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RESEARCH

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# Global trends and hotspots of neuromodulation in spinal cord injury: a study based on bibliometric analysis

Shutao Gao[1†], Yukun Hu[1†], Shizhe Li[1], Wei Li[2] and Weibin Sheng[1,3*]

## Abstract

**Objective** Spinal cord injury (SCI) is a debilitating condition that can result in permanent disability. Neuromodulation is a promising technology that has gained popularity as a treatment for SCI. This study aims to analyze the published literature to investigate the global trends and hotspots in research on neuromodulation in the context of SCI.

**Methods** All relevant publications on the topic of neuromodulation in SCI from January 1, 2005, to September 17, 2024, were acquired from the Web of Science Core Collection database. Bibliometric analysis was performed to evaluate the publication distribution by country, institution, author, and journal, as well as keyword, using CiteSpace, VOSviewer, and Scimago Graphica software.

**Results** Overall, 3,211 publications were eligible for inclusion in the analysis. The publication number in 2005 and 2024 were 77 and 222, respectively. A steady increasing trend in the publication number over the past two decades was observed. The Unites States published 1544 articles with 52,521 citations, ranking first regarding publication number and total citations. Case Western Reserve University was the most productive institution that published 181 papers. All of the highly productive institutions were located in the United States, Canada, and Australia. The University of California Los Angeles harvested 6626 total citations and 81.8 average citations, ranking first among the productive institutions. Gorgey AS published 60 articles and ranked first regarding total publication number. Edgerton VR harvested 4333 citations and ranked first among the authors for total citations. The analysis of high-yielding journals suggested that *Journal of Spinal Cord Medicine* was the most productive journal with 133 publications. *Spinal Cord* yielded 4200 citations and ranked first among the journals for total citations. The keyword analysis identified "functional electrical stimulation" and "spinal cord stimulation" as research hotspots.

**Conclusion** This study delineates the current knowledge landscape and research trends on the topic of neuromodulation in SCI. The findings highlight the growing interest in this field and underscore the significance of neuromodulation in SCI research.

**Keywords** Neuromodulation, Spinal cord injury, Bibliometric analysis, Web of science

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## Introduction

Spinal cord injury (SCI) is a devastating condition that can result in loss of neurological function, permanent disability, and catastrophic complications, which dramatically affect the life expectancy of affected individuals. The incidence of SCI varies among countries, with an annual estimate of 4–22 cases per 100,000 people globally [1]. The leading causes of SCI include falls, vehicle crashes, and sports-related injuries [2, 3]. The direct cost of SCI is estimated at 1.1–4.6 million dollars per individual over their lifetime. Therefore, SCI imposes a great financial burden to both affected individuals and healthcare systems [4]. Various efforts have been made to identify effective strategies for neuroprotection and regeneration in patients with SCI. Surgical decompression [5, 6], pharmacological agents [7], and hyperbaric oxygen therapies [8] have limited efficacy for the restoration of SCI. For stem cell therapies, low survival and integration rates and multilineage capacity of stem cells within the injured site largely limit the functional recovery following SCI [9]. Immune rejection and ethical considerations are also critical issues impeding the clinical application of stem cell therapies. There are still few effective therapeutic options for SCI.

Neuromodulation is a promising technology that uses electrical stimulation, magnetic stimulation, or chemical agents to alter neuronal activity and activate isolated neuronal circuitry at specific neurological sites [10]. Neuromodulation has been successfully used as a treatment for several neurological disorders, including stroke [11], Parkinson's disease [12], and chronic pain [10]. Concerning the human nervous system is capable of functional and structural changes in response to stimuli, a process known as neuroplasticity, researchers tried to employ neuromodulation technologies for the treatment of SCI. Neuromodulation has presented as an attractive therapeutic option for SCI, with evidence suggesting that enhancing neuronal excitability with either transcranial or transcutaneous stimulation can reestablish some volitional movements and skilled hand function [13]. The underlying mechanisms of neuromodulation for SCI remain indetermined, and different neuromodulation methods may have different presumed mechanisms. For example, electrical stimulation may contribute to the excitability of the dormant circuitry [14]. Spinal cord stimulation may enhance spinal postural-specific neural networks [15]. Besides, neuromodulation may enable lost function to be restored by inducing alterations in neuronal and non-neuronal activity after the cessation of stimulation, thus circumventing damaged neural pathways, fostering neural adaptation and recovery.

Recently, neuromodulation technologies have gained popularity as a treatment for SCI. However, the current research status, emerging hotspots, and research trends in this field remain undefined. Bibliometrics is a qualitative and quantitative approach that can be used to describe key findings and trends in a given field, and it has been widely utilized in SCI [16, 17]. Despite rapidly increasing publications, no structured bibliometric overview is available. In this study, we utilized bibliometrics to analyze the hotspots and trends in research on neuromodulation technology in the context of SCI, thus providing guidance for future research.

## Materials and methods

### Data source and retrieval strategies

A comprehensive literature search of the Web of Science Core Collection (WoSCC) database was performed to identify studies published from January 01, 2005 to September 17, 2024. The literature search was independently conducted by two coauthors (S.G. and Y.H.) according to the following search strategy: TS = ("neuromodulation" OR "vagus nerve stimulation" OR "electrical stimulation" OR "magnetic stimulation" OR "spinal cord stimulation" OR "peripheral nerve stimulation" OR "motor cortex stimulation" OR "brain stimulation" OR "dorsal root ganglion stimulation" OR "cranial stimulation") AND TS = ("spinal cord injury"). Publications satisfying the following criteria were included: (1) papers published in the WoSCC database; (2) publications published in the English language; and (3) original researches and review articles. Correspondingly, meeting abstracts, early access articles, book chapters, and letters were excluded.

