Review

Application of Intelligent Technologies in Rehabilitation Diagnosis and Treatment: Current Status and Future Prospects

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ABSTRACT

This paper comprehensively explores the application of intelligent technologies in rehabilitation diagnosis and treatment. It elaborates on the definition, historical evolution, current application, challenges, and future development trends of intelligent technologies, emphasizing their transformative impact and broad prospects in rehabilitation medicine.

INTRODUCTION

Rehabilitation medicine aims to assist patients in restoring physical functions and enhancing their quality of life. The rapid development of intelligent technologies has introduced unprecedented innovation to rehabilitation diagnosis and treatment. The diverse and integrated applications of these technologies have significantly broadened the scope of rehabilitation treatment, bringing new hope to patients' recovery processes.

OVERVIEW OF INTELLIGENT TECHNOLOGIES

Definition of Intelligent Technologies

Intelligent technologies result from the convergence of multiple disciplines, integrating knowledge from computer science, electronic engineering, neuroscience, control theory, and statistics[1]. Leveraging advanced algorithms and hardware, they simulate human perception, learning, reasoning, and decision - making processes to achieve automated processing of complex information and intelligent interaction[2]. In the context of rehabilitation diagnosis and treatment, intelligent technologies mainly include big data analysis, artificial intelligence (AI), 5G communication, virtual reality (VR), and brain - computer interfaces (BCIs)[3]. These technologies are interrelated and work in harmony, jointly

driving the progress of rehabilitation medicine.

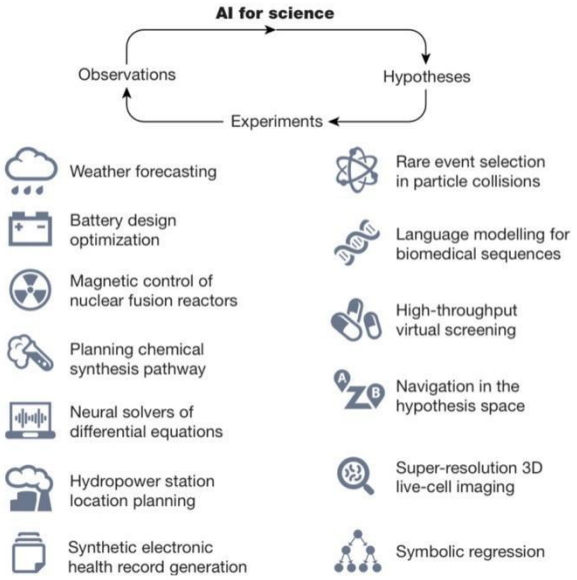

Figure 1. Science in the age of artificial intelligence [2]

Historical Evolution of the Application of Intelligent Technologies in the Rehabilitation Field

The application of intelligent technologies in rehabilitation has evolved gradually. From basic assistance in the early days to the current high - level integration, each stage has propelled the advancement of rehabilitation medicine[4].

In the mid-20th century, the advent of electronic technology brought the firstgeneration assistive devices to the rehabilitation field, such as simple electric wheelchairs and basic functional exercise equipment[4]. Although these devices provided only fundamental mechanical support, they marked the initial combination of technology and rehabilitation, laying the groundwork for subsequent development. At that time, the devices were controlled by simple circuits and lacked adaptability to individual patient needs and complex rehabilitation requirements[5].

In the 1970s and 1980s, with the initial development of computer technology, computer-assisted devices started to be incorporated into rehabilitation treatment[6]. Simple rehabilitation training software emerged, enabling patients to perform standardized limb movement training[6]. For instance, a basic upper - limb movement training program for stroke patients could set the number of repetitions and frequencies to aid in their rehabilitation exercises[7]. However, these early software systems had limited functions and lacked effective data collection and analysis capabilities[8]. Meanwhile, basic prototypes of rehabilitation robots emerged, but their intelligence levels were low, and operations were rather mechanical[9].

