169 while post-treatment was 3.15±0.179. Statistically significant increase seen post-treatment matched to pre-treatment (P≤0.001*).

Comparison among groups

Pre-treatment (FEV1 (Liter)) did not show significant difference among the two groups (P≤1.00). While post- treatment shows statistically significant difference among the 2 groups (P ≤0.001*). (Table 2).

Table 1. Distribution of demographic data among studied groups.

	Group A (N= 2***0***)	Group B (N= 2***0***)	Test value	P-value
Age (Years)	32.4± 8.18	32.85± 7.79	T= 0.178	0.860
BMI (Kg/m^2)	29.65±2.25	29.65±2.18	T=0.00	1.00

Data is not significant since the p-value is bigger than 0.05. A p-value of ≤0.05 shows statistical significance. Data with a p-value of ≤0.01 is very significant. Shown as Mean ± Standard Deviation (SD). The Pearson Chi-Square test is called T-test.

Table 2. Before and after therapy, the FEV1 (liter) values of the groups that were investigated.

			Group A (N= 2***0***)	Group B (N= 2***0***)	Test value	P-value
FEV1 (Liter)	Pre- treatment		3.077±0.169	3.077±0.169	T= 0.00	1.00
	Post- treatment		3.43±0.152	3.15±0.179	T=5.34	≤0.001*
	Paired-t test	Test value	T= 20.23	T= 6.34		
		P-value	≤0.001*	≤0.001*		

Comparison of Pre- and Post- treatment FEV1 (Liter)

Within group comparison

Group A

The mean ± SD (FVC (Liter)) pre-treatment was 3.78± 0.287 while post-treatment was 4.272±0.177

Group B

The mean ± SD (FVC (Liter)) pre-treatment was 3.78± 0.287 while post-treatment was 3.84±0.312. Compared to pre-treatment, post-treatment increased (P=0.001*).

Comparison among groups

Pre-treatment FVC (Liter) did not differ between groups (P=1.00). After therapy, there is a significant difference among the two groups (P≤0.001*). (Table 3).

Table 3. Before and after therapy FVC in examined groups.

			Group A (N= 20)	Group B (N= 20)	Test value	P-value
FVC (Liter)	Pre- treatment		3.78± 0.287	3.784±0.287	T= 0.00	1.00
	Post- treatment		4.272±0.177	3.84±0.312	T=5.35	≤0.001*
	Paired t-test	Test value	T= 13.307	T= 4.07		
		P-value	≤0.001*	0.001*		

Pre- and post-treatment FEV1/FVC ratio comparison

Within group comparison

Group A

The mean ± SD (FEV1/FVC ratio) pre-treatment was 81.56± 4.92 while post-treatment was 80.29±3.37. There was no Statistically significant difference among post-treatment compared with that pre- treatment (P=0.121).

Group B

The mean ± SD (FEV1/FVC ratio) pre-treatment was 81.56±4.92 and post-treatment was 82.209±5.41. Pre- and post-treatment differences were not statistically significant (P=0.06).

Comparison between groups

Pre-treatment and post- treatment (FEV1/FVC ratio) did not show significant difference among the two groups. Table 4.

Table 4. FEV1/FVC ratio before and after treatment among studied groups.

			Group A (N= 20)	Group B (N= 20)	Test value	P-value
FEV1/FVC ratio	Pre- treatment		81.56± 4.92	81.56± 4.92	T= 0.00	1.00
	Post- treatment		80.29±3.37	82.209±5.41	T=1.34	0.188
	Paired t test	Test value	T= 1.62	T= 1.94		
		P-value	0.121	0.06		

Discussion

Compared to standard treatment alone, this study investigated the impact that noninvasive neuromodulation, Furthermore, In low-level spinal cord injury patients, normal respiratory rehabilitation was examined on pulmonary function metrics (forced expiratory volume in one second, forced vital capacity, and FEV1/FVC ratio).

Through the use of guided exercises like deep breathing and diaphragmatic breathing, respiratory training therapies are designed to improve the function of respiratory muscles, increase lung capacity, and encourage the clearance of secretions from the respiratory system. In theory, these therapies have the potential to lessen the occurrence of problems by reducing the distress experienced by the respiratory system and enhancing the patterns of breathing. (Zhang et al., 2025).

