REVIEW ARTICLE

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НЕЙРООҢАЛТУ САЛАСЫНДАҒЫ ДАМЫП КЕЛЕ ЖАТҚАН ТЕХНОЛОГИЯЛАР МЕН ИННОВАЦИЯЛАРДАҒЫ ПРОГРЕСС

Сулинг Ли[1], Фуюн Цзяо[2]

[1] Педиатрия бөлімі, Аньхой медициналық университетінің бірінші еншілес ауруханасы, Хефей, Аньхой 230022, ҚХР, lisuling_pediatrics@outlook.com, https://orcid.org/0009-0008-8433-525X
[2] Шэньси провинциясының балалар ауруханасы, Сиань, ҚХР, 3105089948@qq.com, https://orcid.org/0000-0002-8306-2543

Түйіндеме

Нейрооңалту саласындағы заманауи ғылым мен техниканың қарқынды дамуының арқасында оңалту нәтижелерін айтарлықтай жақсартатын көптеген инновациялық әдістер пайда болды. Бұл шолу ми-компьютер интерфейстерін (BCI) функционалды электрлік ынталандырумен (FES) біріктіруге, виртуалды шындықтың (VR) жекелендірілген оңалтудағы рөліне, нейрондық қайта құруда экзоскелеттік роботтарды қолдануға және жасанды интеллектті қолданатын BCI технологияларымен қатар инвазивті емес нейромодуляция әдістерін әзірлеуге бағытталған. Сонымен қатар, біз Қытайдағы BCI саласының құрылымын және әлемдік нарықтағы өсіп келе жатқан сұранысты қоса алғанда, осы жетістіктерге саяси қолдау мен өнеркәсіптік өндіріс динамикасының әсерін зерттейміз. Соңғы зерттеулердің нәтижелерін және оларды қолдану мысалдарын жүйелі талдау негізінде біз бұл технологиялардың жүйке жүйесін қалпына келтіруге және пациенттердің өмір сүру сапасын жақсартуға қалай ықпал ететінін зерттейміз және осы саладағы болашақ даму тенденцияларын болжаймыз.

Түйін сөздер: нейрооңалту, ми-компьютер интерфейсі, функционалды электрлік ынталандыру, виртуалды шындық, экзоскелеттік роботтар, инвазивті емес нейромодуляция, жасанды интеллект, өнеркәсіптік даму.

ПРОГРЕСС В РАЗВИВАЮЩИХСЯ ТЕХНОЛОГИЯХ И ИННОВАЦИЯХ В ОБЛАСТИ НЕЙРОРЕАБИЛИТАЦИИ

Сулинг Ли[1], Фуюн Цзяо[2]

[1] Отделение педиатрии, Первая дочерняя больница Медицинского университета Аньхой, Хэфэй, Аньхой 230022, КНР, lisuling_pediatrics@outlook.com, https://orcid.org/0009-0008-8433-525X
[2] Детская больница народной больницы провинции Шэньси, Сиань, КНР, 3105089948@qq.com, https://orcid.org/0000-0002-8306-2543

Резюме

Благодаря быстрому развитию современной науки и техники в области нейрореабилитации появилось множество инновационных методик, которые значительно улучшают результаты реабилитации. Этот обзор посвящен интеграции интерфейсов мозг-компьютер (BCI) с функциональной электрической стимуляцией (FES), роли виртуальной реальности (VR) в персонализированной реабилитации, применению роботов-экзоскелетов в нейронном ремоделировании и разработке неинвазивных методов нейромодуляции наряду с технологиями BCI с использованием искусственного интеллекта. Кроме того, мы изучаем влияние политической поддержки и динамики промышленного производства на эти достижения, включая структуру отрасли BCI в Китае и растущий спрос на мировом рынке. На основе систематического анализа результатов последних исследований и примеров их применения мы исследуем, как эти технологии способствуют восстановлению нервной системы и улучшают качество жизни пациентов, а также прогнозируем будущие тенденции развития в этой области.