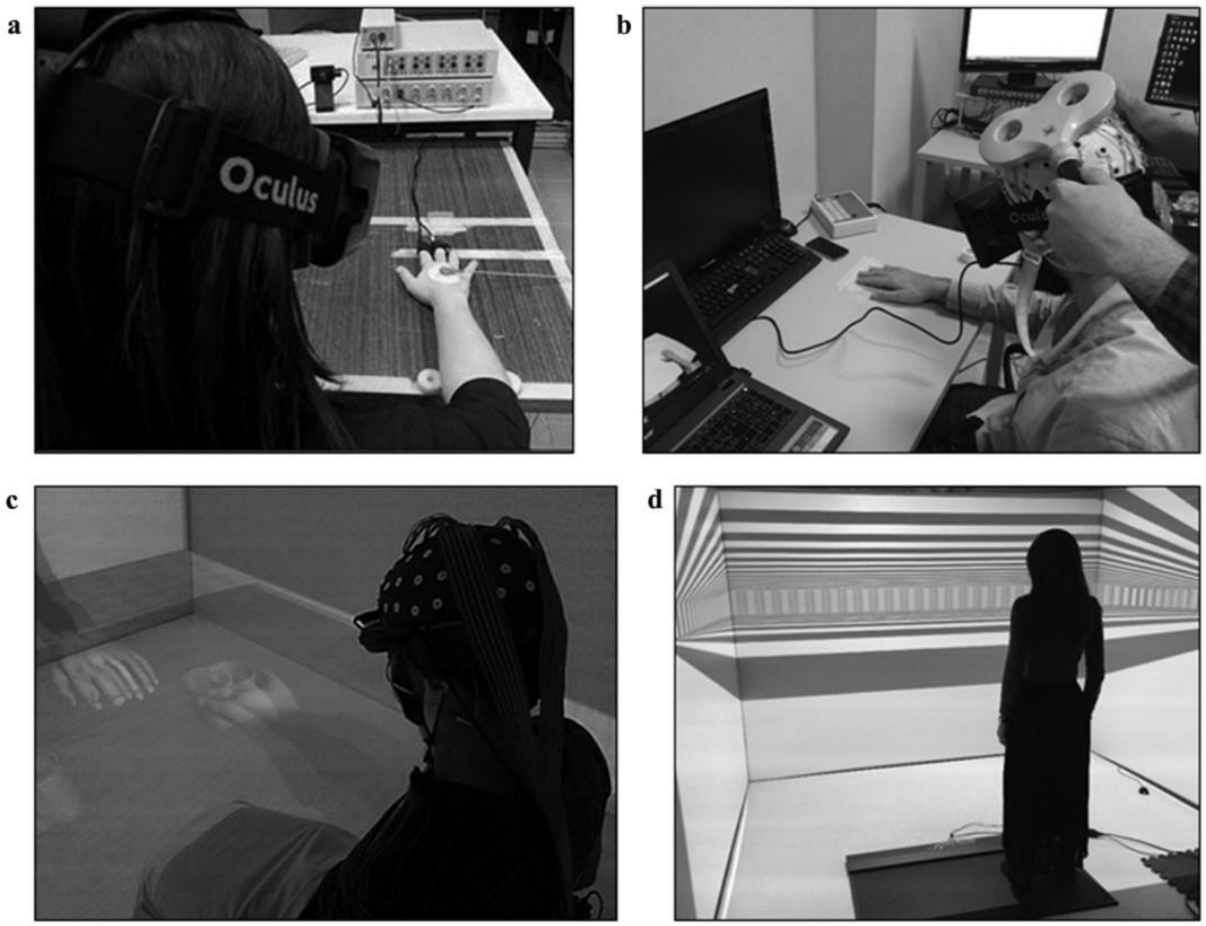

Figure 2. Example of experimental setup in which VR is combined with external recordings instrument at IRCCS Santa Lucia Foundation; Upper part represents the HMD combined with (a) physiological recording and (b) EEG and TMS; Lower part shows the CAVE system combined with (c) EEG, and (d) with a baropodometric platform[8].

In the 1990s, the progress of sensor technology brought new changes to the rehabilitation field[10]. Wearable sensor devices began to be used, allowing for real - time monitoring of patients' physiological parameters such as heart rate, blood pressure, step counts, and joint movement angles[11].

Rehabilitation medical staff could assess patients' rehabilitation status based on these data, initially enabling quantitative evaluation of the rehabilitation process[12]. However, data processing at that time mainly relied on manual analysis, which was inefficient and had difficulty in extracting deep - seated insights from the data.

Entering the 21st century, AI technology has been gradually integrated into the rehabilitation field[13]. Machine-learning algorithms are employed to analyze rehabilitation data, predict patients' rehabilitation progress, and identify potential complications[14]. Rehabilitation robots have also evolved towards greater intelligence and possess certain adaptive capabilities. For example, some rehabilitation robots can automatically adjust training resistance according to patients' force feedback. Nevertheless, at this stage, the accuracy and generalization ability of AI models still require improvement[15].