### Data analyses and visualization

The publications identified in the WoSCC database were downloaded, screened, sorted, and extracted. Bibliometric analysis tools, including CiteSpace (version 6.3 R1), VOSviewer (version 1.6.20), and Scimago Graphica (version 1.0.42), were used for data analysis and visualization. VOSviewer was used to perform co-occurrence analysis [18]. The full counting method was applied to construct keyword networks, with a minimum occurrence threshold of 60. Default parameters were utilized for normalization and clustering. Link strength was calculated based upon co-occurrence frequency. CiteSpace was used to identify the research trends and hotspots in the scientific publications and to identify key topics of interest in the research field [19]. Time Slicing was set from January 01, 2005 to September 17, 2024, segmented into annual intervals. Node configuration encompassed keywords and references, with selection criteria set to retain the top 50 items per time slice. Network optimization employed pathfinding algorithms combined with both slice-wise and merged network pruning strategies, while maintaining default configurations for other parameters. Scimago Graphica was used to produce the map of collaborations among countries. Coordinates were derived

from multidimensional scaling of collaboration networks, applying z-score normalization.

## Results

### Literature selection and overall publication trend

Overall, 3,497 publications were identified. Subsequently, 274 publications were excluded, including 81 meeting abstracts, 76 proceedings papers, 55 editorial materials, 28 early access articles, 19 book chapters, and 15 letters. Of the remaining 3,223 publications, eight corrections, three retracted publications, and one news item were excluded. Finally, 3,211 publications, including 2,506 original research articles and 705 reviews, were eligible for inclusion in the analysis. A flowchart of the literature search and selection is displayed in Fig. 1. Overall, the number of publications on the topic of neuromodulation in SCI showed an increasing trend from 2005 to 2024 (Fig. 2).

### Publication distribution by country

Over the past two decades, 3,016 institutions from 73 countries have contributed publications on neuromodulation in the context of SCI. These studies were published in 650 academic journals and had 11,663 contributing authors. The data from these publications were used to produce a world map illustrating the collaborations among countries. The results showed that the United States had close collaborations with China, Canada, and England. However, the international collaborations among other countries appeared weak (Fig. 3). The United States ranked first in terms of the number of publications and total citations, suggesting that the United States has had a crucial influence in the field of spinal cord stimulation. Despite ranking fifth for the number of publications, Switzerland ranked first in terms of the average number of citations, suggesting its tremendous contribution to this field. China ranked third for the number of publications, while it ranked last for the average number of citations, suggesting that China was not among the highly influential countries in this field (Table 1).

### Publication distribution by institution

An estimated 3,016 institutions contributed to the identified publications. The top 10 contributing institutions are displayed in Table 2. Case Western Reserve University

