REVIEW ARTICLE

Recent Advances in the Diagnosis and Treatment of Brain-Spinal Injuries: From Molecular Imaging to and Brain-Computer Interfaces

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Abstract

Purpose: This review aims to synthesize current literature on recent advances in the diagnosis and treatment of Brain and Spinal Cord Injuries (SCIs), focusing on molecular imaging, cell therapy, Brain-Computer Interfaces (BCIs), and Craniosacral Therapy (CST).

Materials and Methods: A systematic search was done in PubMed/MEDLINE, Scopus, WoS, Cochrane Library, and Google Scholar to identify relevant articles published between 2015 and 2025. Keywords included "Brain Injury," "Spinal Cord Injury," "Molecular Imaging," "Cell Therapy," "Brain-Computer Interface," and "Craniosacral Therapy".

Results: Molecular imaging techniques, such as functional Magnetic Resonance Imaging (fMRI), Diffusion Tensor Imaging (DTI), and Positron Emission Tomography (PET), enhance diagnostic accuracy by visualizing neural activity and structural integrity. Cell therapy, particularly with Mesenchymal Stem Cells (MSCs), promotes axon regeneration and reduces inflammation. BCIs offer the potential for restoring motor function and enhancing neural plasticity. The evidence for CST is mixed, with some studies suggesting benefits in pain relief and cognitive improvement, while others raise concerns about methodological limitations.

Conclusion: Recent advances in molecular imaging, cell therapy, and BCIs offer hopeful avenues for improving the diagnosis and treatment of BSCI. However, further rigorous research is needed to validate the ability of these approaches and to address ethical considerations. While CST has gained attention as a complementary therapy, more high-quality studies are required to determine its effectiveness. This review highlights the need for interdisciplinary collaboration to translate scientific discoveries into clinical practice and to develop the quality of life for those affected by BSCI.

Keywords: Spinal Cord Injury; Molecular Imaging; Brain-Computer Interface; Craniosacral Therapy; Neurotrauma.

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1. Introduction

In recent years, the field of neural injuries has undergone a profound transformation, shifting from primarily addressing symptomatic relief to targeting the underlying biological mechanisms of brain and Spinal Cord Injuries (SCIs) [1]. As we face the increasing prevalence of these injuries—stemming from various causes such as sports accidents, falls, violence, and military conflicts—the need for innovative diagnostic and therapeutic strategies has become more urgent. Brain and SCIs represent one of the most complex challenges in modern medicine [2]. The multifaceted nature of these injuries often leads to a range of secondary effects, including inflammation, oxidative stress, and apoptosis, which can significantly hinder recovery. Traditional diagnostic approaches—primarily reliant on structural imaging—often cannot capture the full extent of injury or accurately predict long-term outcomes. However, recent progress in molecular imaging techniques has transformed our understanding of these conditions, enabling more targeted therapies [3]. Procedures like functional Magnetic Resonance Imaging (fMRI), Diffusion Tensor Imaging (DTI), and advanced Positron Emission Tomography (PET) scans enable real-time visualization of neural activities and metabolic processes, allowing physicians to assess structural integrity and functional capacity [4]. Also, metal Nanoparticles (NPs) are being explored for their possibility to improve both Radiation Therapy (RT) and diagnostics in the treatment of brain and spinal injuries [5, 6].

Alongside advancements in diagnostic methods, innovative treatment strategies are emerging that hold promise for recovery following brain and SCIs. One of the most exciting research areas is cell therapy, which utilizes the potential of stem cells and other cellular therapies to enhance recovery [7]. Studies have shown that various types of stem cells—such as Mesenchymal Stem Cells (MSCs), Induced Pluripotent Stem Cells (iPSCs), and Neural Stem Cells (NSCs)—can significantly improve functional outcomes by facilitating axon regeneration, reducing inflammation, and enhancing recovery [8, 9]. For example, a recent study found that patients receiving transplantation demonstrated a 20% improvement in fine motor skills six months post-treatment, suggesting a potential for functional restoration [10].