Ключевые слова: нейрореабилитация, интерфейс мозг-компьютер, функциональная электростимуляция, виртуальная реальность, роботы-экзоскелеты, неинвазивная нейромодуляция, искусственный интеллект, промышленное развитие.

PROGRESS IN EMERGING TECHNOLOGIES AND INNOVATION IN THE FIELD OF NEUROREHABILITATION

Suling Li[1], Fuyong Jiao[2]

[1] Department of Pediatrics, The First Affiliated Hospital of Anhui Medical University, Hefei, Anhui 230022, PR China, lisuling_pediatrics@outlook.com, https://orcid.org/0009-0008-8433-525X
[2] Children's Hospital of Shaanxi Provincial Peoples Hospital, Xi'an, PR China, 3105089948@qq.com, https://orcid.org/0000-0002-8306-2543

Abstract

With the rapid advancement of modern science and technology, the field of neurorehabilitation has witnessed a surge of innovative techniques that significantly enhance rehabilitation outcomes. This review focuses on the integration of brain-computer interfaces (BCI) with functional electrical stimulation (FES), the role of virtual reality (VR) in personalized rehabilitation, the application of exoskeleton robots in neural remodeling, and the development of non-invasive neuromodulation techniques alongside AI-assisted BCI technologies. Additionally, we examine the influence of policy support and industrial dynamics on these advancements, including the layout of the BCI industry in China and the increasing global market demand. Through a systematic analysis of the latest research findings and application cases, we explore how these technologies facilitate neural recovery and improve patients' quality of life while also forecasting future development trends in the field.

Keywords: neurorehabilitation, brain-computer interface, functional electrical stimulation, virtual reality, exoskeleton robots, non-invasive neuromodulation, artificial intelligence, industrial development.

Correspondent-author: Fuyong Jiao, Honorary President of the Children's Hospital of Xi'an Hospital of Traditional Chinese Medicine for Brain Diseases, Chairperson of the European Center of Traditional Chinese Medicine, and Director of the International Exchange Center of the Hospital Cooperation Alliance of the Shanghai Cooperation Organization, Children's Hospital of Shaanxi Provincial People's Hospital, XI'AN, China.
E-mail: 3105089948@qq.com

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Introduction

Neurorehabilitation stands at the intersection of neuroscience and rehabilitation medicine, aiming to restore and reshape neurological functions through various technological interventions. The field has gained momentum in recent years, driven by advancements in understanding neuroplasticity and the development of innovative rehabilitation technologies. Emerging evidence indicates that neuroplasticity, the ability of the nervous system to reorganize by forming new neural connections, plays a pivotal role in structural and functional recovery post-injury [1]. Traditional rehabilitation methods often fall short in addressing the individual needs of patients, which can lead to suboptimal outcomes. As a response, the integration of emerging technologies has opened new avenues for personalized rehabilitation approaches that not only enhance functional recovery but also improve the overall quality of life for patients [2].

The rapid evolution of technologies such as brain-computer interfaces (BCIs), virtual reality (VR), robotics, and artificial intelligence (AI) has heralded a new era in neurorehabilitation. BCIs, for instance, have demonstrated potential in decoding neural signals and providing real-time feedback, which can significantly enhance neuroplasticity and facilitate motor and cognitive recovery post-stroke [3]. Similarly, VR technology has emerged as a transformative tool, allowing for immersive therapeutic experiences that engage patients in novel ways, promoting both motor and cognitive rehabilitation [4]. Robotics and AI-driven systems are also making strides by providing adaptive assistance tailored to individual patient needs, thereby improving the effectiveness of rehabilitation interventions [5]. The convergence of these technologies not only enhances the therapeutic landscape but also introduces challenges, such as the need for clinical validation and the integration of these systems into existing healthcare frameworks [6].