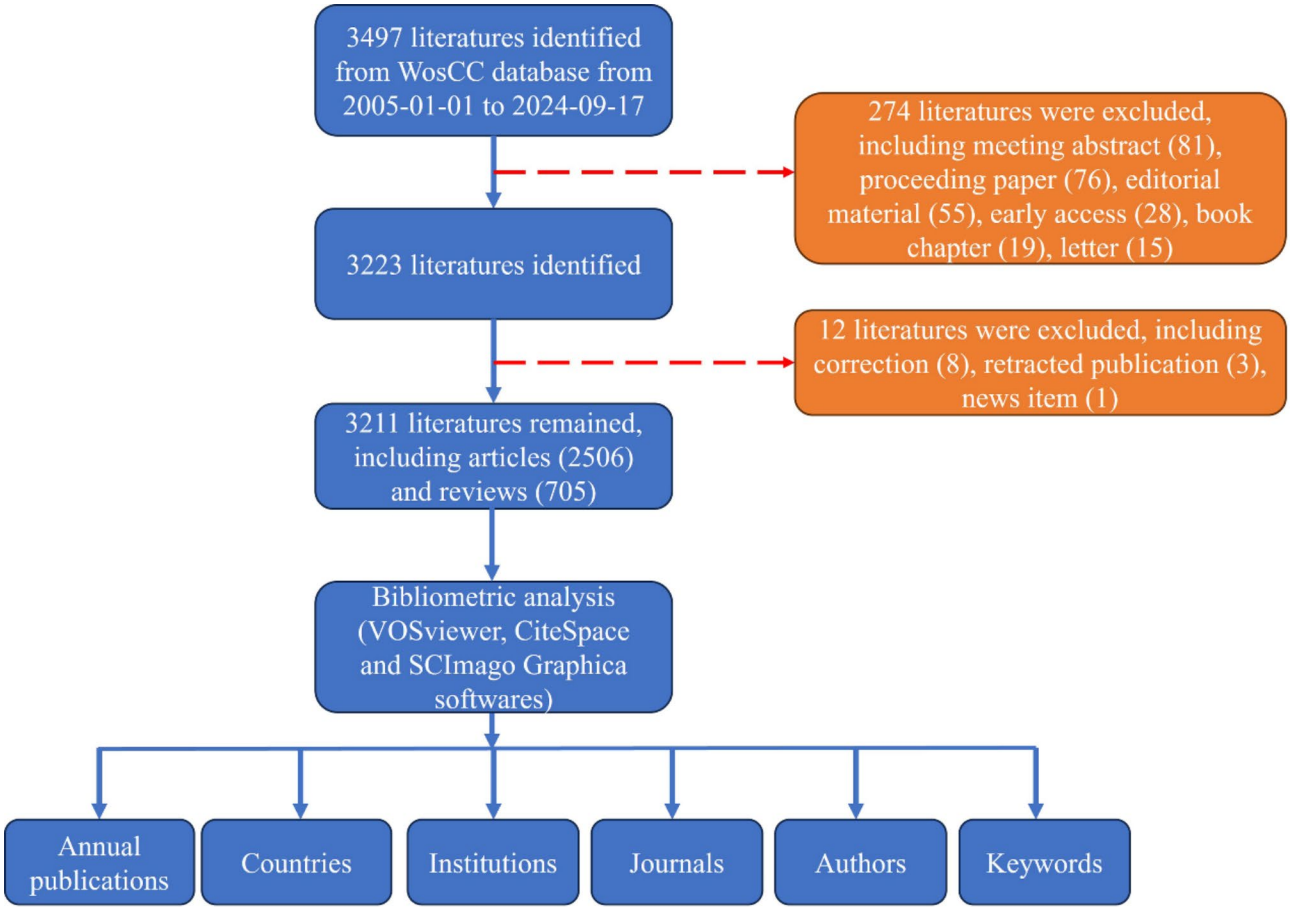


**Fig. 1** Flowchart of literature selection

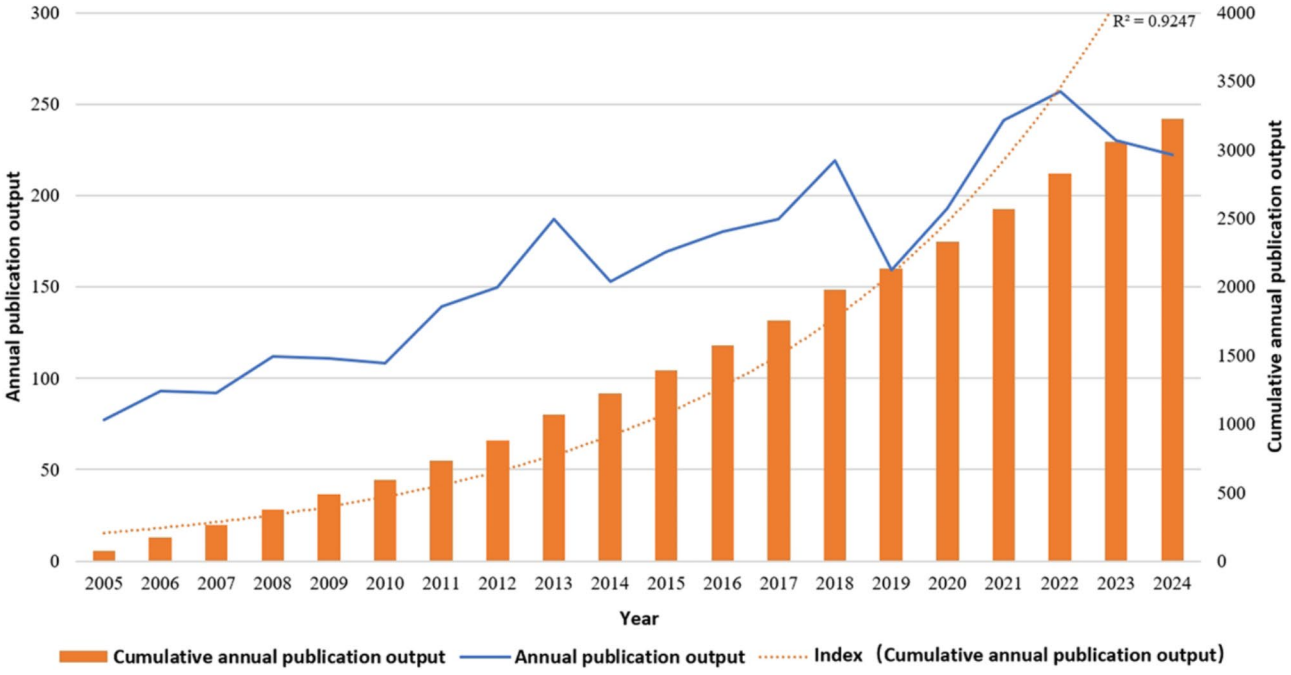


**Fig. 2** Annual publications and growth trends in research on neuromodulation in spinal cord injury

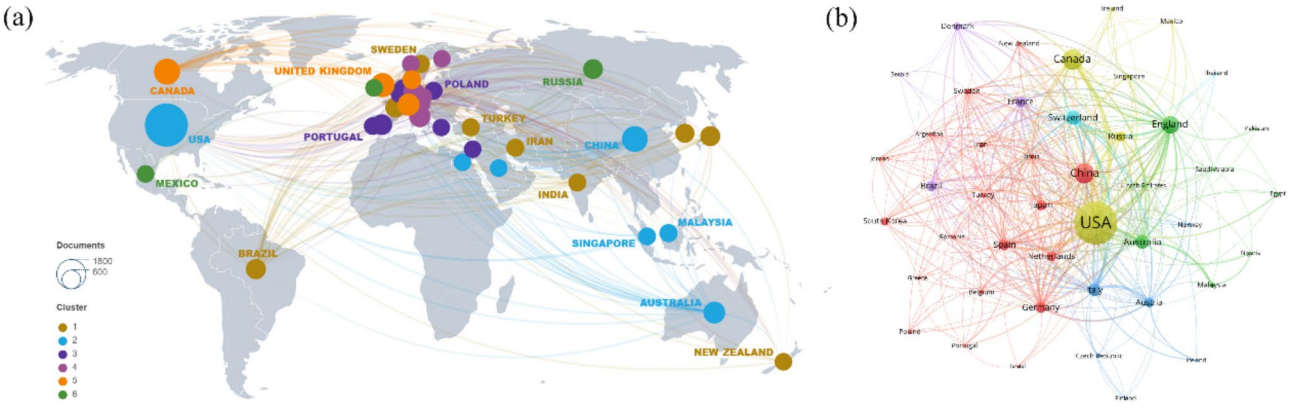


**Fig. 3** Collaborations among countries. (**a**) Country collaboration world map. (**b**) Network map of collaborations among countries