Talking about therapy methods, Craniosacral Therapy (CST) has also gained attention as a complementary and somewhat controversial treatment for individuals suffering from brain and spinal injuries, particularly Traumatic Brain Injury (TBI) and post-concussion syndrome [11]. This gentle, hands-on technique involves applying light pressure to the skull, neck, and spine, to release restrictions in the craniosacral system—comprising the membranes and fluid surrounding the brain and spinal cord. Proponents of CST argue that it can enhance the flow of Cerebrospinal Fluid (CSF), alleviate pain, improve cognitive functions, and promote overall well-being; however, the evidence supporting these claims remains debated [12].

In addition, the emergence of Brain-Computer Interfaces (BCIs) represents a groundbreaking leap forward in rehabilitation technology [13]. BCIs create direct communication pathways between the brain and external devices, enabling people with severe motor impairments to control assistive technologies solely through their opinions [14]. Recent advancements in BCI technology are promising not only for restoring lost functions but also for enhancing neural plasticity during rehabilitation. By integrating BCIs with traditional therapies, researchers are exploring new approaches to accelerate recovery and improve functional independence for patients with SCIs or TBIs.

While these advancements generate hopes for improving patient outcomes, they also educate vital ethical considerations that need to be tackled. Issues such as patient consent, access to advanced treatments, long-term safety profiles, and the implications of emerging technologies on quality of life are significant topics that warrant careful examination. As we rapidly move through this evolving landscape, it is essential to confirm that all patients have equitable access to these innovative treatments while safeguarding their rights and well-being. This study aims to synthesize the current literature on these transformative developments in neurotrauma care. Additionally, by providing an overview of recent advancements—from complex molecular imaging techniques that enhance diagnostic accuracy to pioneering treatments such as cell therapy, and BCIs, and acknowledging debates surrounding complementary approaches—our goal is to lighten the path forward for doctors, researchers, and patients alike. Furthermore, we explore potential future directions for research that could enhance understanding and treatment of brain and SCIs. Ultimately, this review aims not only to inform but also to inspire further exploration in this dynamic field, which holds significant potential for improving the quality of life for people affected by brain and SCIs.

2. Materials and Methods

This review aims to synthesize current literature on recent advances in the identification and management of brain and SCIs, focusing on molecular imaging, cell therapy, BCIs, NPs and CST. A comprehensive search strategy was engaged to classify relevant articles, reviews, and clinical trials, ensuring a thorough examination of the available evidence related to these innovative approaches in neurotrauma care.

A systematic search strategy was meticulously designed and implemented across multiple electronic databases to capture a broad spectrum of relevant publications. The search encompassed PubMed, Scopus, Web of Science (WoS), Cochrane Library, and Google Scholar, ensuring a diverse range of sources were consulted. The search strategy utilized a combination of keywords and MeSH terms, including ("Brain Injury" OR "Traumatic Brain Injury" OR "Spinal Cord Injury" OR "Neural Injury" OR "Neurotrauma") AND ("Molecular Imaging" OR "fMRI" OR "DTI" OR "PET Scan" OR "Biomarkers") AND ("Cell Therapy" OR "Stem Cells" OR "Mesenchymal Stem Cells" OR "iPSCs" OR "Neural Stem Cells") AND ("Brain-Computer Interface" OR "BCI" OR "Neural Interface") AND ("Craniosacral Therapy" OR "CST") AND ("Diagnosis" OR "Treatment" OR "Rehabilitation" OR "Outcomes"). The search strings were adapted for each database to account for differences in indexing and search functionalities, thereby optimizing the retrieval of relevant articles. Inclusion criteria stipulated that studies must be published in English, be original research articles or clinical trials, focus on human subjects or preclinical models of brain or SCI, address one or more of the key areas of interest, and be published within the last 10 years (2015-2025). Exclusion criteria were applied to eliminate studies not available in English, case reports, editorials, opinion pieces, studies focused on neurological disorders other than traumatic brain or spinal cord injury (unless directly relevant to injury mechanisms), and studies lacking sufficient detail on methodologies or results.

3. Results

The perspective on the management of neurological trauma, which has significantly evolved in recent years, is driven by advancements in molecular imaging, cell therapy, physiotherapeutic methods, and BCIs. This discussion integrates current findings from the literature to demonstrate how these innovations are transforming our understanding and treatment of brain and SCIs, with the aim of improving patient outcomes (Figure 1).

