The Application of Brain-Spine Interface on Spinal Cord Injury

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Abstract. Spinal cord injuries (SCI) hold considerable significance owing to their profound and often irreversible effects on crucial neurological functions, resulting in a substantial reduction in overall quality of life for those affected. The essay explores the transformative potential of the brain-spine interface in the context of SCI rehabilitation. It delves into the cutting-edge technology that enables direct communication between the brain and the spinal cord, bypassing damaged neural pathways. The abstract highlights the profound impact of this innovation on individuals with SCI, offering the hope of restoring lost motor and sensory functions. Additionally, it touches upon the challenges and ethical considerations associated with its application. Ultimately, the essay sheds light on the brain-spine interface as a groundbreaking solution that holds promise for enhancing the quality of life for those with spinal cord injuries.

Keywords: Spinal cord injuries, brain-spine interface, spinal cord injuries rehabilitation.

1. Introduction

Two vital components of the nervous system, brain and spinal cord are tightly connected, creating the central axis of the body's neural pathways. A spinal cord injury (SCI) is the damage to any segment of the spinal cord or the nerves situated at the lower end of the spinal canal, leading to the permanent change or loss of bodily functions below the location of the injury, including complete paralysis. The brain-spine interface (BSI) has the capacity to revolutionize the lives of individuals grappling with spinal cord injuries and neurological disorders. The core of BSI is creating a seamless connection between the brain and spinal cord, converting the motor intentions into stimulation to activate muscles [1].

Spinal cord injuries have long been a challenge for medical science and enormous economic impact on individuals and healthcare systems. According to the National Spinal Cord Injury Statistical Center, there are over 12,500 cases of spinal cord injuries in North America every year [2]. In the United Kingdom, there are 19 new cases of SCIs per million population on an annual basis, leading to about 50,000 SCI patients currently in the UK [3]. The clinical outcomes of SCI include irreversible motor and sensory impairments, like paraplegia and quadriplegia, causing the life expectancy of patients to become much lower than normal [4]. However, with the introduction of the brain-spine interface, a new avenue of hope has emerged for individuals struggling with these injuries. The brain-spine interface fundamentally seeks to build a bridge over the communication gap between the brain and the spinal cord, enabling a direct line of interaction that was previously disrupted by injury. Through the creation of an alternative pathway for signals to traverse between the brain and the spinal cord, BSI creates opportunities for individuals with spinal cord injuries to elevate their motor and sensory functions. The foundation of this technology rests upon the principles of neuroplasticity and neural adaptation, leveraging the brain's capacity to reorganize and adjust to new situations [5]. Beyond addressing the physical limitations brought about by SCI, this technology also shows potential for enhancing the overall quality of life and psychological well-being of individuals impacted by such injuries. As a new technology that has not been widely applied in clinical practice, the application of BSI in spinal cord injury has a profound impact on medicine and neurology. Through the latest studies and case studies, BSI has been proved to help an individual with paralysis of the arms and legs to stand and walk naturally [6]. The essay introduces the mechanism and application of BSIs and following challenges, ethical consideration, and future prospect.

2. Mechanism of BSIs

The application of epidural electrical stimulation (EES) to the lumbar and cervical regions of the spinal cord can effectively reawaken the neural circuits [7, 8]. Through implanted electrodes placed on the outer surface of the spinal cord, EES releases electrical input that is able to bypass damaged and disconnected pathways, indirectly conveying the stimulus signal to motor pools via proprioceptive fiber and altering spinal cord excitability [7, 9, 10]. However, patients are constrained in their ability to regulate muscle activity through EES, causing limitations in adapting leg movements [11]. The brain-spine interface is able to fill these limitations.