Purpose of the study

The purpose of this review is to systematically examine the emerging integration of advanced technologies within neurorehabilitation and to assess their collective impact on functional recovery in neurological disorders. We aim to synthesize recent developments in brain–computer interface (BCI) coupled with functional electrical stimulation (FES), virtual reality (VR) and serious game-based interventions, exoskeleton robotics, non-invasive neuromodulation techniques, and AI-enhanced systems. Furthermore, this review discusses how policy initiatives and industrial growth—such as national strategic support in China and expanding global markets—accelerate the translation of technological innovations into clinical and commercial domains. By integrating technological advances with patient-centered rehabilitation needs, this study ultimately aims to identify current challenges, evaluate efficacy, and propose future directions for research and practice in next-generation neurorehabilitation.

1. Integration of Brain-Computer Interface (BCI) and Functional Electrical Stimulation (FES)

1.1 Design and Application of the Tele BCI-FES System

The Tele BCI-FES system, developed by the University of Sheffield, represents a significant advancement in the integration of brain-computer interface (BCI) technology with functional electrical stimulation (FES) for the rehabilitation of upper limb function in stroke survivors. Research shows that after intervention, participants exhibited an average improvement of 3.83 points in their FMA-UE scores following a series of Tele BCI-FES sessions, which approaches the minimal clinically important difference of 4.25 points, and the patient retention rate was as high as 87.5% [7]. Such findings underscore the potential of this system to not only facilitate rehabilitation but also to improve patient adherence and engagement in their recovery process.

Moreover, BCI has been noted for its high participant retention and recruitment rates, demonstrating its feasibility as a telerehabilitation solution. BCI rehabilitation training can further improve upper limb motor function based on traditional rehabilitation training in patients with ischemic stroke [8]. The ability to provide remote support ensures that patients receive guidance and encouragement throughout their rehabilitation journey, which is crucial for maintaining motivation and compliance. Overall, the Tele BCI-FES system exemplifies a promising approach to neurorehabilitation, combining cutting-edge technology with patient-centered care to enhance recovery outcomes for individuals with upper limb impairments following stroke.

1.2 Closed-Loop Feedback Mechanisms Promote Neural Plasticity

Closed-loop feedback mechanisms play a pivotal role in enhancing neural plasticity, particularly in the context of neurological rehabilitation. The integration of multimodal feedback, encompassing visual and haptic stimuli, has been shown to activate the mirror neuron network, which is crucial for motor learning and rehabilitation. This activation is particularly beneficial for patients recovering from motor impairments, such as those resulting from chronic stroke [9]. For instance, studies have demonstrated that multimodal feedback can significantly enhance the reorganization of the motor cortex, thereby improving the motor control capabilities of stroke patients. This multisensory approach not only reinforces the neural connections involved in motor tasks but also facilitates the brain's ability to adapt and reorganize itself in response to training, a phenomenon known as neural plasticity.

Furthermore, the neurophysiological basis for the effectiveness of feedback mechanisms in rehabilitation is rooted in their ability to enhance cortico-muscular coherence. Studies have demonstrated that auditory and visual feedback can significantly reduce movement errors and improve motor performance by optimizing the communication between the brain and muscles [10]. This synchronization is crucial for establishing a robust sensorimotor loop, which is essential for effective motor control and rehabilitation.

Moreover, the role of feedback mechanisms extends beyond motor performance to encompass cognitive and emotional aspects of rehabilitation. The interplay between cognitive processes and motor control is particularly evident in the context of neurofeedback training, where individuals learn to modulate their brain activity to enhance motor function. This approach not only promotes neural plasticity but also addresses emotional and cognitive deficits often associated with stroke recovery [11].

In conclusion, by leveraging multimodal feedback strategies, rehabilitation protocols can effectively engage the brain's adaptive capabilities, leading to improved motor control and functional recovery. The ongoing exploration of these feedback mechanisms will undoubtedly contribute to the development of more effective and personalized rehabilitation interventions in the field of neurorehabilitation.

