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Evaluating Implementation of Functional Connectivity on Brain Computer Interface to Assist Depression Recovery

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Abstract:

Brain computer interface (BCI) has experienced exceptional development through past scientific studies. Yet it possesses few practical methods of assisting the treatment of major depressive disorder (MDD) patients or individuals suffering from depression. This paper evaluates the feasibility of BCI-related technology providing assistance for efficient countermeasures for MDD and general depression with the combination of the functional connectivity (FC) concept. Three correlated works are included for evaluation: A six-month BCI-guided training therapy of robotic hand program, an evaluation of BCI integrated systems implemented with noninvasive MDD recovery methods, and a deep learning model of detecting depression with electroencephalography (EEG) signals calculated from FC matrices. The robotic hand therapy indicates the contribution of EEG obtained by BCI for assessing the FC of subjects. The utilization of BCI systems has presented a success in completing the neuromodulation process, especially in repetitive transcranial magnetic stimulation (rTMS) and magnetic seizure therapy (MST) methods. Signal graphs used in FC matrices when detecting depression were established by the combination of different EEG signal bands, demonstrating a possibility of BCI coping with FC in disposing of depression treatment. This study suggests a potential approach for the practical application of BCI technology along with FC as an important assessment criterion when confronting MDD therapies and depression countermeasures. The evaluation results may contribute to further clinical practice and assistance in correlated studies on depression-related disorders.

Keywords: Brian computer interface; Depression; Major depression disorder; Functional connectivity.

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1. Introduction

In recent decades, the field of Brain-Computer Interfaces (BCIs) has witnessed remarkable growth, largely attributable to the concerted efforts of a global society. This evolution has been fundamentally driven by substantial technological advancements that have significantly enhanced the capabilities to capture and refine neural signals [1]. BCIs can be broadly classified into two categories: non-invasive systems, which typically use EEG signals acquired from scalp electrodes, and invasive systems, which directly measure electrical activity from cortical neurons using implanted electrodes [2]. Each approach offers unique advantages in terms of signal quality, spatial resolution, and practical applicability, catering to different research and clinical needs. This technology allows for seamless communication between the brain and external devices, thereby offering a novel approach to interaction and control that relies on neural signals rather than physical movements. Consequently, BCI has the potential to revolutionize fields such as neural rehabilitation and assistive technology, providing new opportunities for individuals with physical impairments to engage with and control external devices through brain activity alone.

BCI possesses significant potential for a range of applications, notably including support for individuals with paralysis or amputations, providing possibilities of controlling prosthetic limbs or communicating through external devices, and enhancements in cognitive rehabilitation processes in the post-treatment period, especially in addressing conditions such as depression[3][4]. However, despite these promising applications, BCI currently faces substantial limitations, particularly in the domain of mental health.

The effectiveness of BCI in mental health treatments is constrained by inherent challenges in signal processing techniques. Issues such as signal noise, artifacts, and the complex nature of EEG signals compromise the quality and reliability of the captured data, thereby affecting the efficiency and accuracy of BCI systems [5]. These challenges are particularly pronounced in the context of treating mental health conditions like depression, where the precise interpretation of neural activity is crucial [3].

As a complementation of observing and evaluating brain activity, the concept of Functional connectivity(FC) was proposed. FC is defined as the statistical dependence between these parameters, which reflects how various brain areas interact and synchronize their activity. Measurement techniques for functional connectivity fall into two primary categories: direct and indirect methods. Direct methods, such as EEG and Magnetoencephalography (MEG), offer a direct insight into neural function by measuring the average postsynaptic potentials and statistical currents of neuronal populations. These non-invasive techniques provide real-time data on the electrical activity of the brain, revealing the dynamic patterns of neural network activity [6].

On the other hand, indirect methods, such as Functional Magnetic Resonance Imaging (fMRI) and Blood Oxygenation Level Dependent (BOLD) contrast, assess changes related to metabolic demands. These techniques measure variations in blood oxygen levels as a proxy for neural activity, thus offering an indirect view of brain function. While fMRI and BOLD contrast do not capture electrical activity directly, they provide valuable information about the brain's metabolic responses and overall functional state [6].