The operating principle of BSIs is utilizing brain activity to govern spinal stimulation below the location of injury, which mimics the way of transmission of commands from the brain to the spinal cord. BSIs capture the neural signals for motor intentions released from the brain, converting these signals into instructions for spinal stimulation [1, 12]. Studies and data have demonstrated that these motor intentions are detected in patients with motor deficits, proving that BSIs have the ability to improve patients' motor performance [13]. According to Fig. 1, the journey of a command starts in the brain, where neural signals associated with motor intent are detected by advanced brain-computer interface (BCI) systems. These signals are then decoded into actionable commands, representing the desired movement patterns. The decoded commands are subsequently transmitted to a microelectrode array implanted along the spinal cord, which then generates targeted electrical pulses that activate the spinal circuits to start movement based on the individual's intentions [14, 15].

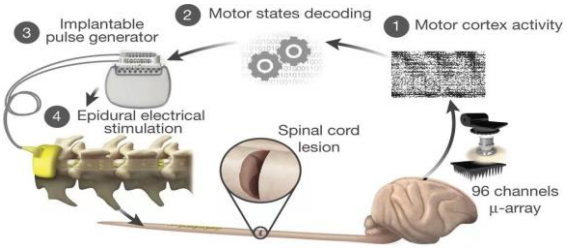


Figure 1. Mechanism of brain-spine interface. The BSI system decodes the signals and sends the microelectrode array to an implantable pulse generator, releasing the electrical stimulation [1]

3. Brain-Computer Interface

BSI and BCI technologies open up a new path for severely paralyzed patients. Traditional therapies rely on pharmacology, which is unable to repair or improve the neural pathways [16]. Comparably, while the brain-spine connection remains active and interacts with the spinal circuits, these circuits progressively adjust to the incoming electrical stimulation, reducing neurological deficits and even repairing the damaged sensorimotor pathway [17]. Nowadays, a growing amount of evidence has proven that BCIs are able to enhance patients' neuroplasticity in the process of rehabilitation [18], which enhances movement precision and patients' movement control (Fig. 2).

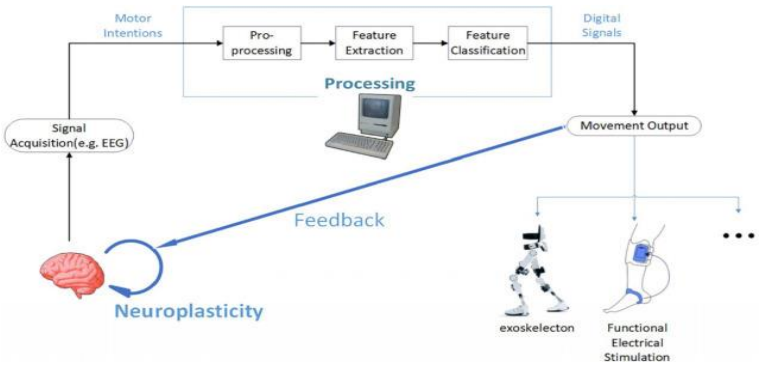


Figure 2. BCIs enhance neuroplasticity. The feedback of the initial intention is sent back to the brain during the movement, which is beneficial to the restoration of neural pathways [19]

BCIs can be categorized into invasive and non-invasive types based on the signal acquisition method they utilize. Invasive BCIs represent the direct implantation of electrodes or sensors into neural tissue of the brain, which focus on neuronal units and local field potentials (LFP), providing a high level of precision, so it is a ideal choice for the application that demands complex control, including the most severe and non-responsive patients [20]. However, this method carries inherent risks such as potential surgical complications, infections, and long-term stability concerns. Based on the risks, even if highly favorable outcomes were anticipated, over 40% of the respondents remained unwilling to undergo neurosurgery [21]. Thus, non-invasive brain computer interfaces have become a popular research area [22]. Non-invasive BCIs rely on external sensors, such as electroencephalography (EEG) or functional magnetic resonance imaging (fMRI) [23]. This approach eliminates the need for surgery with the lower cost, but the spatial and temporal resolution it offers is not as high as invasive BCIs, limiting the precision of control.