2. Virtual Reality (VR) and Serious Games for Personalized Rehabilitation

2.1 Clinical Effects of Home-Based VR Rehabilitation Systems

The integration of virtual reality (VR) technology into rehabilitation practices has shown promising clinical outcomes, particularly in home-based settings. A notable example is the application of the RAPAEL Smart Glove, developed by Juntendo University in Japan, which combines VR training with occupational therapy [12]. This innovative approach specifically targets upper limb rehabilitation for chronic stroke patients, demonstrating significant improvements in motor function compared to traditional rehabilitation methods. Studies have indicated that patients using the RAPAEL Smart Glove experience enhanced upper limb functionality, with improvements observed in activities of daily living and overall physical performance. For instance, a clinical trial involving stroke patients revealed that up to 62% of participants exhibited enhanced physical activity levels post-intervention, with notable gains in daily living activities and affective functions [13].

Furthermore, the home-based rehabilitation model significantly reduces dependence on healthcare resources, allowing patients to engage in therapy at their convenience and pace. This increased accessibility fosters higher patient participation and adherence to rehabilitation protocols, which are often challenging in traditional clinical settings. The combination of immersive VR experiences with occupational therapy principles appears to create a more engaging and effective rehabilitation environment, which is particularly beneficial for stroke survivors who may struggle with conventional therapy approaches.

2.2 Dynamic Difficulty Adjustment (DDA) System's Intelligent Adaptation Mechanism

The ROBiGAME, developed at KU Leuven in Belgium, exemplifies the innovative use of artificial intelligence (AI) in dynamic difficulty adjustment (DDA) systems within the realm of neurorehabilitation. This robot-assisted therapy integrates serious gaming to provide a unique platform for enhancing upper limb recovery in stroke patients. The DDA mechanism is pivotal in this context, as it allows for real-time adjustments to the task difficulty based on the patient's performance metrics, specifically their Fugl-Meyer Assessment for Upper Extremity (FMA-UE) scores. This individualized approach ensures that the rehabilitation tasks remain challenging yet achievable, promoting sustained engagement and motivation among patients. The ability of ROBiGAME to adapt task difficulty dynamically-within approximately thirty minutes of gameplay-has been clinically validated, demonstrating a strong correlation between the task difficulty parameters and the patients' motor and attentional impairments. For instance, the study found a significant relationship between the adjusted difficulty levels and the FMA-UE scores, with a correlation coefficient of $r = 0.84$ ($p < 0.05$) indicating that the system effectively tailors the rehabilitation experience to match each patient's unique capabilities and needs [14].

The intelligent adaptation mechanisms embedded within the DDA system of the ROBiGAME represent a significant advancement in the field of neurorehabilitation. By leveraging AI algorithms to assess and adjust task difficulty in real-time, this innovative approach not only personalizes the rehabilitation experience but also maximizes patient motivation and training efficiency. The clinical validation of the DDA mechanism highlights its potential for broader application in rehabilitation settings, suggesting that similar adaptive systems could be integrated into various therapeutic modalities to enhance patient outcomes across different neurological conditions. As the field continues to evolve, the integration of such technologies may pave the way for more effective, individualized rehabilitation strategies that harness the power of AI to optimize recovery processes.

3. Exoskeleton Robots and Neural Remodeling

3.1 Application of Single-Limb Exoskeleton Robots in Gait Rehabilitation

The use of single-limb exoskeleton robots, such as the Angele LiteStepper, has emerged as a promising approach in the rehabilitation of patients with gait impairments, particularly following neurological injuries like stroke. The efficacy of this approach was highlighted in a study where a four-week training program using the LiteStepper resulted in significant improvements in balance and gait parameters among subacute stroke patients, as evidenced by enhanced scores on the Berg Balance Scale (BBS) and other gait metrics [14]. These findings underscore the potential of exoskeleton-assisted rehabilitation to not only facilitate movement but also to enhance overall stability and mobility in individuals with compromised gait function.

Further supporting the effectiveness of such interventions, research monitoring demonstrated increased activation in the affected motor cortex during the use of the LiteStepper [15]. This neurophysiological evidence suggests that the exoskeleton not only aids in physical rehabilitation but also stimulates neural pathways associated with motor control, potentially leading to neuroplastic changes that enhance recovery. The ability of the exoskeleton to engage the motor cortex indicates its role in promoting adaptive responses in the brain, which is crucial for recovery after a stroke. In conclusion, the integration of robotic assistance with neurophysiological monitoring and personalized feedback mechanisms offers a comprehensive approach to rehabilitation that addresses both the physical and psychological aspects of recovery.

