Dean&Francis

ISSN 2959-6157

EEG and FNIRS Hybrid Brain Computer Interface Technology in Rehabilitation Medicine

Chenghao Jiang

College of Photonic and Electronic Engineering, Fujian Normal University, Fujian, China

*Corresponding author: MRAMI35492@my.sunywcc.edu

Abstract:

The field of rehabilitation healthcare is facing both opportunities and challenges due to issues such as the increase in the number of patients with chronic diseases and the ageing of the population. With the increasing demand for rehabilitation healthcare, these issues are gradually gaining attention. Brain computer interface (BCI), as a brand new diagnostic and therapeutic means, cross-fertilises multiple disciplines, while hybrid brain-computer interface (HBCI) technology is a research hotspot in recent years, which breaks through the limitations of the unimodal BCI technology by combining the two paradigms, and brings a new hope to patients with stroke and other diseases. This paper first analyses the current situation of the rehabilitation medical field and discusses the importance of receiving rehabilitation medical treatment for patients with chronic diseases and other diseases. Subsequently, it introduces the development history of brain-computer interface technology, analyses its research status, and explains its technical principles. Then, the application of hybrid brain-computer interface technology is analysed from three types of diseases, namely, limb movement disorders, chronic consciousness disorders, and mental illnesses. Finally, the current problems of hybrid brain-computer interface technology are discussed, and the prospect of the application of hybrid brain-computer interface technology in the field of rehabilitation medicine is outlooked.

Keywords: Brain-computer interface; hybrid modality; rehabilitation medicine; EEG-fNIRS signals.

1. Introduction

BCI, as a new and cutting-edge technology to realise human-computer interaction, is essentially to build a direct connection between the human or animal brain and external devices, and then to achieve efficient information exchange between the brain and the devices [1]. Although BCI is often perceived as a recent innovation, its conceptual roots trace back to 1924 when Hans Berger pioneered the key concept of Electroencephalography (EEG) [2]. Since then, people have ventured to speculate that the brain is still capable of effective communication and precise control even without the involvement of peripheral nerves and muscles. In 1988, the brain-computer interface developed by Matsushita Electric began to become an important tool for research in neuroinformatics, psychology, and computer science. However, it was after the 1990s that the technology really began to achieve milestones. In 1990, researchers used the BCI to control a speech synthesiser and successfully implemented the complete process from consciousness to speech synthesis. By the beginning of the 21st century, brain-computer interface technology had developed significantly, driven by advances in neuroscience and mathematics which led to the emergence of many new approaches. Modern BCI systems have improved dramatically compared to the 1980s. For example, a new BCI system developed at the University of California Davis Health Centre is able to convert brain signals into speech with an accuracy rate of 97 per cent, which was previously unimaginable. These technological advances include the use of multi-channel EEG signals as inputs to capture signals from the brain more accurately the use of artificial intelligence and machine learning and other methods of data processing to improve the accuracy of brain-computer interface systems through the use of non-invasive modalities to visualise the activity of brain regions through advanced imaging techniques to further advance the development of brain-computer interface technology. With the continuous progress of science and technology and the gradual deepening of research, brain-computer interface technology has shown remarkable development potential. It has broad application prospects in many fields, especially in digital rehabilitation medical care. The gradual maturity and perfection of this technology has brought new hope to many patients.

HBCI technology is the fusion of multiple physiological signals that represent the cognitive state of a person at different levels. This approach offers several advantages. The fusion of multiple physiological signals provides a better characterisation of the user's state, which helps to optimise the performance of the BCI system and enhance the user experience. Compared with unimodal brain-computer interfaces, HBCI can better meet the functional requirements of human-computer interaction.

Among various HBCI approaches, the combination of EEG and fNIRS has shown particular promise. This paper focuses on the application of EEG and fNIRS mixed-modal brain-computer interface technology in the medical field. EEG, an EEG recording technique, and fNIRS, a functional near-infrared spectroscopic imaging technique, are relatively well-developed and mature, and are widely used in studies to detect EEG signal activity, and also play an important role in the field of rehabilitation medicine.