Depression, particularly Major Depressive Disorder (MDD), is a widespread and concerning mental health condition that demands urgent attention. Globally, over 300 million people suffer from depression, with an alarming 15% average suicide rate among patients [5]. Symptoms of MDD consist of decreased social interest, diminished neurological activities in brain regions, and suicidal thoughts that constantly remain in patients awareness [5]. The logical framework and functionality of brain for MDD patients are distinguished from normal individuals, and this is especially obvious in cortical layers of the brain [5].

One promising yet under-explored avenue is the application of FC concepts to BCI systems for mental health treatment, which have demonstrated success in other connectivity contexts. FC, which involves analyzing the temporal correlations between different brain regions, has the potential to enhance the accuracy and effectiveness of BCI in mental health applications. Despite its potential, this concept has not been extensively applied to BCIs targeting depression recovery. While BCI offers considerable promise for advancing mental health treatment, significant challenges remain in optimizing FC techniques. Current systems are limited by issues related to electrical activities and neural functionalities, which impedes their practical efficacy and widespread adoption.

The purpose of this paper is to investigate the application of functional connectivity on BCI systems to improve the efficiency of depression recovery. Approaches for functional connectivity to be adapted for BCI applications will be explored, with a focus on its potential to deepen the connectivity between neural populations and machinery units, thus enhancing the clarity and reliability of EEG signals.

2. Materials&Related works

2.1 Example selection

The study of functional connectivity often involves the detailed process of collecting and analyzing electroencephalographic (EEG) signals. This makes it possible for FC to obtain a comprehensive insight into neural networks' dynamic behavior and potentially revealing biomarkers for various neurological and psychiatric conditions. Initially, the preparation phase includes selecting and calibrating EEG equipment, as well as preparing the subject by obtaining informed consent and ensuring proper scalp cleanliness and electrode placement using conductive gel for optimal contact. Electrodes are then positioned according to standardized systems like the International 10-20, secured with caps or adhesives, and connected to amplifiers. During signal acquisition, parameters such as sampling frequency and filter settings are carefully adjusted to ensure data accuracy, and recording is conducted under various experimental conditions while monitoring for signal quality.

Subsequent data processing involves preprocessing steps to remove artifacts and further filter the signal, followed by detailed functional connectivity analysis. This analysis includes calculating power spectral density to examine brain wave characteristics, assessing correlations or coherences between brain regions, and conducting time-frequency analysis to explore how frequency characteristics change over time. The final results are interpreted in the context of experimental tasks, with findings organized into reports for further research or clinical use. This integrated approach enables a comprehensive understanding of brain connectivity through EEG.

To support this research on implementing FC in BCI techniques, relevant studies and experimental examples from two primary sources are included for review: Frontiers in Human Neuroscience (https://www.frontiersin.org/journals/human-neuroscience) and the Journal of Integrative Neuroscience. These sources provided valuable insights into current BCI applications and functional connectivity research.

2.2 BCI-guided training therapy

Brain computer interfaces (BCIs) have been increasingly explored as an approach for neurological therapy assistance. A notable example of this application comes from a 2020 study, where a research group investigated BCI-related motor therapy using a robotic hand for chronic stroke patients. The research team stated that it is possible to combine the BCI system and distal robotic hand technology in order to detect biological signals emitted by the brain and provide assistance with manipulating the robotic hand for chronic stroke patients, eventually ensuring a certain level of recovery due to the enhancement of neuroplasticity and experience of motor studying in the therapeutic process. The team emphasizes that distal robot-assisted training therapies' effectiveness over the upper limb was proven to be more desirable than proximal ones. In terms of comprehending the results of recovery therapies for patients' neuroplasticity, the concept of functional magnetic resonance imaging (fMRI) is included. FC acts as an important index for estimating the temporary trend of neuronal activities in individual brain regions, therefore it is commonly used in experiments that require insights into neurological networks' dysfunction and functional disorders [7].

