



Review

SPINAL CORD STIMULATION: AN OVERVIEW

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ABSTRACT

PURPOSE: To review and summarize the most recent evidence on spinal cord stimulation (SCS) for chronic pain management and motor function improvement, with a focus on clinical outcomes, mechanisms, and safety. **METHODS:** A literature search was conducted using major scientific databases, including PubMed, MEDLINE, Cochrane, Embase, and Web of Science. Only studies published in the current year were included. Eligible publications involved human or animal research related to pain relief, motor recovery, device performance, or safety. Data were synthesized descriptively. **RESULTS:** Recent studies confirm that SCS provides effective and sustained pain relief, improves functionality, and reduces opioid use. Novel stimulation modalities—such as high-frequency and closed-loop systems—demonstrated superior outcomes compared to traditional tonic stimulation. Mechanistic investigations revealed that SCS modulates neural pathways, reduces inflammation, and promotes neuroprotection. Additionally, emerging evidence supports its role in motor rehabilitation for spinal cord injury and neurodegenerative diseases. Explantation rates remain low, but concerns persist regarding insufficient pain relief, device limitations, and economic impact. **CONCLUSIONS:** SCS is a safe and increasingly versatile therapy for chronic pain and motor dysfunction. Continued research is needed to refine patient selection, stimulation strategies, and long-term outcomes.

Keywords: Spinal cord stimulation, neuromodulation, chronic pain, motor function, high-frequency stimulation.

INTRODUCTION

Chronic low back pain is one of the most widespread health issues globally and ranks as the leading cause of disability worldwide. Globally, hundreds of thousands of lumbar spine surgeries are performed each year as a treatment for chronic low back pain, yet many patients continue to experience persistent symptoms despite surgical intervention (1). While procedures like microdiscectomy for radicular pain report relatively high success rates (75–80%), outcomes from more complex surgeries such as spinal fusion are often less favorable (2). In fact, nearly half of patients undergoing fusion surgery for persistent low

back pain report no improvement or worsening of symptoms after one year.

A significant number of patients continue to suffer from pain after spinal surgery, a condition previously known as Failed Back Surgery Syndrome (FBSS), now more accurately described as Persistent Spinal Pain Syndrome Type 2 (PSPS-T2) (3). This diagnosis reflects the wide range of underlying causes, including epidural scarring, biomechanical changes, central sensitization, surgical complications, or even misdiagnosis (3). Due to these varied factors, treatment of PSPS-T2 remains a complex clinical challenge.

Conservative treatments such as physical therapy, spinal injections, medication management (including neuropathic agents, NSAIDs, and opioids), and behavioral therapies often provide limited relief. Repeated surgeries tend to yield diminishing results and carry

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increasing risk, highlighting the need for alternative approaches (4).

Spinal Cord Stimulation (SCS), first introduced in 1967 following the Gate Control Theory of pain, has since become a well-established, minimally invasive option for managing chronic neuropathic pain. The technique involves placing electrodes in the epidural space to modulate pain signals through electrical impulses, targeting large afferent fibers in the spinal cord (5). Modern developments have led to advanced stimulation modes, including high-frequency, burst, and closed-loop systems, which offer more personalized and effective treatment (5).

SCS has demonstrated meaningful reductions in pain for individuals with PSPS-T2, complex regional pain syndrome (CRPS), post-surgical neuropathic pain, and other chronic pain conditions. It has also been associated with improved quality of life, reduced opioid use, and enhanced functionality (6). Despite the proven benefits, few studies deeply examine the therapy's impact on occupational outcomes—such as employment status or return-to-work quality—though existing evidence underscores its potential to positively influence these factors (7).

Given the significant burden chronic back and leg pain places on physical health, mental well-being, and economic productivity, spinal cord stimulation offers a promising intervention for patients unresponsive to traditional care.

MATERIAL AND METHODS

A thorough search of scientific databases including PubMed, MEDLINE, Cochrane, Embase, and Web of Science was conducted to gather relevant studies on spinal cord stimulation for chronic pain and motor function improvement. Search terms focused on key concepts such as spinal cord stimulation, neuropathic pain, spinal cord injury, and neuromodulation. Additional articles were identified through manual screening of references.

To ensure the review reflects the most current state of research and technological advancement, we limited our search to publications from the current year. This decision was made to include only the most up-to-date evidence, given the rapid evolution of neuromodulation techniques and clinical practice in recent years.