2. EEG-fNIRS Hybrid BCI in Rehabilitation Medicine

2.1 Current status of rehabilitation medicine

According to a report published by XYZ-Research, the global rehabilitation healthcare market size grew from approximately USD 140 billion in 2017 to approximately USD 180 billion by 2022. The market size is expected to surpass USD 200 billion in 2023. Among them, North America accounts for the largest market share of about 40%, followed by Europe, Asia-Pacific, and other regions with market shares of 30%, 20%, and 10%, respectively. As the aging population worsens, the demand for rehabilitation care will also increase, and it is essential for patients to receive rehabilitation treatment. Taking stroke patients as an example, most stroke patients often suffer from varying degrees of motor dysfunction, deterioration of language function and cognitive dysfunction, because of which they are unable to perform sports or communicate smoothly and freely. The root cause of these dysfunctions lies in the brain, and patients often need to undergo rehabilitation, including physiotherapy, occupational therapy, speech therapy, psychotherapy and Chinese medicine rehabilitation. The aim of rehabilitation is not only to restore the body to its normal state, but also to achieve neural remodelling of the brain's motor functions. According to statistics, 90% of stroke patients are able to regain some level of self-care ability after rehabilitation. Among these, 30% show more significant improvement and are able to perform simple tasks. Only 6 per cent of patients who do not receive rehabilitation therapy can regain the state of self-care [3].

In recent years, the emergence of BCI technology and its excellent performance in the field of rehabilitation medicine have brought the hope of patients to return to the society. BCI technology is a development trend in the field of modern rehabilitation therapy, which has been developing rapidly in the field of medicine, and its potential medical value has received widespread attention, and the experts are committed to the research of BCI technology to promote the development of brain science.

2.2 Research progress of EEG-fNIRS HBCI

ISSN 2959-6157

technology

BCI technology has three ways of collecting EEG signals: invasive, partially invasive and non-invasive. The first two require brain implantation surgery, although they provide better quality signals. This paper argues that non-invasive methods are more acceptable for acquiring EEG signals. However, these methods have a lower signal-to-noise ratio and require more post-processing, which may make it difficult to detect the user's motor intentions. The use of non-invasive methods as a way of acquiring EEG signals is more acceptable, but it has a lower signal-to-noise ratio and a higher requirement for post-processing of the signals, which may lead to difficulties in detecting the user's motor intentions.

In order to further improve the accuracy of human-computer interaction, HBCI technology was proposed. As early as 2010, Allison et al. proposed combining motor imagery (MI) and steady-state visual evoked potentials (SSVEP). This combination aimed to address the problem of "BCI blindness" in unimodal BCI systems, where some users' brain response signals are too weak to be effectively used by the BCI system. Allison et al. proposed combining the MI and SSVEP signals. Their experimental results showed that this HBCI system achieved an accuracy of 81.0% [4]. This allows the accuracy of the user's motor intention measurement to be further improved.

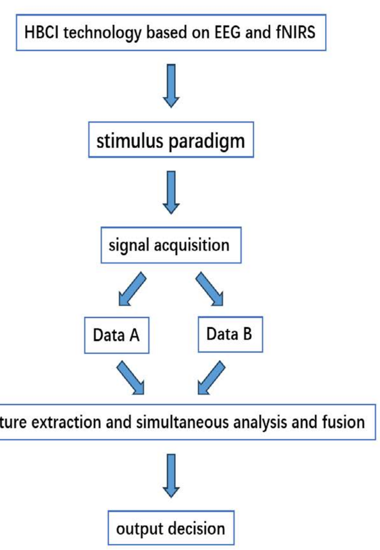
The research and development of HBCI technology further breaks through the limitations of unimodal BCI technology. In this paper, this paper focus on the BCI technology based on EEG and fNIRS, which is the fusion of multiple BCI signals, and its basic principle is shown in Fig. 1. EEG, or electroencephalography, is a widely used technology in human-computer interaction that collects low-amplitude electrical signals from the cerebral cortex via a wearable electrode cap. While effective, it's susceptible to noise and has poor spatial resolution [5]. fNIRS, or functional near-infrared spectroscopic imaging, is a technique that detects changes in blood oxygen levels in the cerebral cortex. This method reflects the neural activity of the brain, making it ideal for research on cerebral cortex neural activity [6]. The BCI signals are combined with each other, which can be used to improve the performance of MI-based BCI [7].