The research team selected 14 chronic stroke patients appropriate for the therapy. The experiment protocol was designed to engage patients in motor imagery tasks. Specifically, subjects were instructed to imagine grabbing and releasing a cup, with visual cues provided on a monitor. The EEG signals of patients would be obtained with a remote signal collecting system along with 16 electrodes attached to the ipsilesional and contralesional hemisphere of the motor-relevant region. According to the research team, the result of the experiment falls into two hypotheses: the alphabetic wave of patients should be boosted due to the feature of it associating with relaxed mental states and improved cognitive function, and evidentiary clinical results are expected to appear in positive functional activity because subjects' neuroplasticity dependent on functional connectivity is expected to be evidently stimulated, hence leading to better recovery in motor-related brain regions.

To evaluate the effectiveness of the therapy, the research team employed a comprehensive functional connectivity (FC) analysis. They strategically chose seed regions in the ipsilesional primary motor cortex (IM1) and supplementary motor area (ISMA) by analyzing the FC patterns originating from these seeds, as shown in Fig. 1. The researchers aimed to detect changes in brain network organization that could indicate therapeutic progress. In addition, the fractional amplitude of low-frequency fluctuations (fALFF) was considered as a crucial value to determine if the FC of the target seed is increased. This approach allows for a more nuanced understanding of how the BCI intervention affects brain connectivity patterns related to motor function [7].

The study implemented a comprehensive intervention program, consisting of 20 training sessions using BCI-guided robotic hand therapy. To assess the long-term effects of this intervention, the researchers conducted follow-up evaluations 6 months after the completion of the training. In comparison, the FC of the seed implemented at IM1

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and ISMA has experienced an evident increase both in pre-to-post sections and post-to-post 6-month sections of the therapy. To better indicate the results, the fALFF was proven to have an obvious increase in the ipsilesional precentral area and superior parietal lobule, the contralesional precentral area and ipsilesional superior frontal area, and the bilateral supplementary motor area, in comparison to pre-to-post, pre-to-post 6 months, and post-to-post 6 months respectively. The results of this experiment presented a clear indication that the neuroplasticity of patients who were suffering a chronic stroke can be improved by participating in BCI-guided robot hand training therapy and remaining benefiting from the course through an extended period of up to 6 months or more [7].

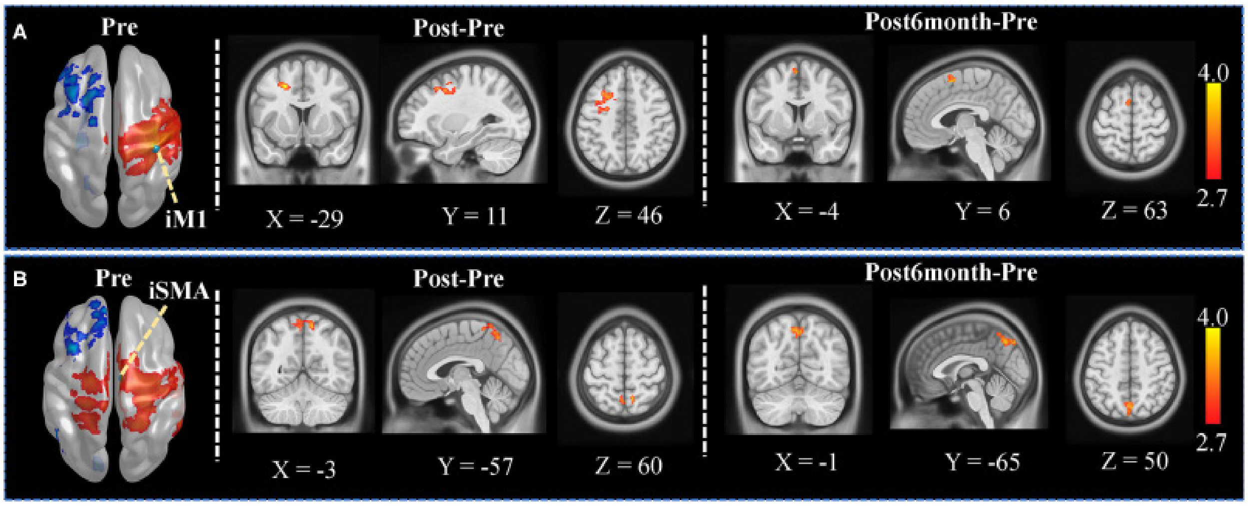

Fig. 1 The seed-based whole brain analysis marking the FC of iM1 and iSMA areas [7].