**Table 1** The top 10 productive countries in the field of neuromodulation and spinal cord injury

| Rank | Country | Documents | Percent (%) | Citations | Average citations | Total link strength |
|---|---|---|---|---|---|---|
| 1 | USA | 1544 | 48.08 | 52,521 | 34.0 | 767 |
| 2 | Canada | 376 | 11.71 | 14,127 | 37.6 | 261 |
| 3 | China | 363 | 11.30 | 6679 | 18.4 | 159 |
| 4 | England | 277 | 8.63 | 12,836 | 46.3 | 328 |
| 5 | Switzerland | 188 | 5.85 | 13,031 | 69.3 | 278 |
| 6 | Australia | 176 | 5.48 | 4857 | 27.6 | 224 |
| 7 | Italy | 156 | 4.86 | 7613 | 48.8 | 250 |
| 8 | Germany | 127 | 3.96 | 8273 | 65.1 | 180 |
| 9 | Spain | 127 | 3.96 | 7012 | 55.2 | 192 |
| 10 | France | 115 | 3.58 | 4476 | 38.9 | 150 |

**Table 2** Top 10 most productive institutions in the field of neuromodulation and spinal cord injury

| Rank | Institution | Country | Documents | Citations | Average citations | Total link strength |
|---|---|---|---|---|---|---|
| 1 | Case Western Reserve University | USA | 181 | 4974 | 27.5 | 2507 |
| 2 | University of Alberta | Canada | 109 | 4881 | 44.8 | 2407 |
| 3 | University of Toronto | Canada | 103 | 4355 | 42.3 | 1990 |
| 4 | University of Miami | USA | 90 | 2521 | 28.0 | 1720 |
| 5 | University of California, Los Angeles | USA | 81 | 6626 | 81.8 | 5349 |
| 6 | Univ British Columbia | Canada | 80 | 2827 | 35.3 | 2165 |
| 7 | University of Pittsburgh | USA | 76 | 3181 | 41.9 | 1715 |
| 8 | University of Sydney | Australia | 74 | 1463 | 19.8 | 898 |
| 9 | University of Louisville | USA | 69 | 2900 | 42.0 | 3609 |
| 10 | Northwestern University | USA | 66 | 2431 | 36.8 | 1381 |

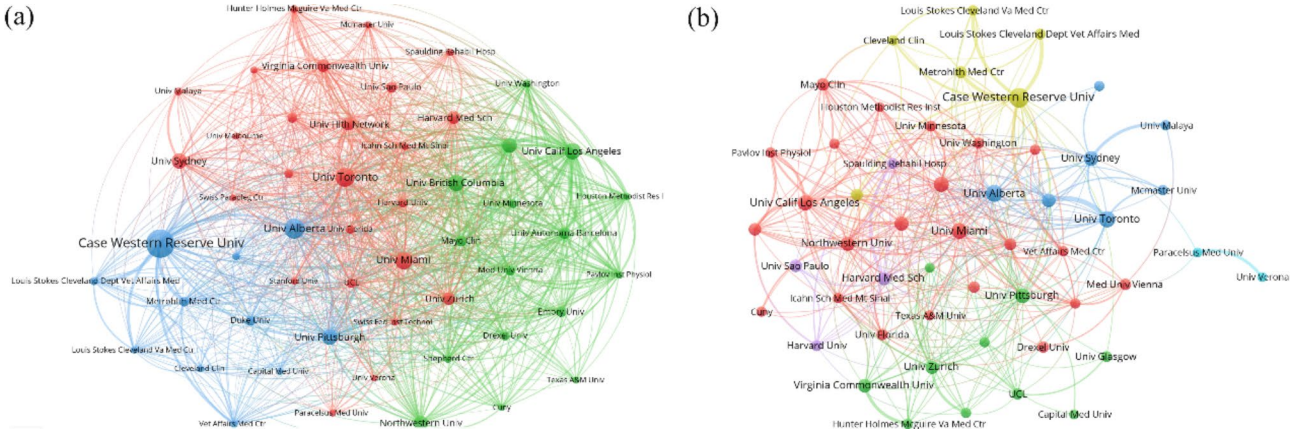


**Fig. 4** Collaborations among institutions. (**a**) Publication distribution by institution. (**b**) Network map of collaborations among institutions

**Table 3** The top 10 most productive authors in the field of neuromodulation and spinal cord injury

| Rank | Author | Country | Documents | Citations | Average citations |
|---|---|---|---|---|---|
| 1 | Gorgey AS | USA | 60 | 1287 | 21.45 |
| 2 | Triolo RJ | USA | 55 | 1480 | 26.91 |
| 3 | Edgerton VR | USA | 48 | 4333 | 90.27 |
| 4 | Popovic MR | Canada | 35 | 1202 | 34.34 |
| 5 | Perez MA | USA | 34 | 1221 | 35.91 |
| 6 | Mushahwar VK | Canada | 33 | 876 | 26.55 |
| 7 | Davis GM | Australia | 31 | 428 | 13.81 |
| 8 | Courtine G | Switzerland | 30 | 3430 | 114.33 |
| 9 | Harkema SJ | Switzerland | 30 | 1265 | 42.17 |
| 10 | Audu ML | USA | 26 | 661 | 25.42 |

published the most papers, followed by University of Alberta and University of Toronto, respectively (Fig. 4a). All high-yield institutions were located in the United States, Canada, and Australia, indicating that these countries had made remarkable contributions to this field. In terms of citations, University of California Los Angeles ranked first for both average and total citations, as well as yielding the highest total link strength. The co-authorship network analysis between institutions indicated strong collaboration among institutions (Fig. 4b).