In recent years, the rapid development of cutting-edge technologies such as big data, 5G, VR, and BCIs has comprehensively advanced the rehabilitation field into a new intelligent era. Big data analysis aggregates vast amounts of rehabilitation data, providing a solid foundation for formulating personalized rehabilitation programs[16]. 5G technology enables real - time, high - definition interaction in remote rehabilitation diagnosis and treatment[16]. VR technology creates immersive rehabilitation training environments[17]. BCIs offer hope to patients with severe motor dysfunctions. The integrated application of these technologies has enhanced the accuracy, efficiency, and personalization of rehabilitation

treatment[18].

APPLICATION OF INTELLIGENT TECHNOLOGIES IN REHABILITATION DIAGNOSIS AND TREATMENT

Data - Driven Rehabilitation Decision - Making: Application of Big Data

Big data plays a pivotal role in rehabilitation diagnosis and treatment[16]. By amassing multi - dimensional clinical data from a large number of rehabilitation patients, including patient basic information, disease types, rehabilitation treatment plans, and treatment outcome feedback[19], data mining and analysis techniques can uncover the underlying laws of rehabilitation treatment. This provides strong support for doctors to design personalized rehabilitation programs. For example, through big - data analysis, it has been found that for knee - joint - replacement patients, early combination of specific rehabilitation training and physical therapy can improve the rehabilitation effect by approximately 25% compared to single physical therapy[20]. Some rehabilitation institutions utilize big - data platforms to monitor and analyze patients' rehabilitation data in real - time, promptly detecting and rectifying abnormal situations[21]. For instance, a rehabilitation institution, through big - data monitoring, noticed that a knee - joint - replacement patient's rehabilitation progress slowed down, and the joint swelling index was abnormal. After data analysis, the rehabilitation training intensity and physical therapy plan were promptly adjusted, and local massage and cold - compress treatments were added[21]. Eventually, the patient's rehabilitation situation improved significantly, and the rehabilitation efficiency was greatly enhanced.

Intelligent Rehabilitation Treatment: Application of Artificial Intelligence

AI is the core driver of the intelligent transformation in rehabilitation diagnosis and treatment. Machine-learning algorithms can deeply analyze patients' rehabilitation data, predict the rehabilitation process and potential complications[22]. Deep - learning technology, applied to medical image recognition, helps doctors accurately diagnose the imaging data of rehabilitation patients, significantly improving diagnostic accuracy[23]. AI - driven rehabilitation robots can automatically adjust training parameters and difficulty levels according to patients' real - time movement states and rehabilitation needs[24]. Clinical studies have shown that patients trained with AI - based rehabilitation robots experience a limb - movement - function recovery speed that is about 20% faster than those using traditional training methods[24]. In a particular rehabilitation hospital, a stroke patient underwent training with an AI - based rehabilitation robot. The robot automatically adjusted the training resistance, speed, and movement mode according to the real - time movement status of the patient's limbs, such as limb strength and joint mobility. After three months of training, the patient's limb movement function recovery was significantly better than that of patients using traditional training methods. Additionally, AI interacts with patients through natural - language - processing technology, answering questions, providing rehabilitation guidance, and offering psychological support, thus providing patients with emotional care and professional advice[17].

Remote Rehabilitation Diagnosis and Treatment: Integration of 5G and Other Technologies

The high - speed and low - latency characteristics of 5G technology provide a solid technical guarantee for remote rehabilitation diagnosis and treatment[25]. Rehabilitation doctors can remotely monitor and guide patients' rehabilitation training in real - time via the 5G network. When combined with VR technology, patients can use VR devices at home to conduct immersive rehabilitation training and transmit training data to doctors in real - time[26]. Rehabilitation patients in remote areas can receive the diagnosis and treatment services of big - city experts with the help of the 5G remote - rehabilitation system, effectively addressing the issue of uneven medical resource distribution[27]. For example, a fracture patient, Xiao Wang, in a remote mountainous area, used the 5G

remote - rehabilitation system, equipped with a smart bracelet and a VR device, to transmit his rehabilitation training data and scenarios to experts in big cities in real - time. The experts guided Xiao Wang's rehabilitation training and adjusted the training plan based on these data and scenarios. Xiao Wang could receive top - level expert services at home, avoiding long - distance travel, and his rehabilitation process proceeded smoothly[25]. Some medical institutions use 5G technology to carry out services such as remote consultations and remote surgical guidance, improving the accessibility and quality of rehabilitation medical services, allowing patients to obtain the diagnostic opinions of top - level medical experts locally[25].