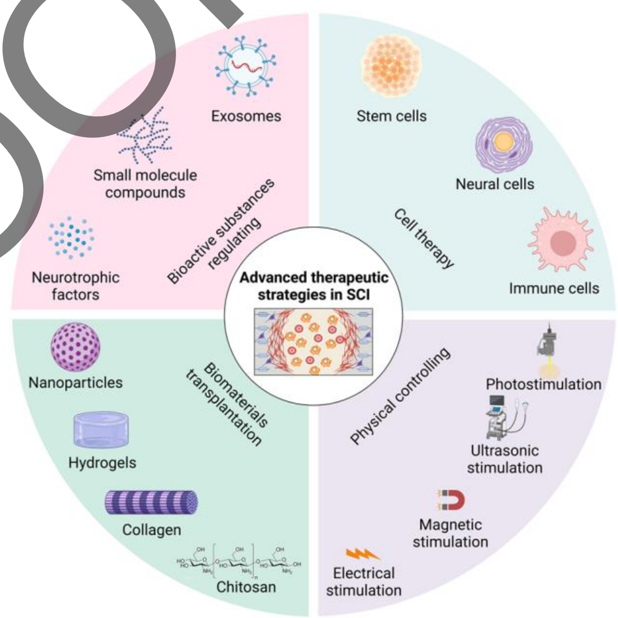

Figure 1. Schematic representation of numerous cutting-edge therapeutic approaches for repairing spinal cord injury (SCI) derived from the reviewed studies. Adapted from Hu *et al.* study [15]

3.1. Molecular Imaging Techniques

Molecular imaging techniques have developed as a pivotal tool in the assessment and management of SCI. These advanced imaging methods facilitate not only the diagnosis of injuries but also the monitoring of therapeutic interventions, particularly in the context of emerging treatments such as stem cell therapy [16]. This section explores various molecular imaging techniques and highlights their applications, benefits, and limitations in the field of SCI.

3.1.1. MRI

MRI is widely considered the gold standard for evaluating SCIs due to its capability to provide high-resolution images of soft tissues without ionizing radiation. Recent advancements in MRI technology, including fMRI and resting-state fMRI (rs-fMRI), have enhanced our understanding of cortical plasticity following SCI [17, 18]. For example, Greicius *et al.* have shown that rs-fMRI can reveal significant changes in functional connectivity among regions of the brain following injury, which may be related to recovery outcomes [19]. This Voxel-Based Morphometry (VBM) has been used to assess structural changes in the brain following SCI, indicating a reduction in the volume of motor and sensory areas compared to healthy individuals. This information is essential for understanding the neuroplastic changes that occur after injury and for developing targeted rehabilitation strategies [20, 21]. Despite its advantages, MRI has limitations in assessing certain aspects of SCI, particularly regarding cell viability and metabolic activity. Therefore, there is a growing interest in combining MRI with other imaging methods to provide a more comprehensive evaluation [22].

3.1.2. PET

PET is another powerful molecular imaging method that has gained attention in SCI research. PET allows for the visualization of metabolic processes and can be particularly useful for assessing neural integrity and synaptic function [23]. Recent studies have examined the use PET imaging as a non-invasive biomarker for the detection of spinal lesions following SCI. This technique shows promise in quantifying synaptic loss and may serve as an objective measure for evaluating new therapeutic approaches [24, 25]. Additionally, PET can be combined with Computed Tomography (CT) to enhance anatomical localization while providing functional information about metabolic activity. It has been shown that the integration of PET with CT imaging improves the detection of subtle changes in spinal metabolism over time, which is vital for monitoring recovery and treatment efficacy [26, 27]. One of the challenges associated with PET imaging is its relatively lower spatial resolution compared to MRI. However, ongoing advancements in the development of radiotracers are expected to enhance the sensitivity of PET for distinguishing spinal injuries [28].

3.1.3. Clinical Outcomes

The integration of multiple imaging methods—such as combining MRI with PET or optical imaging—has developed as a talented strategy to overcome individual limitations while enhancing overall diagnostic capabilities. For example, the use of superparamagnetic iron oxide NPs (SPION) for MRI allows researchers to track stem cell migration and simultaneously assess metabolic activity through PET. This multifaceted approach provides a more comprehensive understanding of the structural and functional changes resulting in SCI [29]. Studies have shown that combining these techniques can significantly enhance the limitations of cell count detection within the body, allowing researchers to more effectively monitor therapeutic interventions [30, 31].

