A Review Of Artificial Intelligence towards Neuromodulation in Spinal Cord Injury Patients

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**ABSTRACT**

Spinal Cord Injury (SCI) is a neurological disorder which involves damage to the spinal cord, a bundle of nerve fibers that carry nerve signals from the brain to the rest of the body. While there are existing treatments for SCI, neuromodulation(a new emerging treatment) is looking to be more promising and efficient than others. The integration of artificial intelligence (AI) in various fields have been shown to bring about multiple benefits such as increasing efficiency and quality by detecting errors and optimizing processes. The same can be predicted for the integration of artificial intelligence in neuromodulation for SCI. In this review, we will interrogate the use of AI to enhance the efficacy of neuromodulation in SCI treatment.

**1. INTRODUCTION**

Spinal Cord Injury (SCI) is a neurological disorder that involves damage to the bundle of nerve fibers that sends and receives signals from the brain [(Bryant, 2024)](https://www.zotero.org/google-docs/?37UlwD). The symptoms a person with SCI can experience include paralysis, loss of bladder and bowel control, numbness or a loss of sensation in the hands and feet [(Bryant, 2024)](https://www.zotero.org/google-docs/?HBWBNC). People with SCI experience varying levels of severity [(Gupta et al., 2024)](https://www.zotero.org/google-docs/?nThcZ1). The symptoms of mild spinal cord injury include minor sensory and motor loss, with some function preserved below the level of injury. Inflammation and edema are typically less severe in patients with less severe injuries, which leads to better recovery prospects [(Wu et al., 2021)](https://www.zotero.org/google-docs/?fao7PA). However, individuals with moderate-level injuries experience far-reaching symptoms such as weakness or partial paralysis [(Juli Setiadi & Herlina, 2023)](https://www.zotero.org/google-docs/?M1NbLH). Lastly, those with severe SCI experience symptoms such as loss of bladder control, total motor sensory paralysis and diminished respiratory function. Thus, regardless of the level of the severity, SCI has multiple debilitating consequences to the patient.

Multiple statistical reports show that SCI is a prevalent condition that affects a significant number of people. According to WHO, there are over 15 million people living with SCI globally [(Brigden, 2024)](https://www.zotero.org/google-docs/?aVZ9P6), with an estimated 3.6 million people requiring ongoing care. After SCI, sophisticated and costly medical support is required. Patients with SCI worldwide have a lifetime financial burden that can vary from $1.5 million to $3 million [(Diop et al., 2021)](https://www.zotero.org/google-docs/?1vrFLd). In the meantime, people with SCI in the United States incur an average yearly medical expense of up to $676,000, placing a significant financial strain on both the patients and the healthcare system. As a result, treating SCI and lowering costs continue to be challenging, worldwide public health issues.

There are multiple treatments available for SCI ranging from cell therapeutics to drug therapeutics [(Zhou et al., 2019)](https://www.zotero.org/google-docs/?M7pU3n). These treatments have shown great promise in treating patients with SCI. For example, cell therapeutics which include the use of embryonic stem cells (ESCs), induced pluripotent stem cells (iPSCs), mesenchymal stem cells (MSCs), and neural stem/progenitor cells (NSPCs) provide neuroprotective benefits and help regulate the immune response, which is important for reducing secondary damage post-injury [(Zeng, 2023; Zhou et al., 2019)](https://www.zotero.org/google-docs/?PibshB). The efficacy of these cell types vary when measured with different metrics related to SCI. These metrics include motor and sensory functional recovery, neural tissue preservation, and reduction in gliosis and inflammation.

Embryonic Stem Cells can differentiate into any cell type, including neurons and glial cells, which are important for spinal cord repair.In a study by Kim et al, a differentiated type of ESC was integrated into the host tissue, and significantly improved locomotor function [(Hu et al., 2024)](https://www.zotero.org/google-docs/?5e2Szb). However, their use raises ethical concerns related to the destruction of embryos. Moreso, ESCs are prone to tumor formation, but this can be circumvented by transplanting them in a differentiated form [(Zeng, 2023)](https://www.zotero.org/google-docs/?lDrZQ8).