Immersive Rehabilitation Training: Application of Virtual Reality

VR technology creates diverse rehabilitation training scenarios, such as daily - life and sports simulations[28]. Patients can significantly increase their training interest and participation in the virtual environment. For patients with cognitive impairment, VR - based cognitive rehabilitation training can effectively improve cognitive abilities by simulating real - life situations. Research indicates that the training compliance of patients using VR for rehabilitation training is about 35% higher than that of traditional training methods[29]. Some rehabilitation institutions have developed VR - based rehabilitation training systems tailored to different rehabilitation needs, such as a movement - rehabilitation system for stroke patients and a cognitive - rehabilitation system for Alzheimer's disease patients, achieving favorable clinical results[30]. A VR-based movement - rehabilitation system for stroke patients, developed by a certain rehabilitation institution, enables patients to perform rehabilitation training in a virtual environment by simulating daily - life actions like getting up, washing, and walking. The patients' movement functions recovered well, and their daily - living self - care abilities were significantly enhanced[31].

Emergence of Brain - Computer Interface

In the frontier exploration of rehabilitation diagnosis and treatment, BCI technology has started to demonstrate unique value. Some medical teams have applied it to the rehabilitation treatment of patients with severe motor dysfunctions[32]. For example, for patients with amyotrophic lateral sclerosis, through BCI devices, they can control wheelchair movement and operate smart - home devices using brain signals, greatly enhancing their life autonomy. In scientific research experiments, BCI - based rehabilitation training systems also show promising prospects. By interpreting patients' brain - movement intentions, highly targeted rehabilitation training can be provided to help patients restore limb movement functions to a certain extent[33]. However, currently, the application scope of this technology is relatively narrow, mainly concentrated in a few medical institutions with strong scientific research capabilities and has not been widely popularized[34]. At present, the main challenges of BCI technology include low - accuracy signal acquisition and analysis due to the weakness and complexity of human brain electrical signals, which are easily affected by factors such as scalp resistance and muscle - electrical interference, resulting in signal noise and distortion that impede accurate brain - command interpretation[35]. The comfort and safety of long - term device wearing also need to be addressed.

Most current devices are large and inconvenient to wear, and long - term use may cause skin allergies and discomfort, along with risks of infection and potential brain - tissue damage. Moreover, its integration with other intelligent technologies is in its infancy, and more research and practical exploration are required to combine the collected brain signals with big - data analysis and AI algorithms for more accurate rehabilitation - treatment - plan formulation and process prediction[36].

CHALLENGES IN THE APPLICATION OF INTELLIGENT TECHNOLOGIES

Lack of Technical Standards and Norms

Currently, the application of intelligent technologies in rehabilitation diagnosis and treatment lacks unified technical standards and norms, leading to poor compatibility between different devices and systems[37]. This poses difficulties for the collaborative operation of various intelligent rehabilitation devices and systems in

practical applications and hampers data sharing and interaction, thereby impeding the promotion and application of intelligent technologies. Rehabilitation robots produced by different manufacturers have different communication protocols and data formats, causing great inconvenience for doctors when using multiple robots for comprehensive patient rehabilitation. Simultaneously, the lack of unified technical standards also challenges product - quality supervision and safety assessment, increasing risks for patients using intelligent rehabilitation devices[38].

Data Security and Privacy Protection

Although technologies like blockchain have provided a certain degree of data
- security assurance, with the large - scale collection and sharing of rehabilitation data, the risk of data leakage still persists[39]. Rehabilitation data contains sensitive patient information, such as medical history, health status, and treatment records. Once leaked, it can seriously threaten patients' privacy and safety. Additionally, in the process of data sharing, ensuring the legal use and access control of data remains an urgent issue. For example, in multi - institutional cooperative rehabilitation research, guaranteeing the legal and compliant use of patient data by all parties and preventing data abuse is a major challenge currently faced[40].

Shortage of Professional Talents

The application of intelligent technologies in rehabilitation diagnosis and treatment requires compound talents with knowledge of both rehabilitation medicine and intelligent technologies[41]. Currently, the shortage of such talents restricts the in - depth development of intelligent technologies in the rehabilitation field. Rehabilitation - medicine professionals have limited understanding and mastery of intelligent technologies, making it difficult to fully exploit the advantages of these technologies in rehabilitation diagnosis and treatment. On the other hand, intelligent - technology professionals often lack knowledge of rehabilitation medicine and clinical needs, resulting in limitations in the practical application of developed intelligent rehabilitation products and systems[42]. For example, some intelligent rehabilitation devices are complex to operate and do not conform to the clinical usage habits of rehabilitation medicine, affecting the user experience of medical staff and patients[43].