3.2 Improved Robot-Object Interaction Technology Enhances Upper Limb Function

The integration of advanced technologies in neurorehabilitation has led to significant advancements in the field, particularly in enhancing upper limb function through improved robot-object interaction. A notable example is the collaboration between the University of Toronto and the development of the 3D-printed TRI-HFT (Toronto Rehabilitation Institute - Hand Function Test) objects, which have been designed to work seamlessly with robotic arms [16]. This innovative approach has demonstrated a high success rate in grasping tasks, which is crucial for rehabilitation post-stroke or other neurological impairments. The TRI-HFT objects are specifically engineered to provide a realistic interaction experience, thereby enhancing the training environment for patients. By utilizing these objects in conjunction with robotic arms, therapists can create a more engaging and effective rehabilitation process that mimics real-world interactions. This not only aids in the physical recovery of patients but also addresses the psychological aspects of rehabilitation, as patients feel more connected to their tasks when they involve tangible objects they can manipulate. The advancements in robot-object interaction technology represent a promising frontier in the field of neurorehabilitation. By enhancing the realism of rehabilitation tasks and promoting active engagement, these technologies not only improve upper limb function but also foster a more holistic approach to recovery.

4. Non-invasive Neural Modulation Techniques

4.1 Innovative Applications of Tongue Stimulation Combined with AI-BCI

The development of non-invasive brain-computer interface (BCI) technology by Helius Medical's subsidiary, Revelation Neuro, represents a significant advancement in the field of neurorehabilitation. This innovative approach utilizes tongue stimulation as a means to modulate brain activity, thereby facilitating improvements in motor function recovery. The underlying principle of this technology is based on the ability to stimulate peripheral nerves in the tongue, which can influence central nervous system pathways associated with motor control and cognitive functions. By integrating artificial intelligence algorithms, the system can adaptively respond to the user's neural signals, optimizing the therapeutic effects of the stimulation in real-time. This dynamic interaction not only enhances the efficacy of rehabilitation protocols but also personalizes treatment plans according to the individual needs of patients, particularly those recovering from conditions such as stroke or traumatic brain injury. The innovative application of tongue stimulation combined with AI-BCI technology holds significant promise for advancing neurorehabilitation. Its ability to modulate brain activity in a non-invasive manner opens new avenues for improving motor and cognitive functions in patients with neurological impairments.

4.2 Clinical Research on Cerebellar Theta Rhythm Stimulation (iTBS)

Cerebellar intermittent theta burst stimulation (iTBS) has emerged as a promising intervention in neurorehabilitation, particularly in enhancing balance and motor function in stroke patients. A pivotal study conducted at Sichuan University West China Hospital demonstrated that the combination of iTBS with physical therapy significantly improved the balance and motor capabilities of stroke patients compared to those undergoing physical therapy alone [17]. This study involved a controlled trial where participants received either iTBS or sham stimulation before engaging in a structured physical therapy program. The results indicated that those receiving iTBS exhibited marked improvements in various functional assessments, including the Tinetti Balance and Gait scale, underscoring the potential of iTBS as an adjunct to conventional rehabilitation protocols. The ability of iTBS to facilitate motor learning processes, both implicit and explicit, further supports its application in rehabilitation settings, particularly for patients recovering from strokes where motor function is compromised.