### Publication distribution by author

Ninety-six authors with a minimum of 10 publications were identified. The top 10 most productive authors are summarized in Table 3. Five of the top 10 authors came from the United States, two came from Canada, two came from Switzerland, and one came from Australia. Gorgey AS ranked first in terms of the number of publications and citations (60 publications and 1,287 citations), followed by Triolo RJ and Edgerton VR, respectively. Edgerton VR was the author with the highest number of citations, while Courtine G was the author yielding the highest average citations. Besides, Fregni F [20] and Kumru H [21] are the authors who did not have as many total publications but had a high growth rate in recent years. The analysis of authors' contributions and the co-authorship network between authors are displayed in Fig. 5.

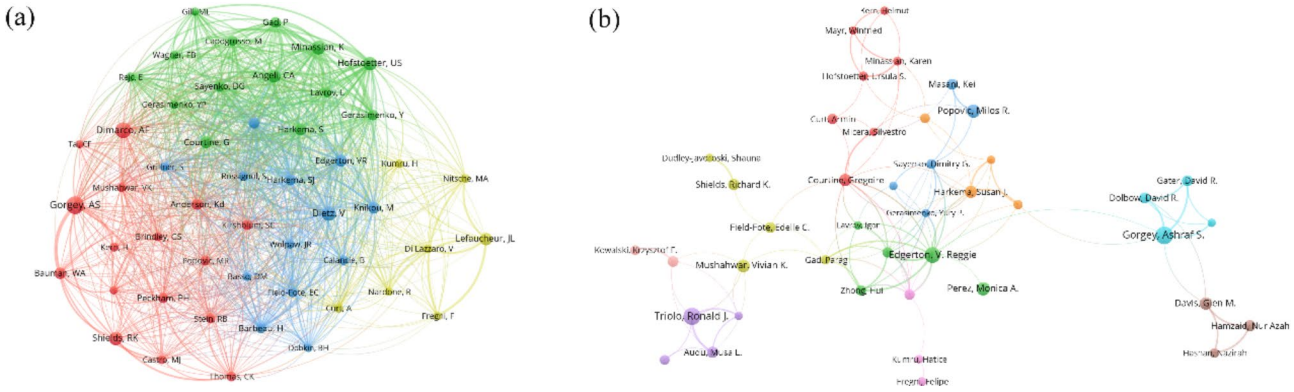


**Fig. 5** Collaborations among authors. (**a**) Publication distribution by author. (**b**) Network map of collaborations among authors

**Table 4** Top 10 most productive journals in the field of neuromodulation and spinal cord injury

| Rank | Journal | Documents | Citations | Impact Factor (2023) | Journal Citation Reports |
|---|---|---|---|---|---|
| 1 | Journal Of Spinal Cord Medicine | 133 | 2455 | 1.8 | Q3 |
| 2 | Spinal Cord | 132 | 4200 | 2.1 | Q3 |
| 3 | IEEE Transactions on Neural Systems and Rehabilitation Engineering | 73 | 1842 | 4.8 | Q2 |
| 4 | Journal of Neurophysiology | 72 | 2143 | 2.1 | Q3 |
| 5 | Experimental Neurology | 68 | 2211 | 4.6 | Q1 |
| 6 | Archives of Physical Medicine and Rehabilitation | 66 | 2222 | 3.6 | Q1 |
| 7 | Journal of Neurotrauma | 62 | 2114 | 3.9 | Q1 |
| 8 | Neuromodulation | 62 | 895 | 3.2 | Q2 |
| 9 | Frontiers in Neuroscience | 59 | 1063 | 3.2 | Q2 |
| 10 | Journal of Neural Engineering | 59 | 1662 | 3.7 | Q2 |

### Analysis of high-yielding journals

Overall, 3,211 eligible papers were published in 650 journals, with 50 of these journals publishing more than 12 papers. The detailed information of the top 10 most productive journals is summarized in Table 4. Based on the analysis of high-yielding journals, the top 10 journals contributed a total of 786 papers (24.5% of the overall publications). *Journal of Spinal Cord Medicine* ranked first with 133 publications, followed by *Spinal Cord* (132 publications) and *IEEE Transactions on Neural Systems and Rehabilitation Engineering* (73 publications). For total citation frequency, *Spinal Cord* ranked first, far exceeding all other journals, despite this journal having a relatively low impact factor. The top 10 prolific journals were mainly distributed in the field of neuroscience. The analysis of contributing journals and the co-citation analysis network are displayed in Fig. 6.

### Analysis of highly cited papers

The total citation number is a crucial indicator for evaluating the impact of a publication. The top 10 most widely cited papers are displayed in Table 5, two of which surpassed 1,000 citations [22, 23]. The papers were published between 2005 and 2017, including six original research articles and four review articles. The most cited publication was a review article published in the journal of *Sensors* [22]. The most highly cited papers were published by dispersed research groups, with the researchers from Switzerland, the United States, and Canada.