According to research, human EEG activity is not directly linked to its corresponding hemodynamics in time and space. However, it's possible to integrate neural activity signals captured by EEG and fNIRS through the mechanism of neurovascular coupling [8]. These signals are compatible and complementary, providing a more comprehensive, accurate, and real-time reflection of brain activity during cognition. This integration also allows for clearer detection of the user's motor intentions. Compared with unimodal BCI technology, the advantages of EEG and fNIRS HBCI technology are not only only reflected in the gain of information content, but also relatively easy to implement technically [9].

In recent years, EEG and fNIRS HBCI technology has developed rapidly and achieved remarkable results, and has been widely used in education, military, medicine and other fields. However, there are still some challenges in its further research, such as data preprocessing, feature extraction and fusion, model training and optimisation, etc. These need to be used in combination with neuroscience, machine learning, deep learning, and other technologies to achieve the breakthrough of HBCI in technology.

Overall, EEG and fNIRS-based HBCI technology has vast prospects and is a very promising field. However, to promote its development and application, future research needs to focus on overcoming the remaining technical challenges.

[redacted]



[redacted]

Fig. 1 Principle of the EEG and fNIRS-based HBCI technology (Photo/Picture credit: Original)

2.3 Application of EEG and fNIRS HBCI technology in the medical field

In recent years, BCI technology has been developing well and rapidly, and has also made great progress, showing remarkable research potential in both civil and defence fields. In the medical field, BCI technology is also widely used because it can achieve direct interaction between the brain and external devices, breaking the conventional brain information output pathway and replacing the natural output pathway that patients have lost due to disease or injury. In this paper, this paper will analyse 3 main areas: physical movement disorders, chronic consciousness disorders, and psychiatric disorders.

2.3.1 Applications in the diagnosis and treatment of limb movement disorders

Limb movement disorders refer to conditions where patients experience impaired motor function of their extremities. These disorders can result from various causes, including traumatic brain injury, stroke, and neurodegenerative diseases. These illnesses result in impaired control of the limbs corresponding to the affected brain area. In some cases, such as certain muscular disorders, the patient's muscles may become atrophied and weak, which also impedes limb movement. In addition, there are also spinal cord injuries, etc., which will also affect the patient's normal limb movement. The application of HBCI technology as an adjunctive therapy can help patients improve or even restore their limb movement status, thus improving their quality of life.

HBCI technology is applied in two ways. The first is assistive, where neural signals of the patient's motor intention are obtained through EEG and fNIRS. These signals are derived from the patient's motor imagery and are used to control external devices, helping the patient complete movements. For example, Yahud designed and developed a robotic hand connected to a BCI, which can realise movements such as pinching a piece of paper in the fingers and grasping a cylinder, which are able to satisfy the patient's needs mostly in real life [10]. The other is rehabilitative, because the patient's central nervous system has plasticity, it can be repeatedly stimulated and fed back through the application of HBCI to enhance the connection between neuronal synapses, so as to repair the damage caused by the patient's injuries and illnesses, in order to restore the limb movement ability. For example, the HBCI hand rehabilitation system designed by Dong Yue, Liu Ke, Wang Tao and others promotes the reconstruction of motor neural circuits in patients by pre-processing the EEG signals, feature extraction and converting the results into control commands to control the rehabilitation robot to perform hand motions, so as to allow the patient to perform proactive rehabilitation training [11].