5. Policy Support and Industry Dynamics

5.1 China's BCI Industry Layout and Development Planning

The development of the brain-computer interface (BCI) technology in China is rapidly evolving, with ambitious goals set for the future, particularly in Sichuan Province. By 2030, the province aims to conduct 3,000 invasive BCI surgeries annually, with a target of expanding the technology's reach to 20,000 users. This initiative reflects a broader commitment to enhance the quality of life for individuals with physical disabilities through advanced neurotechnological solutions. The increasing prevalence of stroke and other neurological disorders has necessitated such ambitious targets, as BCI technology has shown promise in improving rehabilitation outcomes and restoring lost functionalities [18]. The government's proactive stance in promoting BCI technology is evident in its strategic planning and policy frameworks aimed at facilitating the commercialization of neurorehabilitation technologies. Such policies are crucial for bridging the gap between research and clinical application, enabling smoother transitions from laboratory innovations to real-world implementations. As the country continues to advance its capabilities in neurorehabilitation, it is likely to see increased collaboration with international partners, further enhancing its research output and clinical applications. The ongoing evolution of BCI technology holds great potential for transforming the landscape of neurological rehabilitation, ultimately improving the quality of life for countless individuals affected by neurological disorders.

5.2 Global BCI Market Growth Trend Analysis

The global brain-computer interface (BCI) market is poised for substantial growth. This anticipated growth can be attributed to the increasing demand for innovative neurotechnologies that facilitate direct communication between the brain and external devices. The rising prevalence of neurological disorders, coupled with the growing interest in neurorehabilitation and assistive technologies, is driving investment in BCI research and development. Furthermore, advancements in machine learning algorithms and signal processing techniques are enhancing the efficacy of BCI systems, making them more accessible and user-friendly for a broader audience. As the technology matures, it is expected to transition from niche applications to mainstream use, similar to the trajectory observed in personal computing. This evolution is likely to create a competitive landscape, encouraging more players to enter the market and further accelerate innovation in BCI technologies.

Market demand is a critical driver of technological innovation and diversification in the BCI sector. As awareness of the potential applications of BCI technology increases, so does the interest from various industries looking to integrate these systems into their operations. This cross-industry interest is fostering collaborations between tech companies, healthcare providers, and academic institutions, leading to a more robust ecosystem for BCI development. Furthermore, as the technology becomes more refined and cost-effective, it is expected to penetrate consumer markets, enabling applications in everyday life. The ongoing research into non-invasive BCI systems is particularly promising, as it aims to create user-friendly devices that can be easily adopted by the general public, thereby broadening the market reach and application scope of BCI technologies.

In summary, the global BCI market is on an upward trajectory, characterized by significant growth projections and increasing demand across various sectors. The convergence of technological advancements, supportive government policies, and cross-industry collaborations is expected to drive further innovation and application of BCI technologies, ultimately transforming the landscape of human-computer interaction and neurorehabilitation.

Conclusions

In conclusion, the integration of emerging technologies such as Brain-Computer Interface (BCI) combined with Functional Electrical Stimulation (FES), personalized Virtual Reality (VR) rehabilitation, exoskeleton robotics, and non-invasive neuromodulation is catalyzing a transformative shift in the field of neurorehabilitation. These innovations are not merely incremental improvements; they represent a qualitative leap that is reshaping how we approach recovery from neurological impairments.

Looking ahead, it is imperative that we focus on several key areas to maximize the impact of these emerging technologies. First, ongoing optimization of the technologies themselves is essential. This includes refining their efficacy, usability, and safety to ensure they meet the diverse needs of patients. Second, long-term efficacy studies are crucial to validate the benefits of these interventions beyond initial recovery phases. Such research will help establish evidence-based guidelines that can inform clinical practice and reassure stakeholders of the value of these approaches.

Conflict of interests

The authors declare no conflict of interest.

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ПСИХОМОТОРЛЫҚ ТЕРАПИЯ БАЛАНЫҢ ДАМУЫН ҚОЛДАУ ҮШІН ОҢАЛТУДЫҢ БАСЫМ ТӘСІЛІ РЕТІНДЕ: АРТЫҚШЫЛЫҚТАРЫ МЕН ӘРЕКЕТ ЕТУ ТӘСІЛДЕРІ

Доктор Северин Алонсо-Бекье[1]

[1] Психомоторлық терапевт-сарапшы, PhD, ISRP Париж, Франция, sbekier@isrp.fr, https://orcid.org/0009-0004-5654-6827