IPSCs are generated from reprogramming somatic adult cells such as Oct3/4, Sox2, Klf4, and c-Myc. The advent of IPSCs provides a solution to certain problems such as rejection complications, and ethical issues that are linked to the use of ESCs [(Sabri, 2022)](https://www.zotero.org/google-docs/?broken=CdbXvH). IPSCs have been used in various scenarios to improve locomotion and reduce inflammation after SCI.[(Wertheim et al., 2022)](https://www.zotero.org/google-docs/?broken=fZVswm)

MSCs reduce inflammatory markers and modulate immune response, which is important to SCI. They promote the release of neurotrophic factors, such as brain-derived neurotrophic factor (BDNF), which support neuronal survival and regeneration [(Tsuji et al., 2024)](https://www.zotero.org/google-docs/?broken=RpUlDq).

Neural Stem Cells offer significant potential for treating Spinal Cord Injuries(SCI) due to their ability to differentiate into various neural cell types and promote tissue repair. They do this through mechanisms such as synaptic integration, myelin regeneration, and modulation of inflammatory responses(Li et al., 2024)[(Nagoshi et al., 2024)](https://www.zotero.org/google-docs/?broken=0xL4VS).

Drug therapeutics such as Methylprednisolone (MP) are admitted to reduce inflammation and prevent further neuronal damage after SCI. Reducing the secondary inflammatory response, repairing the blood-spinal cord barrier, boosting the spinal cord blood flow, scavenging free radicals, and increasing neurotrophic factor production are the basic mechanisms of MP in SCI [(Hu et al., 2023)](https://www.zotero.org/google-docs/?broken=U3RmYM). Also, drugs such as amitriptyline, gabapentin, and pregabalin are used for treating neuropathic pain. Nonetheless, these treatments still have downsides. For methylprednisolone (a steroid anti inflammatory), some of its limitations include mood disorders, irritability, and glucose intolerance. For the other treatments, limitations include harmful drug-drug interactions due to polypharmacy, receptor adaptation, high cost and strict regulations. Thus, more effective treatments are needed for patients [(P.Tran & Silver, 2015)](https://www.zotero.org/google-docs/?broken=q5Jf8j). This review explores the field of neuromodulation in Spinal Cord Injury. In particular, we will interrogate the use of artificial intelligence to enhance the efficacy of neuromodulation in SCI treatment.

**2. NEUROMODULATION AS A TREATMENT FOR SPINAL CORD INJURY**

Neuromodulation is a field that involves manipulation of nerve activity through targeted delivery of electrical, magnetic or chemical stimuli to specific neurological sites [(Hillery et al., 2024)](https://www.zotero.org/google-docs/?broken=uer8OK). This technique is used to treat a variety of conditions, including chronic pain, neurological disorders, and psychiatric conditions. There are different techniques, including deep brain stimulation, transcranial magnetic stimulation, and transcranial direct current stimulation.With neuromodulatory techniques, patients can have their treatments specifically tailored to their needs.

**2.1 Deep Brain Stimulation**

Deep brain stimulation is a neuromodulatory technique that involves implanting electrodes into specific areas of the brain. The electrodes make electrical impulses that affect brain activity to treat medical conditions [(Herrington et al., 2016)](https://www.zotero.org/google-docs/?broken=qCe78s). DBS is commonly used to treat conditions such as Parkinson's Disease, Tremor, and Epilepsy. The most commonly used DBS system works by implanting stimulating electrodes in the subthalamic nucleus (STN), globus pallidus interna (GPi), or ventral intermediate nucleus of the thalamus (VIM). These electrodes are then connected to a device which is placed under the collarbone. A clinician then controls the device wirelessly to adjust the parameters of stimulation so as to maximize pain relief and reduce side effects [(Herrington et al., 2016)](https://www.zotero.org/google-docs/?broken=J9aAfX).

DBS has been shown to significantly improve motor function in patients with advanced Parkinson’s disease, as shown by improvements in Unified Parkinson’s Disease Rating Scale (UPDRS) scores [(Radu et al., 2024)](https://www.zotero.org/google-docs/?broken=Mkfutl). However, DBS is an invasive surgical procedure that carries inherent risks such as intracerebral hemorrhage, phlebitis, myocardial infarction, pulmonary embolism, and damage to brain tissue. Additionally, DBS requires careful programming and adjustment of stimulation parameters, which can be a complex process. Furthermore, the long-term effects of continuous brain stimulation are not fully understood, and there is a risk of device malfunction or battery depletion over time.