4. Application of BSIs

The application of BSIs represents a remarkable stride in the field of neuroengineering, providing hope of regaining the motor ability for patients with neurological impairments. The origins of brain-spine interface can be traced back to the first animal study demonstrating the neuromodulatory properties of spinal dorsal root stimulation [24]. After that, some early investigations including implanting electrodes directly into the brains of animals led to a significant progress in establishing communication between brain and external devices [25]. Subsequent studies involving epidural spinal stimulation proved the stimulation is able to improve motor capacity and offer potential of recovery from paralyzation [26].

In recent years, brain-spine interface technology has started to transition from theoretical research to practical applications. Clinical trials involving human participants with spinal cord injuries have shown promising results [6]. According to the most recent study, after 40 rehabilitation sessions using the BSI, the ability of a lower limb paralysis patient to voluntarily control locomotion and engage in complex coordination has been improved [6], which cannot be achieved by alone EES, suggesting that BSI is able to promote further recovery of the damaged sensorimotor pathway. This marks the inaugural case in which damaged locomotor circuitry has been partially restored through the utilization of BSI in an individual living with SCI. However, because SCI is characterized by its diversity, it is essential to conduct additional research about further recovery and different effects of BSI across various degrees of injury severity [27].

5. Ethical Considerations and Challenges

5.1. Privacy and Data Security

The convergence of advanced technology and medical innovation, like BSI, introduces ethical and practical complexities, prominently including privacy and data security concerns [28]. Safeguarding patients' neural data is paramount. Privacy measures are vital, given the sensitive nature of neural data. Implementing intricate data security protocols, including encryption during transmission and storage, prevents unauthorized access. Secure storage practices, coupled with regular audits and updates, combat data breaches. Stringent access controls bolster security, allowing only authorized personnel with monitored access [29]. Transparent consent processes, giving patients agency over their data, address ethical aspects.

BSI's integration into medicine offers hope for spinal cord injury patients. Balancing this promise necessitates robust privacy measures. The sensitive nature of neural data requires encryption, secure storage, and strict access controls to thwart unauthorized access [29]. Upholding privacy standards ensures that BSI's transformative potential can be harnessed ethically, promoting patient trust and progress in this groundbreaking technology.

5.2. Informed Consent and Patient Autonomy

As BSI technology enters medical practice, it highlights ethical issues concerning informed consent and patient autonomy. Informed consent ensures patients understand the nature, risks, and benefits of medical procedures [30]. However, BSI's complexity complicates true informed consent. Their cognitive and physical challenges may hinder grasping technical details and implications. Balancing patient autonomy and comprehension becomes crucial. Upholding autonomy means respecting their medical decisions, yet ensuring they understand complex BSI information is equally vital.

On the other hand, medical professionals and ethics committees play a key role in this delicate balance. Information must be tailored to patients' cognitive abilities and background knowledge [31]. Simplified explanations, visuals, and interactive materials enhance comprehension. An ongoing consent process, encouraging questions and reflection, bridges the gap between complex data and patient understanding. Therefore, BSI's introduction raises ethical questions regarding informed consent and patient autonomy.

5.3. Accessibility and Affordability

The promising impact of BSI technology on SCI treatment has brought forth vital discussions on accessibility and affordability. This potential breakthrough, while transformative, faces ethical concerns related to equal access. Choe et al. acknowledge that while the potential breakthrough represented by technologies like BSI holds transformative promise, it is not without its ethical challenges, particularly concerning equal access [32]. For instance, the substantial costs associated with BSI development and implementation pose a risk of exacerbating healthcare disparities. A significant ethical dilemma arises from the potential divide, where only those with financial means can access the benefits, leaving others marginalized. Such inequality conflicts with the principles of equitable healthcare provision.