2.3 BCI integrated system and EEG signal

The representative of depression in clinical trials is MDD, a commonly existing mental health condition, which has identified features such as a massive reduction of interest in social activities and communications, consistent pressure of anxiety, and inevitable risks of suicide. The complex nature of MDD, with its multifaceted symptoms and treatment-resistant cases, presents a unique opportunity for BCI technologies to offer novel therapeutic approaches and enhance this paper understanding of the disorder's underlying neural mechanisms. In 2023, a group of research team identified the lack of effective treatment for MDD, given that major pharmacological antidepressants' treatment efficiency is not guaranteed to be better than a placebo. The research team focused their efforts on general research of neuromodulation, which can be categorized into invasive and noninvasive methods to have an influence on the biological process of transmitting information of neurons, including the concept of neuroplasticity. Four noninvasive and one invasive methods were mentioned as research subjects: Focal electrically administered seizure therapy (FEAST), repetitive transcranial magnetic stimulation (rTMS), accelerated transcranial magnetic stimulation (aTMS), magnetic seizure therapy (MST), and intermittent theta-burst stimulation (iTBS). The advancements in real-time brain imaging and EEG were demonstrated for the convenience of improving the efficiency of neuromodulation. The accessibility of analyzing the communication process of brain regions enabled BCI technology to cope with the aforementioned methods of neuromodulation to potentially enhance the effectiveness of treatment along with decreased side effects. The integration of the BCI system with rTMS and MST was specifically presented due to the EEG provided by the BCI system, which has contributed to the effectiveness of the therapy. The precision of feedback obtained from neural responses ensures the ability to customize rTMS, while the effective monitoring of brain activities promotes an important factor of a closed-loop system for TMS to scan for real-time images throughout the process of surgery. To conclude, the acquisition of EEG performed under the integration of BCI systems has a significant positive impact on the precision of surgery and thus be clinically beneficial to treatments for MDD [1].

2.4 EEG signal's channel in FC matrices

MDD remains a significant mental health concern, often compounded by insufficient public awareness and inadequate attention to patients' mental well-being. This lack of social recognition, coupled with challenges in effective early diagnosis, creates a concerning situation where individuals with mild depression are at risk of progressing to more severe forms of MDD. Recognizing this progression risk underscores the critical importance of developing accurate diagnostic tools for early detection and intervention in mild depression cases. Hence this research team in 2020 focuses on forming a feasible method to recognize mild depression with promising precision. The research team decided to utilize graph theory to distinguish mildly depressed patients from normal participants. Using convolutional neural networks (CNN), the research team is able to classify the biological images of patients' EEG, which was expected to be calculated with the four FC matrices of coherence, correlation, phase locking value (PLV), and phase lag index (PLI) to convert into identifiable biological images. In this case of the experiment, the subjects' EEGs were obtained in an innovative method. Using the HydroCel Geodesic Sensor set, a set of electrodes with 128 channels is applied with an impedance of less than 60k, and thus sampling EEG signals at a frequency of 250Hz. The band-pass value for EEG signals was controlled at 0.5Hz and 70Hz. Net Station Waveform Tools were used to discard ocular and muscle activity. In case the eye movement's signals' frequency is 0-16Hz, overlapping the alpha rhythm frequency of 8-13Hz, the FastICA was implemented to differentiate between overlapped signals. The experiment included two blocks that were designated to be shown in front of the participants to acquire their neural network responses, which were Emo-block, the block that provides a picture of emotional expression against a neutral one, and Neu_block, the block that would simply display two neutral expressions. To optimize the performance of their classification model, the research team innovatively transformed the FC data into a format more suitable for CNN analysis. They selected the three signal bands that showed the highest classification performance and mapped them onto the R, G, and B channels of a color image. This approach effectively condensed complex frequency-domain information into a visually interpretable format. The specific bands chosen for this three-channel conversion are detailed in Table 1. By representing brain connectivity data as images, the team leveraged the powerful pattern recognition capabilities of CNNs, potentially enhancing the accuracy and efficiency of mild depression detection [4].