**2.2 Transcranial Magnetic Stimulation**

Transcranial Magnetic Stimulation(TMS) is a non-invasive neuro-modulatory technique that changes the electrical property of cortical neurons by using a rapidly changing magnetic field [(Awad et al., 2015)](https://www.zotero.org/google-docs/?broken=XJKvXq). There are various forms of TMS, such as Single-Pulse TMS(spTMS), Paired-Pulse TMS (ppTMS), and Repetitive TMS (rTMS). Repetitive Transcranial Magnetic Stimulation (rTMS), the most common form, is a form of TMS and its mechanism includes placing a coil on the scalp near the area of the brain to be stimulated. Then, the coil generates magnetic pulses that pass through the skull and induce electrical currents in the brain tissue. These electrical currents can either be high-frequency or low-frequency. High frequency magnetic stimulation increases cortical motor excitability and low frequency stimulation decreases cortical motor excitability [(Lin et al., 2023)](https://www.zotero.org/google-docs/?broken=0W6572).

An FDA approved treatment for major depressive disorder, TMS is commonly used in diseases such as depression and obsessive compulsive disorder [(Filipčić et al., 2019)](https://www.zotero.org/google-docs/?broken=95S2js). It was first used in the context of Spinal Cord Injury in the late 90s to study motor cortical circuitry, focusing on understanding the neural mechanisms underlying motor function recovery [(Bailey et al., 2014)](https://www.zotero.org/google-docs/?broken=FiFnmF).

It has been used as a treatment method for SCI in various studies. It improves motor function by increasing motor excitability and decreasing corticospinal tract inhibition. It can also be used to reduce neuropathic pain and spasticity [(Yuhong et al., 2023)](https://www.zotero.org/google-docs/?broken=48e61o).

When compared to other neuromodulatory techniques, TMS has certain advantages such as its noninvasiveness, which minimizes risks associated with surgical interventions; it also allows for high temporal and spatial resolution which allows it to precisely target cortical areas [(Brighina et al., 2020)](https://www.zotero.org/google-docs/?broken=c8VQ8C). However, TMS still faces limitations. There is still limited data in current literature regarding the efficacy of rTMS for spinal cord injury, suggesting that results neither support nor discourage its use [(Chen et al., 2023)](https://www.zotero.org/google-docs/?broken=unlWpX). Also, there is a lack of standardized protocol for its application in SCI, and this complicates the interpretation of results and limits comparability across studies . Lastly, TMS is subjective in nature and is heavily reliant on patient participation.

**2.3 Functional Electrical Stimulation:**

Functional electrical stimulation (FES) is a widely used procedure in neuromodulation that involves applying electrical stimuli to paralyzed nerves or muscles while a specific task is being performed. It is often used with tasks like cycling or rowing [(Luo et al., 2020)](https://www.zotero.org/google-docs/?broken=PrjVvE).

These electrical impulses can either be delivered to targeted nerves or surrounding skin above the muscles. However, targeting nerves instead of muscle fibers is preferred because it requires less power by using smaller charge densities, leading to more effective results with a lower risk of tissue damage.

FES has emerged as a promising intervention for individuals with SCI with its first use occurring in 1973 at the University of Virginia, where implanted electrodes were used to stimulate the femoral and sciatic nerves of a paraplegic individual [(Cooper et al., 2006)](https://www.zotero.org/google-docs/?broken=OwZHC2). In a study by Atkins et al, it was concluded that FES shows promise in improving muscle health, primarily by partially reversing muscle atrophy and intramuscular fat content [(Atkins & Bickel, 2021)](https://www.zotero.org/google-docs/?broken=YqiInf).

There is limited literature surrounding FES treatment for Spinal Cord Injury. However, personalized medicine, fine tuning training schedules and stimulation parameters to individual patient needs, as well as increasing sample size, and conducting multicenter studies may provide more insights into the specific efficacies of FES treatments.

**2.4 Spinal Cord Stimulators:**

While stimulations such as FES are used for the restoration of function in SCI patients, Spinal Cord Stimulators are devices designed to reduce chronic pain by delivering electrical impulses to the spinal cord through electrodes.

The origin of SCS dates back to 1965, where a group of scientists proposed a theory known as the Gate Control Theory, a theory which explains how the spinal cord controls pain signals that travel to the brain. However, it has been discovered that this theory might not have much significance to SCS. Nonetheless, conventional SCS- the common stimulation technique originated from this theory [(Martin et al., 2024)](https://www.zotero.org/google-docs/?broken=G93EAa).