Studies included in this review comprised clinical trials, systematic reviews, and experimental research involving humans or animal models. Only publications available in English and providing clear information on outcomes related to pain relief, motor function, device safety, and explantation were considered. Articles such as case reports or those lacking sufficient data were excluded. Data from the selected studies were extracted independently by two reviewers, focusing on intervention details, patient outcomes, and safety profiles. The quality of the included studies was assessed using standard tools to evaluate bias and overall evidence strength. Due to variations in study designs and reported results, data were synthesized descriptively rather than quantitatively.

As this work is a review of existing literature, no new ethical approval was necessary.

RESULTS

Spinal cord stimulation has gained increasing attention as a viable alternative, especially for patients who do not achieve adequate relief through medications, physical therapy, or surgery. This review focuses on **the** latest studies published within the current year, providing an up-to-date overview of recent findings in the field. All included publications are detailed in **Table 1**.

Kaye's systematic review highlights that SCS offers superior outcomes compared to conventional medical management (CMM) in terms of both short- and long-term pain reduction, enhanced functionality, improved psychological wellbeing, and decreased opioid use (8). His analysis of multiple studies involving over a thousand patients further emphasizes that emerging SCS modalities—such as high frequency, differential target multiplexed and multiphase stimulation—demonstrate even greater efficacy than traditional tonic stimulation. Importantly, adverse event rates across these studies were low, reinforcing the favorable safety profile of SCS. The underlying biological mechanisms of SCS have been explored in depth by Kang, who provides a comprehensive overview of its molecular and neurophysiological actions (9). According to Kang, SCS not only modulates neural circuits via the activation of large-diameter A β fibers to inhibit pain transmission, but also influences neurotransmitter release, exhibiting anti-inflammatory and

neuroprotective effects. This broader understanding of SCS mechanisms lays a solid theoretical foundation for its clinical use and may open avenues for novel applications in pain management. Rodas's retrospective study of the Freedom® SCS System further supports the clinical efficacy and safety of SCS in patients with chronic bilateral back and leg pain, particularly those suffering from nerve compression and complex regional pain syndrome (CRPS) (10). Rodas reports substantial reductions in pain scores sustained up to one year post-implantation without serious adverse events, underscoring the benefits of minimally invasive SCS techniques in patients often resistant to other treatments (10). Przybysz's systematic review focusing on Persistent Spinal Pain Syndrome Type 2 (PSPS-T2) also provides robust evidence that tonic SCS leads to significant pain relief and functional improvement compared to conventional medical approaches or sham treatments (11). Though responder rates varied, many patients achieved at least 50% pain reduction at six months, with meaningful gains in quality of life. However, this review noted that newer stimulation technologies such as high-frequency or closed-loop systems were not evaluated, suggesting that future research could reveal even greater benefits (11). Finally, Wang's exploration of SCS in the context of spinal cord injury-associated pain highlights the neuromodulatory, neurochemical, and anti-inflammatory mechanisms underlying its effectiveness. SCS helps restore balance in excitatory and inhibitory neurotransmitters and promotes nerve repair processes, offering a promising therapeutic option for this particularly challenging patient population (12). Nevertheless, Wang emphasizes the need for larger, long-term randomized controlled trials to validate these findings and optimize treatment protocols (12). Wahezi et al. provide a comprehensive systematic review analyzing explantation rates and causes across over 13,000 patients implanted with permanent SCS devices between 1984 and 2024. Their findings indicate that approximately 9.8% of patients undergo device explantation, with the predominant reason being insufficient pain relief, accounting for 38% of cases (13). Additional causes include lead failure (15%) and infection (14%). Importantly, most explantations occur within the first year post-implantation. This raises concerns about patient selection, device longevity, and satisfaction despite the general safety and efficacy profile of