Studies have shown that EEG and fNIRS-based HBCI technology can improve rehabilitation outcomes compared to unimodal BCI. This technology can provide a more efficient rehabilitation training component for treating limb movement impairments.

2.3.2 Applications in the diagnosis and treatment of chronic disorders of consciousness

Chronic disorders of consciousness encompass a spectrum of conditions, primarily including persistent vegetative state and minimally conscious state. These conditions can vary in severity and manifestation. Since they cannot communicate normally, they often miss the best time for rehabilitation. And the emergence of HBCI technology solves most of the problems. Through the application of BCI technology to obtain and analyse the patient's EEG signals, this paper can assess the patient's state of consciousness, aid in the diagnosis of consciousness disorders, and potentially guide treatment strategies. The patients with consciousness disorder can also achieve communication through BCI technology.

This paper can stimulate the patient's senses by using things familiar to the patient, such as the patient's or loved one's name, photos, and other information as target stimuli. At this time, the BCI device can capture the EEG signals generated after the patient receives the target stimuli and analyse his or her state of consciousness, so that the doctor can better judge whether the patient has the possibility of arousal and carry out targeted treatment.

The application of BCI technology based on EEG and fNIRS can detect and analyse the patient's EEG signals more accurately and comprehensively, thus better providing a basis for the doctor's judgment.

2.3.3 Application in the diagnosis and treatment of mental diseases

HBCI technology, integrated with advanced machine learning algorithms, can analyze EEG and fNIRS signals with enhanced accuracy to determine a patient's emotional states. This improved capability offers a more objective and precise approach to diagnosing and treating mental illnesses, potentially leading to more personalized and effective interventions. For instance, it can assist in researching the pathogenesis of depression and autism, potentially leading to more effective treatment strategies for these and other psychiatric disorders. Through the modulation of BCI, patients can be treated precisely and individually with deep brain discharge stimulation technology. In addition, patients can also be trained with BCI-based neurofeedback, which can improve their clinical symptoms.

BCI technology has a promising future in the diagnosis and treatment of mental illnesses, and many research institutes and companies have carried out related research,

ISSN 2959-6157

such as Elon Musk's BCI research company Neuralink, which is dedicated to exploring the development of BCI technology to diagnose and treat mental illnesses such as autism, schizophrenia and memory loss.

3. The challenges of EEG and fNIRS HBCI technology in the medical field

Currently BCI technology has become a major trend in the development of the medical field, but it still faces many problems. From the cost point of view, BCI technology is not yet mature compared with other AI products due to its high R&D cost, shortage of R&D personnel, and unclear profit model, so only a few companies have carried out the development and research on BCI technology. Technically, BCI technology is still in its early stages. The complexity and vast number of neurons in the brain pose significant challenges. Consequently, the accuracy in recognizing and interpreting the mixed brain interface signals needs further improvement. In addition, the stability and adaptive ability of BCI systems are poor, and signal pre-processing and analysis methods need to be improved. Ethically, especially invasive BCI is difficult to be accepted by the general public due to the possibility of certain damage or and infection to human brain tissue, which has led to current research focusing more on non-invasive BCI. In terms of clinical application, there are fewer mature products of HBCI technology, so it is relatively limited in clinical application. As a new type of AI medical diagnostic and treatment device, it is also indispensable to pass the approval and certification of the relevant national institutions, and the relevant policies on medical devices with HBCI technology are still being improved.

The challenges faced by HBCI technology in the medical field highlight that BCI technology is still in the development and research stage. There is a long way to go before BCI products can be widely used in clinical applications. The effectiveness and safety of these products need further evaluation. Moreover, there is a lack of uniform standards in this field, which needs to be addressed.