Conventional SCS carries electrical pulses to activate the electrical pulses at an optimal level of 30-60 Hertz. At this intensity, pain perception is reduced in patients. However, patients will have a tingling sensation known as paresthesia [(Martin et al., 2024)](https://www.zotero.org/google-docs/?broken=M5xenY).

One of the primary advantages of SCS is its ability to provide substantial pain relief for conditions that have not responded adequately to traditional treatments. By interfering with the transmission of pain signals to the brain, SCS can significantly reduce pain intensity and improve quality of life. This can lead to reduced reliance on opioid medications, mitigating the associated risks of addiction and overdose. Moreover, SCS can enhance functional capacity, allowing patients to engage in activities they were previously unable to perform due to pain.

However, SCS is not without its limitations. While many patients experience significant pain relief, others may only achieve partial or no relief. Additionally, some individuals may experience side effects such as tingling, numbness, or muscle contractions at the stimulation site. These side effects are generally mild and often subside over time. More serious complications, such as infection or device malfunction, are rare but can occur. Furthermore, SCS is an invasive procedure that requires surgical implantation of a device, which carries inherent risks[(Trentman & Weinmeister, 2006)](https://www.zotero.org/google-docs/?broken=hmH4zP).

**3.1 LIMITATIONS IN NEUROMODULATION FOR SPINAL CORD INJURY.**

Current neuromodulation techniques for SCI show promise but face several limitations that hinder their effectiveness. The challenges associated with the adaptation of neuromodulation techniques include complex power delivery, inefficient bidirectional communication, expensive and bulky devices which are inaccessible, and lack of comprehensive understanding of the mechanisms[(Salis et al., 2024; Zhang et al., 2021)](https://www.zotero.org/google-docs/?broken=5zHt1j).

**3.1.1 Lack of Comprehensive Understanding**

The poor understanding of neuromodulation mechanisms arises from the complex interactions between different neuromodulatory systems, which directly or indirectly influence each other, and this makes it difficult to know exactly how failures in these systems lead to specific symptoms or pathologies [(Avery & Krichmar, 2017)](https://www.zotero.org/google-docs/?broken=5ZBRFj).

**3.1.2 Optimal Parameter Selection**

The problem of parameter selection in neuromodulation for spinal cord injury comes from unpredictable electric field changes due to electrode geometry, positioning, and individual anatomical variations[(Hofstoetter et al., 2018)](https://www.zotero.org/google-docs/?AjjmYj). All these make it harder for patients to receive personalized treatments. However, optimal parameter selection in neuromodulation for spinal cord injury is important, as effective stimulation of patients would lead to better outcomes for the patients.

**3.1.3 Inefficient Bidirectional Communication**

Bidirectional communication in neuromodulation devices is a technology that allows for simultaneous electrical nerve recording and stimulation on the same nerve [(Xu et al., 2018)](https://www.zotero.org/google-docs/?broken=5r8tld). Many existing technologies often struggle with simultaneous data transmission and power management and this is critical for real time applications. The benefits of bidirectional communication in neuromodulation devices include real time data exchange between the implanted device and external systems thereby enhancing the functionality of the prosthetic [(Salis et al., 2024)](https://www.zotero.org/google-docs/?broken=IZAu39).

Current neuromodulation techniques for spinal cord injuries face limitations such as lack of comprehensive understanding of the underlying mechanisms, making it difficult to provide optimal care for patients; challenges in selecting optimal stimulation parameters due to variations in anatomy and electrode positioning; and inefficient bidirectional communication in devices, which limits real-time data exchange and power management. Addressing these challenges is crucial to advancing neuromodulation. AI offers potential solutions by improving device optimization, personalization, and overall system efficiency.

**3.2 AI FOR ENHANCING NEUROMODULATION IN SCI:**

Although it is relatively new, a sizable number of scientists have begun to implement artificial intelligence in solving these problems. Firstly, explainable artificial intelligence (a new set of techniques) has been proposed by Jean Marc Fellous et al in understanding the mechanism of neuromodulation. The study makes note of the fact that current artificial Intelligence approaches that are applied to neural data do not provide an understanding of the underlying neural process or how the outcome came to be and thus proposes the use of explainable artificial intelligence(XAI). XAI can extract actionable information from complex neural systems, moving beyond correlational analyses to a more causal understanding of network activity. This would help in understanding how the process of neuromodulation works for SCI patients, thus making the process more efficient.([Marc-Fellous et al., 2019)](https://www.zotero.org/google-docs/?broken=hJAVSn).