However, addressing this concern necessitates healthcare systems and policymakers prioritizing both accessibility and affordability of BSI technology [33]. Public-private collaborations, research funding, insurance coverage, and government support can pave the way for broader accessibility. Thus, tackling healthcare disparities is a multidimensional challenge that requires systemic reform. Advocacy for comprehensive coverage and BSI technology integration in insurance plans is essential for equal access. Moreover, investment in research and development aimed at reducing production costs can enhance affordability. Thus, using non-invasive BCI which has lower cost is increasingly becoming the focus of recent research. In general, the potential of BSI technology to transform SCI treatment is substantial, yet ethical considerations involving accessibility and affordability demand attention. Ensuring fair access is crucial, necessitating collective efforts from healthcare stakeholders, policymakers, and society.

5.4. Ethical Implications of Enhancing Human Capabilities

The ethical dimensions of enhancing human capabilities through BSI technology are intricate. Neural-interface like BSI offers the potential to greatly enhance motor and sensory functions, blurring the line between natural and augmented abilities [34]. A key concern is altering natural bodily functions. BSI's restoration and potential enhancement of abilities challenge conventional concepts of human capabilities, raising questions about ethical implications and the line between restoration and enhancement.

6. Future Prospects and Impacts

The evolving realm of BSI technology is driven by continuous research and relentless technological strides. These developments hold tantalizing potential for unlocking new frontiers in neurorehabilitation and SCI treatment [6]. As neuroscience and engineering converge, potential BSI breakthroughs stand ready to reshape healthcare and the lives of SCI-affected individuals. A

significant area of advancement centers on refining control over neural connections. Current BSI technology has made impressive progress in establishing direct brain-spinal cord communication pathways, enabling signal transmission around damaged neural pathways. Enhanced neural signal precision could restore finer motor control and sensory perception, elevating quality of life and independence [35]. Additionally, Lorach and his colleagues are focusing on similar devices that can restore arm movements, which requires additional investigation. Electroencephalography (EEG) applications are frequently constrained by the low signal to noise ratio and the presence of artifacts, especially when EEG is worked simultaneously with electromagnetic stimulation [36]. Thus, how to obtain the user's brain signals more accurately is the main research direction.

BSI's potential to restore lost functions and enhance capabilities prompts debates about what defines a disability and society's perception of those with physical impairments [37]. This integration challenges conventional stereotypes and fosters more inclusive attitudes. Therefore, conversations surrounding BSI encompass human enhancement and ethical limits in medical technology. Defining the boundary between restoration and augmentation becomes intricate in the BSI context. Thus, ethical debates will determine the moral scope of enhancements and potential limits on their extent. As BSI evolves, meaningful ethical dialogues and responsible decisions are essential for positive impact on individuals, communities, and society at large.

7. Conclusion

The brain-spine interface (BSI) is a transformative leap in spinal cord injury (SCI) rehabilitation, promising renewed mobility and quality of life. BSI's profound impact lies in restoring lost abilities and redefining functional independence for SCI patients. This renewed mobility empowers individuals, enabling engagement in once-unattainable activities. Beyond physical benefits, BSI fosters psychological rejuvenation, catalyzing a sense of agency and self-esteem. Moreover, BSI signifies a paradigm shift in SCI treatment, offering a cutting-edge solution that bridges brain-spinal communication. This innovation transcends limitations, redefining lives and empowering those impacted by SCI.

Privacy and data security measures are imperative to protect patients' neural data, while ensuring informed consent and patient autonomy in the face of technical complexity is essential. The potential future of BSI offers the possibility of enhancing neural connections, revitalizing intricate motor control, and transforming how society perceives disabilities.

References

[1] Capogrosso M, Milekovic T, Borton D, et al. A Brain–Spine Interface Alleviating Gait Deficits After Spinal Cord Injury in Primates. Nature, 2016, 539 (7628): 284-288.