4. Conclusion

This paper focuses on the application of Hybrid Brain-Computer Interface (HBCI) technology, specifically combining EEG and fNIRS, in the field of rehabilitation medicine. Firstly, this paper analyzes the current situation in rehabilitation medicine, using stroke patients as an example. By comparing recovery rates, it demonstrates the necessity of rehabilitation treatment for patients with limb movement disorders and other conditions. Then, the HBCI technology based on EEG and fNIRS is proposed, which brings innovative solutions to the field of rehabilitation medical treatment. Compared with unimodal BCI, HBCI technology significantly improves the accuracy of signal acquisition and analysis. For instance, studies have shown that HBCI can increase signal detection accuracy, at 81.0%, providing more accurate and richer data support for rehabilitation treatments. Finally, this paper analyses the applications in three major medical rehabilitation fields: physical movement disorders, chronic consciousness disorders, and mental diseases. It analyses the important role of HBCI in the field of rehabilitation medical treatment from both diagnosis and treatment aspects.

However, HBCI is still only in the primary stage and needs to be developed and improved to achieve wider application in the medical field. Future research should focus more on brain science, incorporating perspectives from neuroscience, machine learning, and deep learning. This interdisciplinary approach will help address the challenges in HBCI technology development. By doing so, this paper can provide stronger theoretical support for advancing this field. Secondly, to achieve the maturity and reliability of BCI products in the future, it is necessary to break through the research and development of key BCI technologies one by one, starting from the demand. In addition, this paper must address product safety, privacy, and other ethical concerns. New technologies like BCI need to be regulated by relevant policies. It's crucial to establish a unified evaluation system to ensure the responsible development, application, and popularization of BCI technology at every stage.

References

[1] VIDAL J J. Toward direct brain-computer communication. Annual Review of Biophysics and Bioengineering, 1973, 2(1): 157-180.

[2] JIN Erfeng, SONG Baolin. Analysis of the perception of other minds and application prospect of multimodal brain-computer interface under the threshold of body phenomenology. Science and Technology Management Research, 2023, 43(24): 214-220.

[3] Li Hui, Jiang Yafang. Research progress of early rehabilitation nursing interventions for stroke patients. Chinese Journal of Nursing, 2010, 45(2): 187-189.

[4] Allison B Z, Brunner C, Kaiser V, et al. Toward a hybrid brain-computer interface based on imagined movement and visual attention. Journal of Neural Engineering, 2010, 7(2): 026007.

[5] Xu Baoguo, He Lesheng, Song Aiguo. Design and application of computer interaction experimental platform based on EEG. Journal of Electronic Measurement and Instrument, 2008, 22(1): 81-85.

[6] Hu Fei, Qian Cheng. Advances in functional near infrared spectroscopy and its application to user experience measurement. Collection, 2019, 1(1): 1-8.
[7] Lee M-H, Fazli S, Mehnert J, et al. Improving the performance of brain-computer interface using multi-modal neuroimaging. The 2nd IAPR Asian Conference on Pattern Recognition, Okinawa, IEEE, 2013: 511-515.
[8] Cheng S.C. Multimodal neural-vascular coupling characterisation and mechanism study for stroke rehabilitation assessment. Dissertation, Yanshan University, 2023.
[9] Putze F, Hesslinger S, Tse C-Y, et al. Hybrid fNIRS-EEG based classification of auditory and visual perception processes. Frontiers in Neuroscience, 2014, 8: 1-13.
[10] Yahud S, Osman N A A. Prosthetic hand for the brain-computer interface system. 3rd Kuala Lumpur International Conference on Biomedical Engineering, 2006: 1-5.
[11] Dong Yue, Liu Ke, Wang Tao, et al. Hybrid modality-based brain-computer interface technology applications: a new direction for neurorehabilitation. Information and Communication Technology and Policy, 2024, 50(5): 41-46.