In a paper by Giovanni Aellio et al, an AI-driven approach known as Gaussian process-based Bayesian optimization (GPBO) is used to address the challenge of parameter selection in neuromodulation devices, where parameters need frequent recalibration. The algorithm focuses on optimizing the selection of active sites (the electrode contacts on a neural interface that are used to deliver electrical stimulation to the nervous system) to elicit specific sensation locations and adjusting the injected charge to maintain a consistent perceptual threshold[(Aiello et al., 2023)](https://www.zotero.org/google-docs/?YQ3guu).

Lastly, a paper by Contreras et al concludes that neuromorphic neuromodulation powered by AI holds significant potential for revolutionizing implantable devices for patient-specific treatment. By using neuromorphic architectures(an approach to computing that mimics the way the human brain works), these devices can solve problems such as power consumption and large memory requirements[(Contreras et al., 2023)](https://www.zotero.org/google-docs/?IGZBaT).

**LIMITATIONS**

While promising, AI-driven neuromodulation is not without its limitations. The reliability of AI models depends on the quality and volume of neural data, which is often noisy, incomplete, or difficult to acquire. Additionally, the computational demands of processing neural data in real time pose significant challenges, particularly for portable devices. Ethical considerations, such as ensuring data privacy and avoiding biases in AI algorithms, also require careful attention.

**CONCLUSION AND FUTURE DIRECTIONS.**

In conclusion, artificial intelligence is greatly changing the outlook on neuromodulation in SCI. These can offer more accurate diagnoses, allowing personalized treatment strategies that might considerably improve outcomes for the patients. However, there is still a scarcity of research being done on the subject. For future direction, more studies need to be carried out to help integrate AI fully into clinical practice.

**BIBLIOGRAPHY**

[Aiello, G., Valle, G., & Raspopovic, S. (2023). Recalibration of neuromodulation parameters in neural implants with adaptive Bayesian optimization. *Journal of Neural Engineering*, *20*(2), 026037. https://doi.org/10.1088/1741-2552/acc975](https://www.zotero.org/google-docs/?broken=InyJUe)

[Atkins, K. D., & Bickel, C. S. (2021). Effects of functional electrical stimulation on muscle health after spinal cord injury. *Current Opinion in Pharmacology*, *60*, 226–231. https://doi.org/10.1016/j.coph.2021.07.025](https://www.zotero.org/google-docs/?broken=JQPig4)

[Awad, B. I., Carmody, M. A., Zhang, X., Lin, V. W., & Steinmetz, M. P. (2015). Transcranial Magnetic Stimulation After Spinal Cord Injury. *World Neurosurgery*, *83*(2), 232–235. https://doi.org/10.1016/j.wneu.2013.01.043](https://www.zotero.org/google-docs/?broken=uTNUyd)

[Awuah, W. A., Ahluwalia, A., Darko, K., Sanker, V., Tan, J. K., Tenkorang, P. O., Ben-Jaafar, A., Ranganathan, S., Aderinto, N., Mehta, A., Shah, M. H., Lee Boon Chun, K., Abdul-Rahman, T., & Atallah, O. (2024). Bridging Minds and Machines: The Recent Advances of Brain-Computer Interfaces in Neurological and Neurosurgical Applications. *World Neurosurgery*, *189*, 138–153. https://doi.org/10.1016/j.wneu.2024.05.104](https://www.zotero.org/google-docs/?broken=k6e7ir)

[Bailey, A., Peter, M., & Aimee, N. (2014, June 17). *Transcranial Magnetic Stimulation to Investigate Motor Cortical Circuitry and Plasticity in Spinal Cord Injury*. https://www.researchgate.net/publication/286158411\_Transcranial\_Magnetic\_Stimulation\_to\_Investigate\_Motor\_Cortical\_Circuitry\_and\_Plasticity\_in\_Spinal\_Cord\_Injury](https://www.zotero.org/google-docs/?broken=RjvMwN)