[2] Hachem LD, Ahuja CS, Fehlings MG. Assessment and Management of Acute Spinal Cord Injury: From Point of Injury to Rehabilitation. The Journal of Spinal Cord Medicine, 2017, 40 (6): 665-675.

[3] Patek M, Stewart M. Spinal Cord Injury. Anaesthesia & Intensive Care Medicine, 2023.

[4] Sekhon LH, Fehlings MG. Epidemiology, Demographics, and Pathophysiology of Acute Spinal Cord Injury. Spine, 2001, 26 (24S): S2-S12.

[5] Hutson TH, Di Giovanni S. The Translational Landscape in Spinal Cord Injury: Focus on Neuroplasticity and Regeneration. Nature Reviews Neurology, 2019, 15 (12): 732-745.

[6] Lorach H, Galvez A, Spagnolo V, et al. Walking Naturally After Spinal Cord Injury Using a Brain–Spine Interface. Nature, 2023: 1-8.

[7] Choi EH, Gattas S, Brown NJ, et al. Epidural Electrical Stimulation for Spinal Cord Injury. Neural Regeneration Research, 2021, 16 (12): 2367.

[8] Courtine G, Gerasimenko Y, Van Den Brand R, et al. Transformation of Nonfunctional Spinal Circuits into Functional States After the Loss of Brain Input. Nature Neuroscience, 2009, 12 (10): 1333-1342.

[9] Edgerton VR, Courtine G, Gerasimenko YP, et al. Training Locomotor Networks. Brain Research Reviews, 2008, 57 (1): 241-254.

[10] Wenger N, Moraud EM, Raspopovic S, et al. Closed-Loop Neuromodulation of Spinal Sensorimotor Circuits Controls Refined Locomotion After Complete Spinal Cord Injury. Science Translational Medicine, 2014, 6 (255): 255ra133-255ra133.

[11] Lorach H, Charvet G, Bloch J, Courtine G. Brain–Spine Interfaces to Reverse Paralysis. National Science Review, 2022, 9 (10): nwac009.

[12] Alam M, Rodrigues W, Pham BN, Thakor NV. Brain-Machine Interface Facilitated Neurorehabilitation via Spinal Stimulation After Spinal Cord Injury: Recent Progress and Future Perspectives. Brain Research, 2016, 1646: 25-33.

[13] López-Larraz E, Montesano L, Gil-Agudo Á, Minguez J, Oliviero A. Evolution of EEG Motor Rhythms After Spinal Cord Injury: A Longitudinal Study. PloS One, 2015, 10 (7): e0131759.

[14] Kato K, Sawada M, Nishimura Y. Bypassing Stroke-Damaged Neural Pathways via a Neural Interface Induces Targeted Cortical Adaptation. Nature Communications, 2019, 10 (1): 4699.

[15] Mrachacz-Kersting N, Jiang N, Stevenson AJT, et al. Efficient Neuroplasticity Induction in Chronic Stroke Patients by an Associative Brain-Computer Interface. Journal of Neurophysiology, 2016, 115 (3): 1410-1421.

[16] Benjamin EJ, Blaha MJ, Chiuve SE, et al. Heart Disease and Stroke Statistics—2017 Update: A Report from the American Heart Association. Circulation, 2017, 135 (10): e146-e603.

[17] Curt A, Van Hedel HJ, Klaus D, Dietz V, Em-Sci Study Group. Recovery from a Spinal Cord Injury: Significance of Compensation, Neural Plasticity, and Repair. Journal of Neurotrauma, 2008, 25 (6): 677-685.

[18] McFarland DJ, Daly J, Boulay C, Parvaz MA. Therapeutic Applications of BCI Technologies. Brain-Computer Interfaces, 2017, 4 (1-2): 37-52.

[19] Zhuang M, Wu Q, Wan F, Hu Y. State-of-the-Art Non-Invasive Brain–Computer Interface for Neural Rehabilitation: A Review. Journal of Neurorestoratology, 2020, 8 (1): 12-25.