High Costs

The research, development, purchase, and maintenance costs of intelligent rehabilitation devices and systems are relatively high, making them unaffordable for some medical institutions and patients[44]. The price of a set of advanced AI - based rehabilitation robot equipment can reach hundreds of thousands or even millions of yuan. Coupled with subsequent maintenance and upgrade costs, it represents a substantial expense for many primary medical institutions. For patients, the high cost of using intelligent rehabilitation devices for treatment increases their economic burden and, to some extent, hinders the widespread application of intelligent technologies[45].

Technical Bottlenecks of Brain - Computer Interface

As a promising emerging technology, BCI faces several challenges in rehabilitation diagnosis and treatment[46]. The accuracy of signal acquisition and analysis needs to be improved due to the characteristics of human brain electrical signals, which are extremely weak and complex and easily influenced by factors such as scalp - resistance differences and muscle - electrical interference, leading to signal noise and distortion that make accurate brain - command interpretation arduous. The comfort and safety of long - term device wearing are also crucial issues to be resolved[47]. Most current devices are large - sized and inconvenient to wear, and long - term use may cause skin - related discomforts such as allergies, along with potential risks of infection and brain - tissue damage, restricting its wide application in rehabilitation diagnosis and treatment. Moreover, the integration of BCI technology with other intelligent technologies is still in its initial stage. How to effectively combine the brain signals collected by BCIs with big - data analysis and AI algorithms to achieve more accurate rehabilitation - treatment - plan formulation and rehabilitation - process prediction requires a great deal of research and practical exploration[48, 49].

FUTURE PROSPECTS

Technological Integration and Innovation

In the future, intelligent technologies such as blockchain, big data, AI, 5G, and VR will be more deeply integrated to build a more intelligent and personalized rehabilitation diagnosis and treatment system[50]. Blockchain will be utilized to ensure the secure sharing of big data, and AI will analyze big data to provide more precise plans for VR - based rehabilitation training[51]. The combination of AI and VR will enable more intelligent rehabilitation training. Based on patients' real - time performance and rehabilitation progress, the virtual scene and training tasks will be adjusted in real - time to offer a personalized rehabilitation - training experience[52]. With the development of emerging technologies such as quantum computing and edge computing, the application of intelligent - technology clusters in rehabilitation diagnosis and treatment is expected to achieve new breakthroughs, leading to more efficient data processing and more accurate rehabilitation prediction[53].

BCI technology will play a vital role in this integration trend. It is anticipated to collaborate closely with other intelligent technologies. By accurately obtaining patients' brain commands through BCIs and combining them with AI and big - data analysis, more personalized and accurate rehabilitation treatment plans can be formulated for patients. AI algorithms will conduct in - depth analysis of the complex brain signals collected by BCIs, excavating hidden information and more accurately assessing patients' rehabilitation needs and potential problems. 5G technology will ensure the high - speed and stable transmission of BCI signals, enabling remote real - time monitoring and adjustment of rehabilitation treatment plans[54].

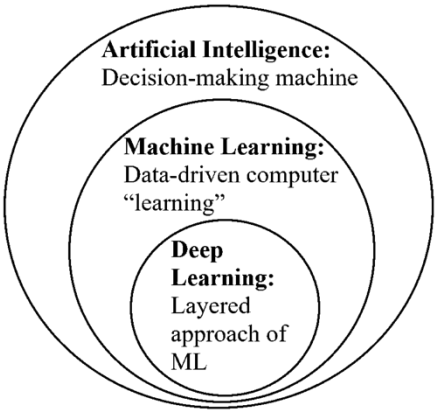

Figure 3. This figure shows definitions of artificial intelligence, machine learning (ML), and deep learning.

Expansion of Application Scenarios

Intelligent technologies will be more extensively applied in all aspects of rehabilitation diagnosis and treatment, covering rehabilitation prevention, assessment, treatment, and follow - up[55]. In terms of rehabilitation prevention, through big - data analysis and AI - based prediction technology, early screening and intervention can be carried out for high - risk groups to prevent the occurrence and development of diseases. In rehabilitation assessment, multi - modal data - fusion technology will be used to achieve more comprehensive and accurate assessments by integrating patients' physiological data, imaging data, behavioral data[56], etc. In rehabilitation follow - up, intelligent wearable devices and remote - monitoring technology will be employed to track patients' rehabilitation situations in real - time, providing continuous rehabilitation guidance and support. Intelligent technologies will also be extended to areas such as home - based and community - based rehabilitation, achieving full - coverage of rehabilitation services, so that more patients can enjoy convenient and efficient rehabilitation services[57].