### Keyword analysis

Keyword co-occurrence analysis was performed to understand the research hotspots and directions in the field of neuromodulation in SCI. Totally, 10,409 keywords were extracted from the publications. A network map was produced for keywords that appeared at least 60 times, totaling 51 keywords (Fig. 7a). Visualization of the keyword distribution by publication year indicated that most of the keywords were published from 2014 to 2019. The keywords "neuromodulation," "spinal cord stimulation," "electrical stimulation," and "epidural stimulation" were identified as relatively new keywords that had emerged recently (Fig. 7b). Visualization of keyword clusters suggested that "stimulation," "spinal cord injuries," and "functional electrical stimulation" had been research hotspots since 2005 (Fig. 7c).

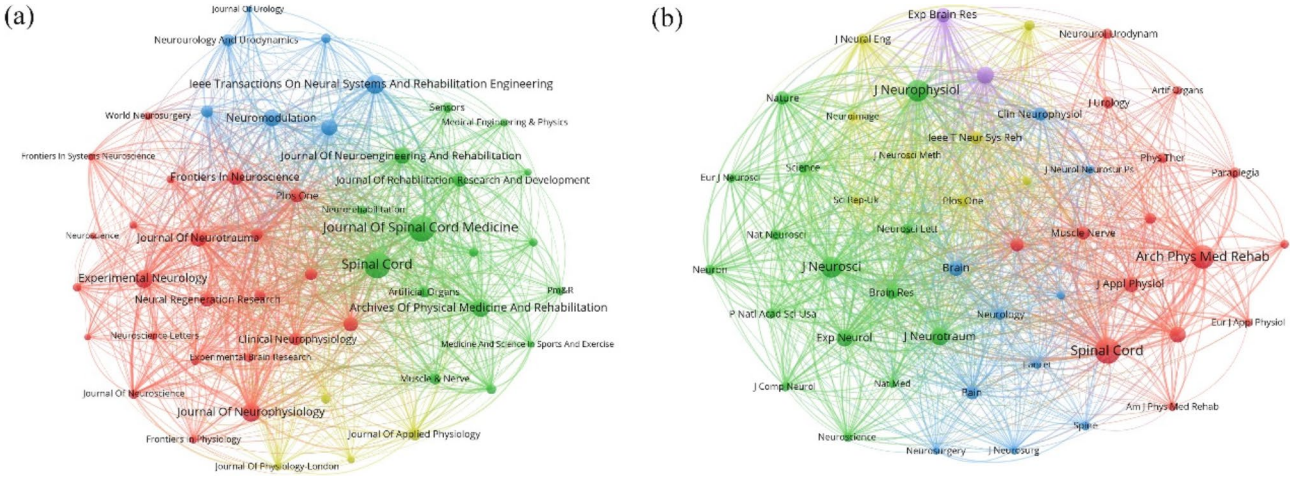


**Fig. 6** Analysis of high-yielding journals. (**a**) Visualization of high-yielding journals. (**b**) Network map of co-cited journals for research on neuromodulation in spinal cord injury

**Table 5** The top 10 most cited paper in the field of neuromodulation and spinal cord injury

| Rank | Title | First author | Year | Journal | Impact factor | Citations |
|---|---|---|---|---|---|---|
| 1 | Brain computer interfaces, a review | Nicolas-Alonso LF | 2012 | Sensors (Basel) | 3.4 | 1290 |
| 2 | Traumatic spinal cord injury | Ahuja CS | 2017 | Nature Reviews Disease Primers | 76.9 | 1174 |
| 3 | Biomaterials. Electronic dura mater for long-term multimodal neural interfaces | Minev IR | 2015 | Science | 44.7 | 764 |
| 4 | Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: a case study | Harkema SJ | 2011 | Lancet | 98.4 | 746 |
| 5 | A critical review of interfaces with the peripheral nervous system for the control of neuroprostheses and hybrid bionic systems | Navarro X | 2005 | Journal of Peripheral Nervous System | 3.9 | 615 |
| 6 | The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury | Esquenazi A | 2012 | American Journal of Physical Medicine Rehabilitation | 2.2 | 604 |
| 7 | Targeted neurotechnology restores walking in humans with spinal cord injury | Wagner FB | 2018 | Nature | 50.5 | 590 |
| 8 | Restoring cortical control of functional movement in a human with quadriplegia | Bouton CE | 2016 | Nature | 50.5 | 549 |
| 9 | A sham-controlled, phase II trial of transcranial direct current stimulation for the treatment of central pain in traumatic spinal cord injury | Fregni F | 2006 | Pain | 5.9 | 540 |
| 10 | Cognitive motor processes: the role of motor imagery in the study of motor representations | Munzert J | 2009 | Brain Research Reviews | 5.93 | 515 |

Burst words represent keywords that have received widespread attention from related researchers during a certain period of time. The top 25 "burst words" were identified and are displayed in Fig. 7d. The strongest burst word was "spinal cord injuries," which appeared in 2005 and was absent in 2015. Moreover, "reliability" and "motor function" were identified as the latest keywords with strong citation bursts, suggesting that these keywords have been research hotspots in recent years.