[20] Flint RD, Wright ZA, Scheid MR, Slutzky MW. Long Term, Stable Brain Machine Interface Performance Using Local Field Potentials and Multiunit Spikes. Journal of Neural Engineering, 2013, 10 (5): 056005.

[21] Blabe CH, Gilja V, Chestek CA, Shenoy KV, Anderson KD, Henderson JM. Assessment of Brain–Machine Interfaces from the Perspective of People with Paralysis. Journal of Neural Engineering, 2015, 12 (4): 043002.

[22] Huang Z, Zhou Z, Zeng J, Lin S, Wu H. Flexible Electrodes for Non-Invasive Brain–Computer Interfaces: A Perspective. APL Materials, 2022, 10 (9).

[23] Tonin L, Millán JDR. Noninvasive Brain–Machine Interfaces for Robotic Devices. Annual Review of Control, Robotics, and Autonomous Systems, 2021, 4: 191-214.

[24] Grillner S, Zangger P. On the Central Generation of Locomotion in the Low Spinal Cat. Experimental Brain Research, 1979, 34: 241-261.

[25] Vidal JJ. Toward Direct Brain-Computer Communication. Annual Review of Biophysics and Bioengineering, 1973, 2 (1): 157-180.

[26] Ichiyama RM, Gerasimenko YP, Zhong H, Roy RR, Edgerton VR. Hindlimb Stepping Movements in Complete Spinal Rats Induced by Epidural Spinal Cord Stimulation. Neuroscience Letters, 2005, 383 (3): 339-344.

[27] Hachem LD, Balbinot G, Fehlings MG. A Digital Bridge to Reverse Paralysis. Cell Research, 2023: 1-2.

[28] O'Hara PA. Neurobiological Political Economy of Artificial General Intelligence and Autonomous Humanoid Robotics. Journal of Economic Issues, 2022, 56 (4): 1118-1167.

[29] Jwa AS, Poldrack RA. Addressing Privacy Risk in Neuroscience Data: From Data Protection to Harm Prevention. Journal of Law and the Biosciences, 2022, 9 (2): lsac025.

[30] Barnett JE, Wise EH, Johnson-Greene D, Bucky SF. Informed Consent: Too Much of a Good Thing or Not Enough? Professional Psychology: Research and Practice, 2007, 38 (2): 179a.

[31] Schulz PJ, Nakamoto K. Patient Behavior and the Benefits of Artificial Intelligence: The Perils of "Dangerous" Literacy and Illusory Patient Empowerment. Patient Education and Counseling, 2013, 92 (2): 223-228.

[32] Cho N, Squair JW, Bloch J, Courtine G. Neurorestorative Interventions Involving Bioelectronic Implants After Spinal Cord Injury. Bioelectronic Medicine, 2019, 5 (1): 10.

[33] World Health Organization. Intersectoral Global Action Plan on Epilepsy and Other Neurological Disorders 2022–2031.

[34] Heng W, Solomon S, Gao W. Flexible Electronics and Devices as Human–Machine Interfaces for Medical Robotics. Advanced Materials, 2022, 34 (16): 2107902.

[35] Insausti-Delgado A, López-Larraz E, Nishimura Y, Ziemann U, Ramos-Murguialday A. Non-Invasive Brain-Spine Interface: Continuous Control of Trans-Spinal Magnetic Stimulation Using EEG. Frontiers in Bioengineering and Biotechnology, 2022, 10: 975037.

[36] Insausti-Delgado A, López-Larraz E, Omedes J, Ramos-Murguialday A. Intensity and Dose of Neuromuscular Electrical Stimulation Influence Sensorimotor Cortical Excitability. Frontiers in Neuroscience, 2021, 14: 593360.

[37] Raffin E, Hummel FC. Restoring Motor Functions After Stroke: Multiple Approaches and Opportunities. The Neuroscientist, 2018, 24 (4): 400-416.