3.2. Innovations in Cell Therapy

Cell therapy has arisen as a transformative line for treating SCIs, offering hope for regeneration and functional improvement where traditional methods have fallen short. This section explores recent advancements in cell therapy, focusing on various types of stem cells, their mechanisms of action, the consequences of clinical trials, and future directions in SCI treatment. Investigating the therapeutic challenges of solid tumors through cell tracking and molecular imaging could enhance the delivery of Chimeric Antigen Receptor (CAR)-T cells to these cancers. Cell therapy has reached significant milestones in various life-threatening diseases, including cancer. The use of fluorescent and radiolabeled CAR-T cells has proven to be a successful strategy for diagnosing or treating malignancies [32]. However, the success of CAR-T cell therapy in hematological cancers has yet to be replicated in solid tumor therapy, largely due to challenges such as tumor heterogeneity, the immunosuppressive tumor microenvironment, and physical barriers that hinder CAR-T cell infiltration. These obstacles lead to reduced therapeutic efficacy and increased toxicity in solid tumors [33]. Therefore, there are many areas for improvement in the cell therapy platform. Understanding the therapeutic barriers associated with solid cancers through cell tracking and molecular imaging may provide a platform for effectively delivering CAR-T cells into solid tumors, potentially overcoming these challenges and enhancing treatment outcomes.

3.2.1. Types of Stem Cells Used in SCI Treatment

- **MSCs**

MSCs are among the most encouraging candidates for spinal cord injury treatment due to their capability to modulate immune responses, support vascular regeneration, and release neuroprotective factors [34]. Recent studies have highlighted the anti-inflammatory properties of MSCs, which can reduce secondary damage subsequent to SCI. For example, Uccelli *et al.* (2008) discuss how MSCs can enhance the microenvironment of the injured spinal cord by reducing inflammation and promoting neuron survival through supportive nourishment [35]. Clinical trials have also shown that autologous adipose-derived MSCs can lead to improvements in motor and sensory functions. In a *Phase I* clinical trial at the Mayo Clinic, participants who received these stem cells demonstrated significant progress in sensation and movement during a two-year follow-up period [36].

- **NSCs**

NSCs are another important area of exploration for treating SCI. NSCs have a unique aptitude to discriminate into different types of neural cells, including neurons and glial cells, making them ideal for replacing lost or damaged cells in the spinal cord. Recent advances in preclinical studies have revealed that NSC transplantation can lead to improved motor function and reduced lesion size in animal models of SCI [37]. Research on optimizing NSC therapies has notably focused on methods to improve their survival and integration into host tissue. For example, Ronaghi *et al.* (2010) emphasize the potential of NSCs to generate a conducive environment for axonal growth [38].

- **iPSCs**

iPSCs characterize innovative progress in regenerative medicine. By reprogramming mature somatic cells to a pluripotent state, iPSCs can distinguish into any cell type, including neurons. This flexibility offers exciting possibilities for personalized medicine in the treatment of SCI. Studies have investigated the use of iPSCs to produce neural progenitor cells that can be transplanted into damaged spinal cords. These progenitor cells have shown promise in enhancing nerve repair and functional recovery in preclinical models [39-41]. However, challenges related to the safety and ethical implications of using iPSCs, particularly regarding tumorigenesis and immune rejection, remain.

3.2.2. Clinical Trials and Effectiveness

Mayo Clinic has been at the forefront of clinical trials investigating the effectiveness of stem cell treatments for SCI. Following promising results from phase I trials involving autologous adipose-derived MSCs, the clinic is now conducting phase II trials (CELLTOP) for further assessment of safety and efficacy, which includes intrathecal injection of these stem cells into patients with severe SCIs. Initial results indicate that patients have experienced improvements in motor function and sensory perception even months after treatment [42]. In a notable case from the CELLTOP trial, a patient who received stem cell injections almost a year after the injury showed significant improvement in strength and range of motion. Such results climax the potential of late interventions to achieve remarkable positive outcomes [43].

While current clinical trials show the potential benefits of stem cell treatment for SCI, numerous contests must be addressed before widespread clinical application can occur. These include determining the optimal timing for intervention, identifying patient populations that are likely to be assisted from the treatment, and establishing standard protocols for cell preparation and administration [38, 44]. In addition, researchers are exploring combination therapies that integrate stem cell treatments with other methods such as gene therapy or biomaterials considered to augment cell survival and integration into the injured spinal cord. For example, Zeng *et al.* (2023) demonstrated that scaffolding materials providing structural support may improve graft acceptance and promote axon growth after transplantation [45, 46].