Table 1. The bands for each function connectivity matrix [4]

	Coherence	Correlations	PLV	PLI
Neu_block	Delta, beta, theta	Gamma, theta, alpha	Gamma, alpha, delta	Alpha, theta, gamma
Emu_block	Gamma, beta, delta	Delta, beta, gamma	Delta, theta, gamma	Gamma, beta, delta

To evaluate the effectiveness of the novel three-channel approach, the research team conducted a comparative analysis. They selected the most promising results from the traditional single-band analysis (including delta, theta, alpha, beta, and gamma bands) across all four matrices. These selected results were then compared against the performance of the three-channel coherence method. The improvements in three-channel bands' coherence can be observed in Fig. 2.

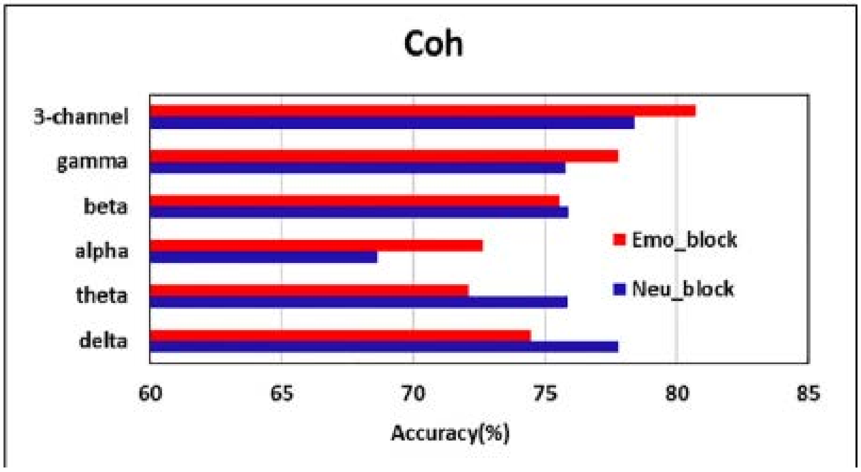

Fig. 2 The accuracy of coherence matrix for different bands [4].

The results demonstrated a considerable improvement in accuracy when using the three-channel FC matrix approach for coherence and correlation analyses. This enhancement suggests that integrating information from

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multiple EEG frequency bands provides a more comprehensive representation of brain activity. The research team hypothesized that this improved performance reflects the complex, multi-frequency nature of neural networks in human brain activities. By analyzing FC matrices with integrated EEG spectra, researchers can capture a more holistic picture of brain connectivity, potentially leading to more accurate and robust detection of mild depression.

3. Discussion

The integration of BCI-guided training with robotic hand assistance represents a pioneering approach to neurorehabilitation. By enabling real-time detection of neural network activities in motor-related brain regions, this method offers unprecedented insights into neuroplasticity and motor learning processes. This indicated a possibility of monitoring mentally dysfunctional patients' neurological condition while proceeding with appropriate treatment, for the FC of an individual involves the responses of neural networks, including neuroplasticity. Furthermore, the effectiveness of the therapy that is shown by increasing FC between iSMA and bilateral SPL not only appeared immediately after the training process, but the recovery also progressed throughout 6 months after the treatment, which proposed a potential that BCI-guided treatment with action training is capable of providing long term positive effects for patients who are severely struggling with motor functioning because MDD's typical symptoms include possible extensive Somatization, a dysfunction of physical activity. Eventually, the reference from this research provides a possibility of creating a personalized, adaptive training platform that could significantly enhance recovery outcomes for patients with motor impairments, potentially extending to conditions beyond MDD, such as stroke or spinal cord injuries.

In the case of analysis of different methods of neuromodulation, the research team explored a few of noninvasive methods of BCI integrated technology, including FEAST, TMS, iTBS, and MST. The use of BCI technology and EEG signals were addressed in rTMS and MST methods, because rTMS utilizes EEG observed in neural networks to ensure the flexibility of treatment during the process, while the latter combines EEG signals with scans that are used locating seizure onset, thus giving more effective treatments. This evaluation demonstrated the contribution of BCI integrated system and EEG to the innovative methods of caring for mentally and neurally damaged patients, providing an era of implementing BCI technology and EEG signals when confronting general negative mental condition, which involves MDD as well.