[Brighina, F., Fierro, B., & Cosentino, G. (2020). Repetitive Transcranial Magnetic Stimulation. In G. Lambru & M. Lanteri-Minet (Eds.), *Neuromodulation in Headache and Facial Pain Management: Principles, Rationale and  Clinical Data* (pp. 119–134). Springer International Publishing.](https://www.zotero.org/google-docs/?broken=dPNXzF) <https://doi.org/10.1007/978-3-030-14121-9_9>

[Brigden, D. (2024, April 16). *Spinal cord injury*. https://www.who.int/news-room/fact-sheets/detail/spinal-cord-injury](https://www.zotero.org/google-docs/?broken=iz1OGj)

[Bryant, E. (2024, July 19). *Spinal Cord Injury | National Institute of Neurological Disorders and Stroke*. https://www.ninds.nih.gov/health-information/disorders/spinal-cord-injury](https://www.zotero.org/google-docs/?broken=4XZm6Y)

[Chen, Y.-T., Su, Y.-C., & Lin, Y.-C. (2023). Effect of Repetitive Transcranial Magnetic Stimulation on Gait Function and Strength Among Patients with Spinal Cord Injury: A Meta-Analysis. *Rehabilitation Practice and Science*, *2023*(2). https://doi.org/10.6315/3005-3846.2227](https://www.zotero.org/google-docs/?broken=fp0auu)

[Cooper, E., McElhaney, J., Han, D., Cooper, B., & Cooper, B. (2006). Functional Electrical Stimulation for Spinal Cord Injury Rehabilitation at the University of Virginia and Duke University. In T. Kanno & Y. Kato (Eds.), *Minimally Invasive Neurosurgery and Multidisciplinary Neurotraumatology* (pp. 161–164). Springer Japan. https://doi.org/10.1007/4-431-28576-8\_25](https://www.zotero.org/google-docs/?broken=ZDOC6j)

[Diop, M., Epstein, D., & Gaggero, A. (2021). Quality of life, health and social costs of patients with spinal cord injury: A systematic review. *European Journal of Public Health*, *31*(Supplement\_3), ckab165.177. https://doi.org/10.1093/eurpub/ckab165.177](https://www.zotero.org/google-docs/?broken=dRxC7V)

[Filipčić, I., Šimunović Filipčić, I., Milovac, Ž., Sučić, S., Gajšak, T., Ivezić, E., Bašić, S., Bajić, Ž., & Heilig, M. (2019). Efficacy of repetitive transcranial magnetic stimulation using a figure-8-coil or an H1-Coil in treatment of major depressive disorder; A randomized clinical trial. *Journal of Psychiatric Research*, *114*, 113–119.](https://www.zotero.org/google-docs/?broken=cz9Dvd) <https://doi.org/10.1016/j.jpsychires.2019.04.020>

[Gupta, S., Dhawan, A., Dhawan, J., McColl, M. A., Smith, K. M., & McColl, A. (2024). Potentially harmful drug-drug interactions in the therapeutic regimens of persons with spinal cord injury. *The Journal of Spinal Cord Medicine*, *47*(5), 692–700. https://doi.org/10.1080/10790268.2023.2185399](https://www.zotero.org/google-docs/?broken=KzN77y)

[Herrington, T. M., Cheng, J. J., & Eskandar, E. N. (2016). Mechanisms of deep brain stimulation. *Journal of Neurophysiology*, *115*(1), 19–38. https://doi.org/10.1152/jn.00281.2015](https://www.zotero.org/google-docs/?broken=nB8MEr)

[Hillery, T., Mata, N., & Kim, C. (2024). Chapter 1—History of neuromodulation. In A. Abd-Elsayed (Ed.), *Neuromodulation Techniques for the Spine* (pp. 1–10). Elsevier. https://doi.org/10.1016/B978-0-323-87584-4.00010-3](https://www.zotero.org/google-docs/?broken=SFHCYE)

[Hu, X., Xu, W., Ren, Y., Wang, Z., He, X., Huang, R., Ma, B., Zhao, J., Zhu, R., & Cheng, L. (2023). Spinal cord injury: Molecular mechanisms and therapeutic interventions. *Signal Transduction and Targeted Therapy*, *8*(1), 1–28. https://doi.org/10.1038/s41392-023-01477-6](https://www.zotero.org/google-docs/?broken=UsTOjw)