3.3. CST Method

This method has gained attention as a complementary treatment for individuals suffering from brain and spinal injuries, particularly TBI and post-concussion syndrome. Several studies have reported positive outcomes associated with CST for individuals with brain injuries.

For instance, a study involving retired professional football players with post-concussion syndrome found that ten sessions of CST led to noteworthy improvements in pain amount, range of motion, memory, reaction time, and sleep duration. Participants in this study experienced an increase in average sleep hours from two to four over the course of treatment, with continued improvements noted three months' post-intervention. These results recommend that CST may play a beneficial role in addressing some of the secondary effects associated with TBIs. Additionally, CST is believed to help reduce symptoms such as headaches, dizziness, irritability, anxiety, and chronic pain—common challenges faced by individuals recovering from brain injuries. By optimizing CSF flow and addressing restrictions within the craniosacral system, CST may facilitate the body's natural healing courses. Ghasemi *et al.* (2020) investigated the efficacy of CST on pain, disability, depression, and quality of life in patients with Non-specific Chronic Low Back Pain (NCLBP). Their study, involving 45 patients divided into three groups, concluded that CST significantly improved pain, depression, functional disability, and quality of life for those with NCLBP [11, 12, 47].

3.3.1. Mechanisms of Action

The proposed mechanisms behind CST's effectiveness revolve around its influence on the Central Nervous System (CNS). The therapy is thought to promote relaxation and reduce tension within the body, which may contribute to improved neurological function. By enhancing CSF circulation, CST could potentially assist in removing waste products that accumulate around the brain following injury. This cleansing effect is crucial for maintaining optimal brain health and function. CST practitioners assert that by alleviating restrictions in the craniosacral system, they can enhance communication between different parts of the CNS. This improved communication may lead to better coordination of motor functions and cognitive processes—key areas often affected by brain injuries.

3.4. Nanotechnology Applications in Brain-Spinal Injury

Conventional methods for diagnosing and treating cancer often suffer from a lack of specificity and sensitivity, and they can lead to systemic toxicity. However, the use of NPs, Nano-systems, and Nano-carriers significantly enhances the bioavailability and targeting of cancer therapies, thereby improving both diagnostic accuracy and treatment efficacy. A notable approach involves encapsulating tyrosine kinase inhibitors, which can be effectively used for diagnosing and monitoring various types of cancer. These innovative nanosystem-based strategies can be seamlessly integrated with advanced imaging techniques to study biodistribution, pharmacokinetics, and drug delivery. This integration ultimately enhances diagnostic precision and therapeutic effectiveness, offering a more targeted and efficient approach to cancer management [48]. NPs are being discovered for their possible to improve both RT and diagnostics in the treatment of brain and spinal injuries.

3.4.1. Radiation Therapy Enhancement

NPs enhance RT by localizing radiation in targeted tissues, increasing tumor-icidal effects compared to radiation alone. They achieve this by generating Reactive Oxygen Species (ROS), which damage DNA, inhibit DNA repair systems, disrupt the cell cycle, and control the tumor microenvironment. Nanoparticle-based RT can help overcome radio resistance and drug resistance, offering more control and selectivity in treatment while reducing side effects. Their ability to be functionalized with biomolecules and therapeutic agents further reduces the adverse effects of RT. NPs can increase the radiation susceptibility of tumor cells through various strategies, such as remodeling the tumor microenvironment, enhancing radiation dose deposition, delivering chemical drugs to increase cancer cell sensitivity, and delivering antisense oligonucleotides. The improvement mediated by NPs can be assessed by determining the Dose Modifying Factor (DMF) based on survival curves, and the variation of ROS production upon irradiation. Preclinical studies have shown that NPs can perform as radiosensitizers, improving the effectiveness of RT. These strategies involve designing NPs that can remodel the tumor microenvironment, enhance radiation dose deposition, deliver chemical drugs to increase cancer cell sensitivity to radiation or deliver antisense oligonucleotides. Ayyami *et al.* (2024) found that NPs can act as radiosensitizers, and when engineered to target specific tumor markers, they selectively accumulate within the brain tumor microenvironment, boosting radiotherapy's therapeutic index [49]. High atomic number NPs, like gold, hafnium, platinum, or bismuth, amplify radiation effects when activated by photons, electrons, neutrons, or fast ions [50]. Studies have confirmed that NPs can enhance the radiation dose in loaded tissues, causing radiosensitization through mechanisms like oxidative stress, DNA damage, cell-cycle arrest, and apoptosis [51]. The combination of NPs with RT has been more operative in removing radio-resistant glioblastoma cells compared to radiosensitive strains. However, the radiosensitization of a precise cell line depends on various issues, and diverse cell lines display different replies to NPs. To improve productivity, specific NPs must be used for each cell line. The simultaneous use of several types of NPs to upsurge the competence of management as a radiosensitizer can be very hopeful in the future.