Moreover, in the research of mild depression recognition with EEG based on the inspiration of FC, the research team for this experiment has presented a unique classification method by combining CNN and four types of FC matrices. On this occasion, the EEG signal bands in each of the matrices were carefully selected by the research team, incorporating the top three of their best bands of performance to create a three-channel graph to compare with general bands of signals. The results did not merely indicate the effectiveness of the method to discover mild depression with an acceptable precision, the three-channel band was proven to be the most accurate signal band when detecting depression with an accuracy of 80.74%. This practice emphasized the importance of EEG signals in complementing the technology of detecting the early state of depression, which could be an innovative perspective for BCI to cope with depression recovery technologies. Moreover, patients with mild depression are in lack of social attention and an efficient diagnosis approach, resulting in extensive potential of developing MDD. The implementation of this advanced EEG-based detection technique for mild depression has far-reaching implications for mental health care. By enabling early and accurate identification of individuals at risk of developing more severe depressive disorders, this approach could significantly enhance prevention strategies. Early intervention, made possible by this technology, could potentially reduce the progression of mild depression to Major Depressive Disorder (MDD), thereby alleviating the burden on healthcare systems. Moreover, this method could be integrated into routine health screenings, allowing for a more efficient allocation of medical and technical resources. In specific examples of practice, primary care physicians could be able to utilize this tool for initial assessments, referring only high-risk cases to specialists, thus streamlining the diagnostic process and reducing overall healthcare costs associated with depression treatment.

4. Conclusion

In general, the era of treating depression disregarding the extent could be significantly complemented by BCI-related systems along with the interference of FC's concept, by offering a potential for more personalized and effective treatments across the spectrum of depressive disorders. Earlier research has illustrated the use of BCI technology in assessing the recovery status of patients with chronic stroke, the contribution of EEG being a critical criterion of customizing therapy as well as a cooperative component of identifying the onsets of specific neural abnormalities, and involvement of EEG to promote the accuracy of diagnosing depression in a deep learning model that includes calculation of FC matrices. By integrating BCI systems and FC analysis, clinicians can now gain deeper insights into individual brain function and connectivity patterns, enabling them to tailor treatments more precisely to each patient's unique neurological profile. This shift towards technology-enhanced, personalized treatment strategies marks a significant advancement in addressing depression at all levels of severity.

The integration of BCI technology, FC, and EEG acquired from BCI systems has not only presented a potential opportunity for BCI technology to enhance the efficiency of treating MDD. This research presented a possible approach of directly including BCI technology in the treatment of MDD. A key advantage of the BCI technologies discussed in these studies is their non-invasive nature. This characteristic is particularly crucial in the context of mental health treatments. By utilizing non-invasive BCI methods, researchers have demonstrated the potential to achieve significant therapeutic effects without resorting to surgical interventions. This approach not only minimizes physical risks and side effects associated with more invasive procedures but also makes the treatments more accessible and acceptable to a wider range of patients. The non-invasive nature of these therapies could lead to increased patient compliance and willingness to undergo treatment, potentially improving overall outcomes in depression management. The features of MDD may contain a certain degree of disorder in physical functions and has a possibility of variation over a random period, hence the demands on flexibility and accuracy of therapies are extremely required, which can be resolved by implementing BCI-related methods and EEG signals, while FC serves as adjustable indexes of evaluating the effectiveness of treatments.

The limitations of the research are due to the lack of sufficient samples of related works. The training therapy for chronic stroke has incorporated only 14 patients, while the deep learning model for detecting depression has covered less than 40 participants in total. Furthermore, the implementation of BCI-related systems consists series of machinery products and delicate components. It may be costly to utilize BCI technology to help treat patients with MDD. In future studies, the application of BCI integrated systems directly on treatment for both MDD or moderate depression based on the assessment of FC is recommended, and related evaluation of factors that might have considerable effects should be included.

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