[Katz, D. I., & Dwyer, B. (2021). Clinical Neurorehabilitation: Using Principles of Neurological Diagnosis, Prognosis, and Neuroplasticity in Assessment and Treatment Planning. *Seminars in Neurology*, *41*(2), 111–123. https://doi.org/10.1055/s-0041-1725132](https://www.zotero.org/google-docs/?broken=JEHYyl)

[Larrivee, D. (2019). Neurorehabilitation: Recovery advances through neuromodulation. *Neurology and Neurological Sciences: Open Access Publisher: MedDocs Publishers LLC*.](https://www.zotero.org/google-docs/?broken=tY6Vnk)

[Lin, B.-S., Zhang, Z., Peng, C.-W., Chen, S.-H., Chan, W. P., & Lai, C.-H. (2023). Effectiveness of Repetitive Transcranial Magnetic Stimulation Combined With Transspinal Electrical Stimulation on Corticospinal Excitability for Individuals With Incomplete Spinal Cord Injury: A Pilot Study. *IEEE Transactions on Neural Systems and Rehabilitation Engineering: A Publication of the IEEE Engineering in Medicine and Biology Society*, *31*, 4790–4800. https://doi.org/10.1109/TNSRE.2023.3338226](https://www.zotero.org/google-docs/?broken=0z3m6w)

[Luo, S., Xu, H., Zuo, Y., Liu, X., & All, A. H. (2020). A Review of Functional Electrical Stimulation Treatment in Spinal Cord Injury. *NeuroMolecular Medicine*, *22*(4), 447–463. https://doi.org/10.1007/s12017-019-08589-9](https://www.zotero.org/google-docs/?broken=aOKoQV)

[Marc-Fellous, J., Sapillo, G., & Mayberg, H. (2019, December). *Explainable Artificial Intelligence for Neuroscience: Behavioral Neurostimulation—PubMed*. https://pubmed.ncbi.nlm.nih.gov/31920509/](https://www.zotero.org/google-docs/?broken=1KQBvt)

[Martin, S. C., Baranidharan, G., Thomson, S., Gulve, A., Manfield, J. H., Mehta, V., Love-Jones, S., Strachan, R., Bojanić, S., Eldabe, S., & FitzGerald, J. J. (2024). Spinal Cord Stimulation Improves Quality of Life for Patients With Chronic Pain-Data From the UK and Ireland National Neuromodulation Registry. *Neuromodulation: Journal of the International Neuromodulation Society*, S1094-7159(24)00646-9. https://doi.org/10.1016/j.neurom.2024.06.501](https://www.zotero.org/google-docs/?broken=hTqgVu)

[Morandín-Ahuerma, F. (2022). *What is Artificial Intelligence*. *3*(12).](https://www.zotero.org/google-docs/?broken=2ZLuTw)

[Nagoshi, N., Hashimoto, S., Okano, H., & Nakamura, M. (2024). Regenerative medicine for spinal cord injury using induced pluripotent stem cells: From animals to humans. *Pain*, *165*(11S), S76–S81. https://doi.org/10.1097/j.pain.0000000000003306](https://www.zotero.org/google-docs/?broken=y9aeCt)

[P, K., Velswamy, K., Harshavardhanan, P., R, R., V, J., & S, V. (2021). Machine Learning Techniques Application: Social Media, Agriculture, and Scheduling in Distributed Systems. In *Research Anthology on Architectures, Frameworks, and Integration Strategies for Distributed and Cloud Computing* (pp. 1396–1417). IGI Global Scientific Publishing. https://doi.org/10.4018/978-1-7998-5339-8.ch068](https://www.zotero.org/google-docs/?broken=S7xX6R)

[Panesar, S. S., Kliot, M., Parrish, R., Fernandez-Miranda, J., Cagle, Y., & Britz, G. W. (2020). Promises and Perils of Artificial Intelligence in Neurosurgery. *Neurosurgery*, *87*(1), 33–44.](https://www.zotero.org/google-docs/?broken=5fnNgW) <https://doi.org/10.1093/neuros/nyz471>

[P.Tran, A., & Silver. (2015, April 17). *Systemically treating spinal cord injury | Science*. https://www.science.org/doi/10.1126/science.aab1615](https://www.zotero.org/google-docs/?broken=Hil8Uo)