## Discussion

### Overview of neuromodulation technology in SCI

Despite numerous basic and clinical studies being performed on SCI, few effective and standardized treatments are available for this disorder. Traditional treatments only provide symptomatic relief and reduce the complications resulting from SCI. Recent studies have indicated that stem cell transplantation and tissue engineering regeneration technologies may reconnect the transected spinal cord in rodents, but their clinical efficacy remains unsatisfactory [9]. However, neuromodulation technology may be useful to consolidate neuronal connections or

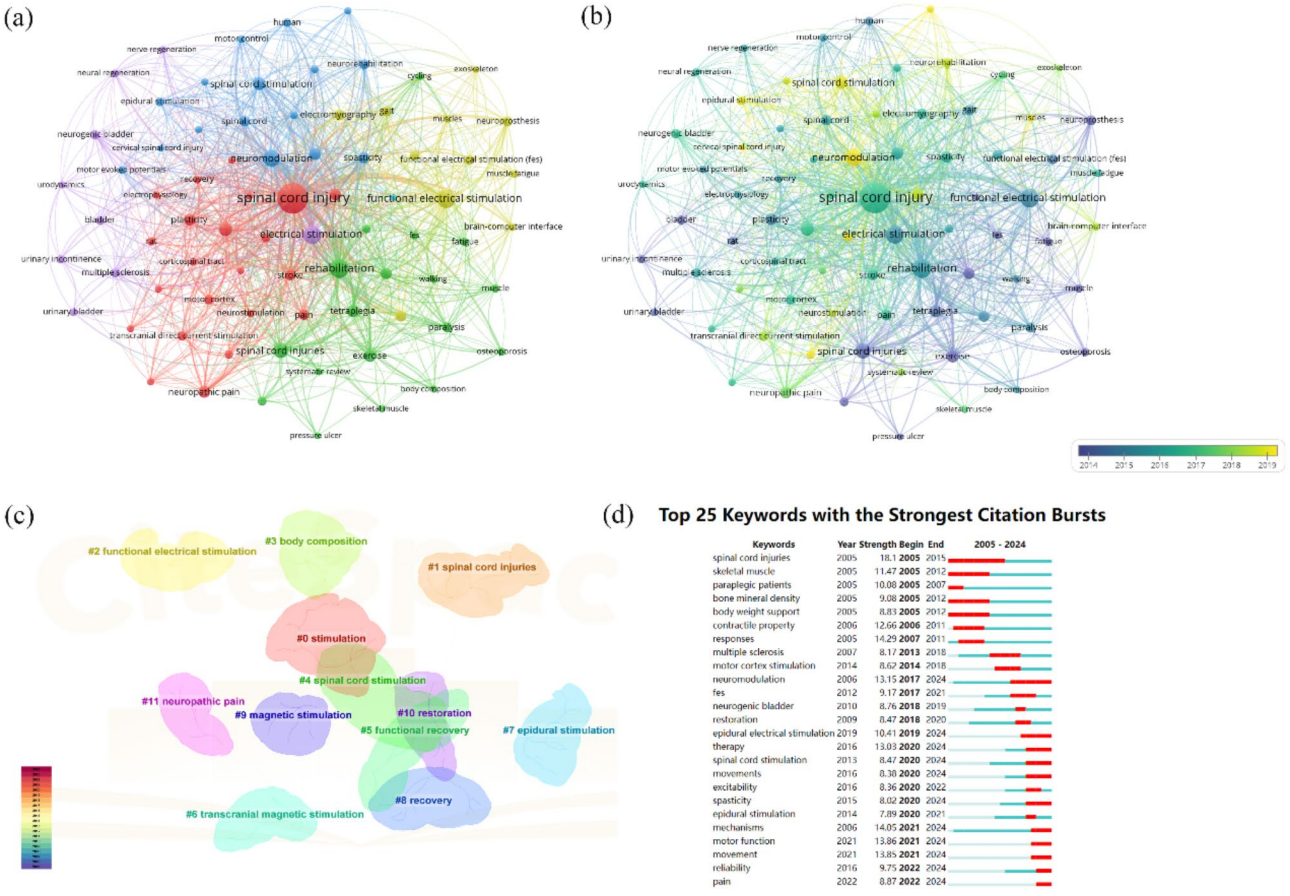


**Fig. 7** Analysis of keywords. (**a**) Network visualization of keywords. (**b**) Distribution of keywords according to publication year. (**c**) Keyword clustering visualization from 2005 to 2024. (**d**) Top 25 keywords with the strongest citation bursts

act synergistically to enhance neuroplasticity, providing a new opportunity for the treatment of SCI.

Neuromodulation may promote an extensive reorganization of cortico–reticulo–spinal circuits that mediate a motor cortex–dependent neurological recovery [24]. Besides, some nerve fibers survive the injury, and these residual neural pathways remain functionally silent as the hypoactivity below the injury. Neuromodulation may remodel the residual descending pathways and promote neurological recovery [25]. In addition, stimulation may enhance corticospinal tract axonal sprouting and outgrowth, thus promoting movement recovery and repair of the corticospinal tract [26]. The present study systematically collected and analyzed the relevant literature on neuromodulation in the context of SCI. The findings indicate that neuromodulation has received substantial attention as a treatment approach for restoration and rehabilitation following SCI.

Through literature searching, screening, and selection, 3,211 publications on the topic of neuromodulation in SCI were identified in the WoSCC database. Since 2005, the overall number of publications has steadily increased. We comprehensively analyzed the contributions by country, institution, journal, and author. We found that the United States far exceeded the other countries in terms of the number of publications and citations, suggesting that the United States has been the most influential country and has played a crucial role in this field. This is likely because the United States possesses technologically advanced equipment and excellent researchers. Of note, China ranked third in terms of the number of publications, while it ranked last in terms of average citations, indicating a poor quality of publications. Therefore, in the future, Chinese scholars should prioritize more meaningful and original studies, focusing on research quality rather than quantity.