3.4.2. Diagnostic applications

Nanotechnology is in preclinical development for neuroimaging, with functionalized NPs like iron oxide, gold, or quantum dots enhancing the imaging of tumor foci, thrombi, or infarcted brain tissues in animal models [52]. High-resolution magnetic particle imaging (MPI) using SIONPs shows promise for real-time, three-dimensional imaging in vascular, tumor, and cell labeling applications. Multifunctional NPs can improve brain tumor imaging, allowing for better characterization, delineation of tumors, visualization of malignant tissue during surgery, and tracking of response to chemotherapy and RT [53]. NPs can cross the blood-brain barrier, making them useful for diagnosing and treating conditions like TBI. A novel nanoparticle delivery system can recognize disease states and reduce inflammation in the brain [54]. NPs can be targeted to injured brains, offering a promising tool for TBI diagnosis and treatment. Biomimetic NPs can access inflamed brain regions and deliver anti-inflammatory drugs, reducing macrophage infiltration and brain lesions [55]. In the realm of diagnostic applications, NPs, particularly those based on iron oxide, are being developed as contrast agents for MRI. For instance, core-shell Fe_3O_4@C NPs have demonstrated effectiveness as T_2 MRI contrast agents due to their ideal relaxometric properties. Similarly, Malekzadeh *et al.* (2022) synthesized an original targeted tumor contrast media for CT-MRI using Fe_3O_4@Au NPs. Furthermore, gold NPs are also being explored for enhancing the imaging capabilities of cancer cells in CT imaging [56, 57].

3.5. BCIs

BCIs signify a groundbreaking technological advancement in the rehabilitation and treatment of SCIs. By creating a straight communication pathway between the brain and external devices, BCIs hold the possibility to restore motor function and advance the quality of life for paralyzed individuals. This section discusses the latest advancements in BCI technology, clinical applications, challenges, and future directions [13].

3.5.1. Mechanisms of Action

BCIs operate by decoding neural signals from the brain, which can then be transformed into commands for external devices, such as robotic limbs or functional electrical stimulation (FES) systems. The decoding process usually involves advanced algorithms that analyze brain activity patterns to determine the desired movements. Recent advancements in machine learning and signal processing have enhanced the accuracy and responsiveness of these systems, making them more effective for clinical applications [13].

3.5.2. Types of BCIs

There are two main types of BCI: invasive and non-invasive. Invasive BCIs involve implanting microelectrode arrays directly into brain tissue, allowing for high-resolution signal acquisition. On the other hand, non-invasive BCIs use external sensors such as Electroencephalography (EEG) to detect brain activity without surgical intervention. Each type has advantages and limitations related to signal fidelity, complexity, and patient comfort [58].

3.5.3. Clinical Applications of BCIs

Recent studies have shown that BCIs can effectively restore motor function in individuals with SCI. For example, Mansour *et al.* (2022) reported that a new Brain-Computer-Spine Interface (BCSI) was developed to control spinal stimulation based on local field potentials recorded from the sensorimotor cortex. This approach successfully improved forelimb function in rats with cervical SCI, demonstrating the potential to translate these findings into human applications [59]. Levett *et al.* (2024) conducted a systematic review focusing on invasive BCIs and demonstrated that these systems can restore motor function in various tasks using data from 21 patients with cervical SCI. Techniques such as microelectrode arrays in the cortex were used to decode neural signals, leading to successful results in non-invasive FES and external device control. These results highlight the effectiveness of BCI technology in facilitating movement recovery [60]. Furthermore, BCIs are promising for enhancing rehabilitation strategies after SCI. By providing real-time feedback on neural activity related to intended movements, BCIs can increase neural plasticity—the brain's ability to reorganize itself functionally and structurally after injury. Motor imagery-based BCIs enable patients to engage in the mental practice of movements, which can help maintain cortical connectivity and potentially enhance recovery [13]. Also, Bonizzato *et al.* (2018) showed that participants using the brain-spine interface (BSI) can regain natural control over their lower limbs after paralysis due to SCI. This system creates a digital bridge between the signals of the cerebral cortex and epidural electrical stimulation targeting specific areas of the spinal cord involved in movement production. The participant reported being able to walk naturally in social environments, indicating significant advancements in BCI technology for.