SCS. Furthermore, the financial burden associated with implantation and revision procedures—ranging from \$35,000 to \$70,000 for initial implantation and \$15,000 to \$25,000 for revisions—underscores the economic implications for healthcare systems. Wahezi highlights limitations inherent to current hardware-driven devices, particularly in waveform adaptability, which may restrict therapeutic flexibility and contribute to suboptimal outcomes (13). On the mechanistic front, Fang's systematic review synthesizes evidence from 40 preclinical animal studies to elucidate spinal mechanisms underlying SCS-induced analgesia (14). The analysis categorizes these mechanisms into three key domains: inhibition of ascending nociceptive transmission, enhancement of descending inhibitory pathways, and neuroimmune modulation. Specifically, SCS was shown to increase inhibitory signaling and suppress excitatory neurotransmitter release at the dorsal horn level, while promoting descending inhibition through serotonergic, opioid, and cholinergic systems. Additionally, SCS modulates neuroimmune responses by attenuating proinflammatory cytokines and regulating microglial and astrocyte activity, often via MAPK-related signaling pathways. Although these findings provide a robust framework for understanding the multifaceted spinal effects of SCS, Fang notes that the exclusive reliance on animal models limits direct extrapolation to human clinical scenarios, emphasizing the need for further translational research (14). In addition to its established role in chronic pain management, spinal cord stimulation is increasingly explored as a therapeutic modality for motor dysfunction resulting from spinal cord injury (SCI) and neurodegenerative diseases. Forouzan's review highlights the expanding potential of SCS in treating SCI-induced paraplegia, a condition that affects approximately 18,000 individuals annually in the United States alone (15). The review emphasizes that beyond pain relief, SCS can facilitate significant functional motor improvements, especially when paired with intensive rehabilitation. Crucial to achieving optimal outcomes is the precise placement of epidural electrodes and customization of stimulation parameters, which, combined with physical training, enhance neuromuscular activation and recovery. This suggests that SCS may serve not only as a neuromodulatory tool for pain but also as a rehabilitative adjunct capable of activating paralyzed muscle groups

and promoting motor function restoration (15). Complementing these findings, Prat-Ortega et al. conducted the first-in-human study assessing epidural SCS in adults with spinal muscular atrophy (SMA), a genetic disorder characterized by motoneuron loss and muscle weakness (16). Their pilot intervention involved epidural stimulation targeting sensory afferents in the lumbosacral spinal cord over a four-week period. Remarkably, participants experienced marked improvements in muscle

strength (up to 180% increase), gait quality (40% longer step length), and endurance, as measured by the six-minute walk test. These functional gains correlated with enhanced motoneuron firing rates and persisted beyond the active stimulation period, indicating potential neuroplastic effects. Importantly, no adverse events were reported, underscoring the safety and feasibility of this approach in a vulnerable population (16).

Table 1. Summary of Key Recent Studies on Spinal Cord Stimulation (SCS)

Author	Study Type	Focus Area	Main Findings	Notable Points
Kaye	Systematic Review	SCS vs. Conventional Medical Management	SCS provides superior pain reduction, improved function, psychological benefit, and reduced opioid use	Newer modalities (HF, multiplexed, multiphase) more effective than tonic SCS; low adverse event rates
Kang	Mechanistic Overview	Molecular and neurophysiological mechanisms of SCS	SCS activates A β fibers, modulates neurotransmitters, and has anti-inflammatory, neuroprotective effects	Provides theoretical foundation for clinical use and future research
Rodas	Retrospective Study	Freedom® SCS in chronic bilateral back/leg pain and CRPS	Significant pain reduction maintained up to 1 year	No serious adverse events; highlights value in treatment-resistant cases
Przybycz	Systematic Review	SCS in PSPS-T2	Tonic SCS effective for pain relief and functional improvement	Responder rates varied; newer SCS technologies not included
Wang	Review	SCS for SCI-associated pain	SCS promotes neurochemical balance and nerve repair	Emphasizes need for large-scale RCTs
Wahezi	Systematic Review (13,000+ patients)	SCS explantation rates and causes	9.8% explantation rate; 38% due to insufficient pain relief	Cost implications significant; hardware limitations may affect outcomes
Fang	Systematic Review (preclinical)	Spinal mechanisms of SCS analgesia	Inhibits nociceptive input, enhances descending inhibition, and modulates neuroimmune responses	Strong preclinical evidence; limited human translation
Forouzan	Review	SCS in SCI-induced paraplegia	Supports motor function recovery with SCS + rehab	Precise electrode placement and stimulation settings are critical
Prat-Ortega	First-in-human pilot study	SCS in Spinal Muscular Atrophy (SMA)	Marked improvement in strength, gait, endurance; no adverse events	Suggests neuroplastic effects and feasibility in neurodegenerative conditions

Together, these studies underscore the broadening horizon of SCS applications, extending from chronic pain relief to functional

motor recovery in neurodegenerative and spinal cord injury contexts. The integration of SCS with rehabilitative therapies and its ability to

modulate neural circuits governing motor control highlight its transformative potential. However, these promising findings also point to the need for larger, controlled trials to optimize stimulation protocols, assess long-term efficacy, and better understand the underlying mechanisms that support sustained functional improvements.

DISCUSSION AND CONCLUSION

The reviewed studies consistently demonstrate that SCS can provide significant pain relief and functional improvements, especially when combined with rehabilitation. Advances in technology, including new stimulation waveforms and improved devices, have enhanced efficacy and safety, although challenges such as device explantation and variability in patient response remain.