In the analysis of publications by institution, the top 10 highly productive institutions were all located in developed countries, including the United States, Canada, and Australia. Case Western Reserve University had the highest number of publications, followed by University of Alberta and University of Toronto, respectively. University of California Los Angeles ranked fifth in terms of the number of publications, while it ranked first in terms of average citations, suggesting that its academic achievements had obtained widespread attention and

interest. The co-authorship network between institutions suggested that University of California Los Angeles had established extensive collaborative associations with other institutions. *Journal of Spinal Cord Medicine* was the most prolific journal, followed by *Spinal Cord* and *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, respectively. *Spinal Cord* had the largest number of citations, indicating its popularity in this field. Therefore, scholars interested in this field should pay particular attention to these journals. We identified that the authors with high productivity and citations mainly come from the United States, Canada, Australia, and Switzerland. Gorgey AS published the greatest number of papers, while Edgerton VR ranked first in terms of the number of citations. Interestingly, Courtine G was one of the most influential authors with the highest average citations in this field. Two of the top 10 cited articles were published by Courtine G and colleagues [27, 28].

The most highly cited paper was a review article published in *Sensors* about brain computer interfaces in neurological disorders [22]. Harkema S and colleagues reported that epidural stimulation technology enabled a man to realize weight-bearing standing, concluding that epidural stimulation might reactivate silent spared neural circuits and promote plasticity [29]. Moreover, Minev IR and colleagues designed an electronic dura mater that was capable of delivering electrochemical neuromodulation and restoring locomotion after SCI [28]. These findings have laid a crucial foundation for clinical translation of future researches related to neuromodulation in SCI.

#### Research hotspots

Cluster analysis enables the identification of leading research directions and progress, while keyword and burst co-occurrence analysis reflects the research hotspots [30]. In this study, visualization of the keyword distribution by publication year indicated that "neuromodulation," "spinal cord stimulation," "electrical stimulation," and "epidural stimulation" emerged more recently. Visualization of keyword clusters suggested that "stimulation" and "functional electrical stimulation" were hotspots in this field. The hotspots were associated with particular clinical endpoints in SCI, including improved gait, upper extremity function, and autonomic regulation. Visualization of burst words demonstrated that "reliability" and "motor function" were the latest keywords with strong citation bursts, suggesting that they had emerged as research hotspots in recent years. Perhaps reliability is emphasized due to an increased focus on standardized outcome measures or reproducible clinical results.

Neuromodulation technology, which mainly consists of spinal cord stimulation and other modalities that aim to modulate neural circuits and regain neuroplasticity, has emerged as a promising therapy for SCI and provided a transformative approach to the restoration of sensorimotor function [31, 32]. Although the exact mechanism of spinal cord stimulation remains unclear, its application in suitable patients has shown favorable outcomes [33]. Notably, in the majority of studies reporting functional improvements following spinal cord stimulation, stimulation has been paired with physical training. Epidural stimulation may induce obstructive neural pathways to produce movement and improve the capability of the spinal cord to transmit sensory messages, thus activating motor neurons [27].

#### Future perspectives

Despite reports on neuromodulation-based technology for SCI surging over the past two decades, substantial obstacles still impede its extensive clinical application. These challenges, such as patient heterogeneity, intervention time, technical accessibility, device affordability, and durability, undoubtedly pose significant barriers to the broad adoption of neuromodulation [13]. Forthcoming artificial intelligence algorithms, interdisciplinary collaborations, integration of virtual and augmented reality technologies, and personalized neuromodulation are anticipated to enhance the efficacy of neuromodulation and broaden the scope of its application in the context of SCI [34]. Artificial intelligence technologies may help researchers track and analyze the real-time changes of neural structure, neurodynamics, neuroplasticity following neuromodulation, and provide neural spatial-temporal information measurement and visualization, thus optimizing the stimulation parameters. Virtual and augmented reality technologies may provide a user–computer interface, which can implement real-time neuromodulation, thus allowing user interaction via multiple sensory modalities and augmenting the affected individuals' attention and motivation. In addition, progress in neuromodulation requires personalized neuroinformatics sustained by a deeper understanding of the underlying neurophysiological mechanisms [10]. Although tough challenges remain, robust clinical evidence supports neuromodulation-induced functional recovery following injury [25]. Scholars' efforts may help to overcome these challenges, and neuromodulation technology is anticipated to become a leading candidate for the restoration of neurological function after SCI.

#### Strengths and limitations

In terms of this study's strengths, bibliometric analysis, a useful approach to describe research hotspots and trends in a given field, was used to describe the landscape of research on neuromodulation in the context of SCI. The findings of this study will assist scholars in understanding the current status of research on neuromodulation in SCI. Moreover, delineating the current hotspots and

future trends on this topic will assist scholars in designing future studies that are highly relevant and that have the potential to advance this field.

This study also has limitations that should be considered. First, the data were only retrieved from the WoSCC database published in English. Therefore, some unpublished or non-WoSCC-cited publications were not incorporated, which might have led to publication or language biases. Multiple databases should be included in future studies to verify the robustness of our findings. Second, authors tend to cite articles published in the journals in which they expect to publish their research findings, and recently published research may not be as frequently cited as older research. Therefore, bibliometric analysis has the potential to generate biased results.

## Conclusion

This study presents an overview of the global trends and hotspots in research on neuromodulation technology in SCI. The findings highlight the growing interest in this field and underscore the significance of neuromodulation as a therapeutic strategy for SCI.

### Abbreviations

| | |
|---|---|
| WoSCC | Web of Science Core Collection |
| SCI | Spinal cord injury |

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### Author contributions

WS, SG, and YH designed this work. SG, YH, SL drafted the manuscript. SG and WL downloaded and analyzed the data. All the authors contributed to the article revision and read and approved the submitted version.

### Data availability

No datasets were generated or analysed during the current study.

## Declarations

### Competing interests

The authors declare no competing interests.

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