Research on respiratory recovery as an aspect of therapy after spinal cord injury remains insufficient, despite the fact that it is of crucial relevance. Pulmonary problems continue to be a substantial contributor to morbidity and death. (Roth et al., 2010). Technology and ingenuity have made neuromodulation a potential treatment. Autonomic functions including respiratory function and cough have improved. (Kumru et al., 2023; Laskin et al., 2022). This study found that adding noninvasive neuromodulation to respiratory therapy improved lung function in low-level spinal cord injury patients. In particular, the intervention group had significantly higher FEV1 and FVC than baseline and controls, although the FEV1/FVC ratio remained stable. These data imply that noninvasive neuromodulation may improve ventilatory muscle function and lung volumes beyond standard therapy.

In support of these results, Tharu et al. (Tharu et al., 2024) conducted a comprehensive literature analysis on respiratory motor network noninvasive electrical stimulation techniques including 194 patients with spinal cord injuries. Researchers discovered that scTS, or spinal cord transcutaneous stimulation,

might be a very effective method for helping people with SCI regain their breathing abilities during rehabilitation. A preliminary clinical study using a bipolar, 5 kHz-modulated, 1 ms pulse width modality was carried out by the authors, and the results showed that scTS was effective in improving respiratory motor function.

The non-invasive neuromodulation group in our study showed improvement, and Duarte et al. (Duarte et al., 2021) found that transcutaneous electrical diaphragmatic stimulation (TEDS) appears to affect invasive mechanical ventilation (IMV) time and ICU stay. They also concluded that this physiotherapeutic technique may be beneficial for SCI therapy.

Kumru et al., 2025 executed a randomized controlled study that corroborated our findings. Compared to the control group, the tSCS group showed significant improvements in MIP, MEP, and forced vital capacity ($p < 0.05$). This suggests that transcutaneous spinal cord stimulation (tSCS) applied to specific areas of the cervical spine can improve breathing after a cervical spinal cord injury. This method has the potential to improve neuroplasticity and reduce the risk of respiratory problems in patients who have had a cervical spinal cord injury.

Although the study of Kumru et al., 2025 agrees with our results in the general trend of noticeable improvement after the intervention, it differs from ours in that it found no statistically significant difference among the tSCS and control groups concerning FVC (L) and FEV_1 (L). This discrepancy may be explained by differences in the level of spinal cord injury, as the previous study was conducted on cervical lesions, whereas our patients had low-level (thoracic and lumbar) injuries, which might respond differently to neuromodulation. It could also be related to variations in stimulation parameters, duration of therapy, or sample characteristics, such as baseline pulmonary function and degree of neurological impairment.

From a clinical perspective, improved FEV1 and FVC are relevant as they indicate stronger ventilatory capacity and potentially more effective cough, which may reduce the risk of recurrent infections and hospitalizations in this population. While the FEV1/FVC ratio did not change significantly, this likely reflects parallel increases in both volume measures rather than a lack of functional benefit.

The strengths of this study include its randomized controlled design with well-matched baseline characteristics (age, BMI) objective outcome assessment using standardized spirometry parameters (FEV1, FVC, FEV1/FVC ratio) and first study, to our knowledge, to specifically evaluate noninvasive neuromodulation in low-level spinal cord injury patients, a population underrepresented in previous research.

However, some limits must be recognized. Limited sample size (N = 40), perhaps constraining the generalizability of the results. All subjects were male, limiting applicability to female patients. Only spirometric measures were assessed; no direct clinical outcomes, including infection rates, hospitalizations, or quality of life, were examined. The intervention strategy was standardized rather than personalized, and the ideal stimulation settings have yet to be determined.

Recommendations for Future Research, future research should conduct larger, multicenter randomized controlled trials including both male and female patients. Extend the follow-up duration to evaluate long-term effects and sustainability of improvements. Incorporate broader clinical outcomes, such as frequency of respiratory infections, length of hospital stay, and patient-reported quality of life. Explore different neuromodulation protocols to optimize stimulation parameters for individual patients. Compare noninvasive neuromodulation with other established interventions (e.g., diaphragm pacing, respiratory muscle training) to position its role in the rehabilitation pathway.

Conclusions

This study demonstrated that noninvasive neuromodulation, when added to standard respiratory rehabilitation, significantly improved pulmonary function in cases with low-level SCIs. Both FEV1 and FVC showed highly significant increases in the intervention group matched to baseline and with the control group, while the FEV1/FVC ratio remained unchanged in both groups. These findings suggest that neuromodulation enhances lung volumes and ventilatory capacity beyond those achieved with conventional rehabilitation alone, highlighting its potential as a promising adjunct therapy in this population.

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