Mechanistically, SCS appears to modulate pain by influencing neural circuits at spinal and supraspinal levels, reducing inflammation, and promoting neurochemical balance. Moreover, recent findings suggest potential benefits of SCS in motor recovery after spinal cord injury and neuromuscular disorders, expanding its therapeutic scope.

Despite encouraging results, limitations exist due to heterogeneous study designs, small sample sizes, and a lack of long-term data. Future research should focus on optimizing stimulation parameters, refining patient selection, and conducting larger, controlled trials to better understand long-term outcomes and mechanisms.

In conclusion, SCS represents a valuable option for managing chronic spinal pain and motor deficits, offering meaningful improvements in quality of life for many patients. Continued innovation and rigorous research will be essential to maximize its clinical benefits and address current limitations.

REFERENCES

1. van Os WKM, Alvarez-Jimenez R, Cohen SP, et al. Discogenic Low Back Pain. *Pain Pract*, 25(7):e70062, 2025
2. Asch HL, Lewis PJ, Moreland DB, et al. Prospective multiple outcomes study of outpatient lumbar microdiscectomy: should 75 to 80% success rates be the norm? *J Neurosurg*, 96(1):34-44, 2020.
3. Treede RD, Rief W, Barke A, Aziz Q, et al. Chronic pain as a symptom or a disease: the IASP classification of chronic pain for the international classification of Diseases (ICD-11) *Pain*, 160(1):19-27, 2025
4. Schneider BJ, Hunt C, Conger A, et al. The effectiveness of intradiscal biologic treatments for discogenic low back pain: a systematic review. *Spine J*, 22(2):226-237, 2022.
5. London D, Mogilner A. Spinal Cord Stimulation: New Waveforms and Technology. *Neurosurg Clin N Am*, 33(3):287-295, 2022.
6. Chitneni A, Jain E, Sahni S, et al. Spinal Cord Stimulation Waveforms for the Treatment of Chronic Pain. *Curr Pain Headache Rep*, 28(7):595-605, 2024
7. Gazozcu F, Schütz A, Schär R, Schlaeppli JA. The Impact of Spinal Cord Stimulation on Patients' Ability to Work and Work-Related Outcomes, *Neuromodulation: Technology at the Neural Interface*, 28(6): 976-985, 2025.
8. Kaye AD, Archer JR, Shah S, et al. Spinal Cord Stimulation for Low Back Pain: A Systematic Review. *Curr Pain Headache Rep*, 29(1):2, 2025.
9. Kang Y, Tang Y, Gao J, et al. Spinal Cord Stimulation for Chronic Neuropathic Pain: Research Progress in Molecular and Circuit Mechanisms. *Pain Physician*, 28(4):E371-E384, 2025.
10. Rodas R. Spinal Cord Stimulation Using High Frequency Electromagnetic Coupling (HF-EMC) Technology to Power an Implanted Neurostimulator With a Separate Receiver for Treating Chronic Back and Leg Pain: A Retrospective Study. *Pain Physician*, 28(1):E43-E47, 2025.
11. Przybysz G, Vu TN, Pisansky AJB, et al. A systematic review of evidence comparing spinal cord stimulation to sham or conservative medical management in the treatment of persistent spinal pain syndrome - Type 2. *Interv Pain Med*, 4(3):100635, 2025.
12. Wang Q, Zhang Y, Zhang H, Li Z. Spinal cord stimulation: An emerging strategy for chronic pain relief after spinal cord injury. *Neural Regen Res*, doi: 10.4103/NRR.NRR-D-25-00553, 2025.
13. Wahezi SE, Yener U, Naeimi T, et al. Spinal Cord Stimulation Explantation and Chronic Pain: A Systematic Review and Technology Recommendations. *J Pain Res*, 18;18:1327-1340, 2025.
14. Fang JY, Yamamoto H, Romman A, et al. Spinal Mechanisms of Pain Modulation by

Spinal Cord Stimulation: A Systematic Review. *Cureus*, 17(6):e85567, 2025.

15. Forouzan EJ, Rashid MY, Nasr NF, et al. The Potential of Spinal Cord Stimulation in Treating Spinal Cord Injury. *Curr Pain Headache Re*, 29(1):35, 2025.

SLAVKOV D., et al.

16. Prat-Ortega G, Ensel S, Donadio S, et al. First-in-human study of epidural spinal cord stimulation in individuals with spinal muscular atrophy. *Nat Med*, 31(4):1246-1256, 2025.