[Radu, C., Dabu, A., Tudor, C., & Teleanu, D. (2024). EFFICACY OF DEEP BRAIN STIMULATION: A COMPARATIVE ANALYSIS OF STN AND GPI TARGETS AND OUR CLINIC’S EXPERIENCE WITH MOVEMENT DISORDERS. *Romanian Neurosurgery*, 120–121. https://doi.org/10.33962/roneuro-2024-123](https://www.zotero.org/google-docs/?broken=EWmLRY)

[Sabri, I. (2022, December). *(PDF) Systematic Review of the Effectiveness of Using iPSC in Spinal Cord Injury*. https://www.researchgate.net/publication/380390383\_Systematic\_Review\_of\_the\_Effectiveness\_of\_Using\_iPSC\_in\_Spinal\_Cord\_Injury](https://www.zotero.org/google-docs/?broken=7rHzHr)

[Sandeep, M. (2024, August). *Demystifying the Role of Artificial Intelligence in Neurodegenerative Diseases*. CoLab. https://colab.ws/articles/10.1007%2F978-3-031-53148-4\_1](https://www.zotero.org/google-docs/?broken=YfwQdS)

[Song, Y., Han, L., Xu, B., & Zhang, T. (2024). *Multiscale fusion enhanced spiking neural network for invasive BCI neural signal decoding* (arXiv:2410.03533). arXiv. https://doi.org/10.48550/arXiv.2410.03533](https://www.zotero.org/google-docs/?broken=R6ZHzS)

[Trentman, T. L., & Weinmeister, K. P. (2006). Spinal Cord Stimulation. In *Encyclopedia of Medical Devices and Instrumentation*. John Wiley & Sons, Ltd. https://doi.org/10.1002/0471732877.emd239](https://www.zotero.org/google-docs/?broken=KsSV6q)

[Tsuji, S., Kuramoto, Y., Rajbhandari, S., Takeda, Y., Yamahara, K., & Yoshimura, S. (2024). Intravenous administration of human amnion-derived mesenchymal stem cells improves gait and sensory function in mouse models of spinal cord injury. *Frontiers in Cell and Developmental Biology*, *12*. https://doi.org/10.3389/fcell.2024.1464727](https://www.zotero.org/google-docs/?broken=KIzpW6)

[Wallace, M. T. (2017). Cooperation between hearing and vision in people with cochlear implants. *Proceedings of the National Academy of Sciences*, *114*(38), 10003–10005. https://doi.org/10.1073/pnas.1712810114](https://www.zotero.org/google-docs/?broken=NHSAI9)

[Wertheim, L., Edri, R., Goldshmit, Y., Kagan, T., Noor, N., Ruban, A., Shapira, A., Gat-Viks, I., Assaf, Y., & Dvir, T. (2022). Regenerating the Injured Spinal Cord at the Chronic Phase by Engineered iPSCs-Derived 3D Neuronal Networks. *Advanced Science (Weinheim, Baden-Wurttemberg, Germany)*, *9*(11), e2105694. https://doi.org/10.1002/advs.202105694](https://www.zotero.org/google-docs/?broken=429bSg)

[Wu, K., Mina, M., & Sahyoun, J.-Y. (2023, June). *Retinal Prostheses: Engineering and Clinical Perspectives for Vision Restoration*. https://www.mdpi.com/1424-8220/23/13/5782](https://www.zotero.org/google-docs/?broken=1Hq6Pg)

[Yuhong, W., Tingting, D., Xiahuang, L., & Huiyun, Z. (2023, July). *Frontiers | Utility of transcranial magnetic stimulation in the assessment of spinal cord injury: Current status and future directions*. https://www.frontiersin.org/journals/rehabilitation-sciences/articles/10.3389/fresc.2022.1005111/full](https://www.zotero.org/google-docs/?broken=I2wQAr)

[Zeng, C.-W. (2023). Advancing Spinal Cord Injury Treatment through Stem Cell Therapy: A Comprehensive Review of Cell Types, Challenges, and Emerging Technologies in Regenerative Medicine. *International Journal of Molecular Sciences*, *24*(18), Article 18. https://doi.org/10.3390/ijms241814349](https://www.zotero.org/google-docs/?broken=NQZSOz)

[Zhou, P., Jingjing, Q., & Panpan, X. (2019, October 16). *Cell Therapeutic Strategies for Spinal Cord Injury | Advances in Wound Care*. https://www.liebertpub.com/doi/10.1089/wound.2019.1046](https://www.zotero.org/google-docs/?broken=l536bx)