3.5.4. BCIs Challenges and Limitations

Despite promising advancements in BCI technology, the complexity of decoding neural signals with precision poses significant technical challenges. Current BCI systems often require extensive calibration and may experience noise interference or signal degradation over time. Additionally, invasive techniques carry risks associated with surgery and long-term implantation [13]. The successful clinical implementation of BCI is also hindered by various factors, including variability in patient conditions and environmental influences during rehabilitation sessions. Most existing research has focused on stable patients in controlled environments. Therefore, further studies are desired to measure the helpfulness of BCI in acute or subacute stages following SCI. Additionally, ethical concerns surrounding invasive methods must be addressed, including issues related to informed consent, long-term consequences of implanted devices, and equitable access to these technologies as BCI research progresses [61, 62].

Recent advances in molecular imaging, cell therapy, and BCIs represent significant strides in understanding and managing brain and SCIs. These innovations not only enhance diagnostic capabilities but also offer promising therapeutic approaches that could transform patient care. As research in these fields continues to progress, several directions in the future are drawing attention:

The combination of molecular imaging with cell therapy and BCIs can lead to synergistic effects that enhance outcomes. For example, using imaging techniques to monitor the integration of stem cells or the effectiveness of BCIs can provide valuable feedback for optimizing treatment protocols. Additionally, designing interventions based on the individual characteristics of the patient is crucial for maximizing the effectiveness of treatments, and ongoing research should focus on identifying biomarkers that can predict responses to specific therapies. Furthermore, efforts should be made to ensure equitable access to advanced treatments for all individuals with SCI, regardless of their socioeconomic status or geographic location .This may include supporting policy changes that facilitate broader access to innovative treatments. On the other hand, with the emergence of new technologies, establishing comprehensive ethical frameworks to guide research and clinical practice will be essential. Engaging various stakeholders—including patients, ethicists, healthcare professionals, and policymakers—in discussions about ethical considerations will help ensure that advancements in SCI treatment align with social values.

The journey toward improving outcomes for individuals with SCIs is ongoing and multifaceted. By embracing innovations in diagnosis and treatment while remaining mindful of ethical considerations, the medical community can continue to take meaningful steps in enhancing the condition of people with SCI. Collaboration across disciplines—from neuroscience and engineering to ethics and policy—will be key in unlocking the full potential of emerging therapies and ensuring access to them for all who need them

4. Conclusion

In conclusion, the landscape of Brain and Spinal Cord Injury (BSCI) management is rapidly evolving, driven by significant advancements in diagnostic and therapeutic approaches. This review highlights the transformative potential of molecular imaging techniques, which provide deeper insights into neural activity and injury mechanisms, facilitating more accurate diagnoses and tailored treatment strategies. Cell therapy, particularly through the use of MSCs and other cellular interventions, demonstrates talented results in encouraging recovery and enhancing functional independence in patients with BSCI. Additionally, Brain-Computer Interfaces (BCIs) characterize a groundbreaking innovation that allows people with severe motor impairments to regain control over their environment through direct brain signaling. These technologies not only aim to restore lost functions but also enhance neural plasticity, offering new hope for rehabilitation. While CST has garnered interest as a complementary treatment modality, the evidence supporting its efficacy remains mixed. Further rigorous research is essential to establish its role in the broader context of BSCI management. Ultimately, the integration of advanced diagnostic tools and novel therapeutic strategies holds great promise for improving outcomes for individuals affected by brain and SCIs. Continued exploration and investment in this dynamic field are essential for enhancing our understanding of BSCI and developing effective interventions that.

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