BCI technology will also expand the application scope of rehabilitation diagnosis and treatment. In addition to the existing motor - rehabilitation and neuro - rehabilitation

fields, in the future, it may assist patients with language dysfunction in converting brain language signals into voice output for communication. In the field of psychological rehabilitation, by monitoring brain signals related to emotions, more targeted treatment plans and intervention measures can be provided for patients with mental illnesses[58].

Talent Cultivation and Cooperation (Continued)

In addition to international student exchanges and joint research projects, professional certification systems can be established to standardize the qualifications of intelligent rehabilitation professionals. Industry - recognized certifications can cover a wide range of knowledge and skills, from basic rehabilitation medicine concepts to advanced intelligent technology applications. For example, a "Certified Intelligent Rehabilitation Specialist" program could require candidates to demonstrate proficiency in operating AI - based diagnostic tools, understanding the principles of VR - based rehabilitation training, and being able to interpret BCI - related data in a clinical context. This would not only enhance the credibility of professionals in the field but also provide a clear benchmark for employers when hiring.

Furthermore, companies in the intelligent rehabilitation sector can invest in in - house training programs. These programs can be tailored to the specific needs of the organization, focusing on the development and application of their own products and technologies. For instance, a company that specializes in developing rehabilitation robots can train its employees on the unique features of their robots, such as advanced motion - control algorithms and personalized training protocols. This would enable employees to better serve customers, provide technical support, and contribute to product innovation.

Another aspect of talent cultivation is the integration of soft skills training. In addition to technical expertise, professionals in the intelligent rehabilitation field need strong communication, teamwork, and problem - solving skills. Communication skills are crucial for interacting with patients, their families, and other healthcare providers. Teamwork is essential as the development and application of intelligent rehabilitation technologies often involve multi - disciplinary teams. Problem - solving skills are required to address the complex and unique challenges that arise during the rehabilitation process. Training programs can include workshops on effective communication, team - building exercises, and case - based problem - solving sessions to enhance these soft skills.

Moreover, online learning platforms can play a significant role in talent cultivation. These platforms can offer a wide range of courses, from introductory courses on intelligent technologies in rehabilitation to advanced seminars on the latest research findings. They can also provide access to a global community of learners and experts, allowing for knowledge sharing and collaborative learning. For example, a professional in a remote area can participate in an online course on the application of 5G in remote rehabilitation, interact with instructors and other learners from around the world, and gain valuable insights and skills[59].

Finally, mentorship programs can be established to pair experienced professionals with new entrants in the field. Mentors can provide guidance on career development, offer practical advice based on their own experiences, and help mentees navigate the challenges of working in the intelligent rehabilitation industry. This one - on - one mentorship can accelerate the learning process and help new professionals build their networks within the industry.

Standardization and Regulation

A complete set of technical standards and norms for intelligent rehabilitation devices and systems must be established, covering communication protocols, data formats, performance evaluation, and safety standards. This will ensure the compatibility, reliability, and safety of intelligent rehabilitation products. Regulatory authorities should formulate corresponding laws, regulations, and policies to supervise the entire process of intelligent technology products, from research and development to application. This comprehensive supervision can guarantee product quality and safety.

In terms of data security and privacy protection, relevant laws and regulations need to be continuously improved. Clear guidelines should be set to define the responsibilities and obligations of all parties involved in data collection,

storage, sharing, and use. Severe punishments should be imposed on illegal acts of data leakage and abuse to safeguard patients' data rights.

For BCI technology, specific technical standards and ethical norms need to be urgently formulated. Technical standards should define requirements for signal - acquisition accuracy, device - brain compatibility, and long - term reliability. Ethical norms should clarify issues such as patient informed consent, privacy protection of brain - related data, and the ethical boundaries of BCI application in different patient groups. This will ensure that the application of BCI technology is carried out within a legal and ethical framework, protecting the rights and interests of patients and promoting the healthy development of the technology.

Cost - Reduction and Popularization

With the development of technology and the expansion of the market, the cost of intelligent rehabilitation devices and systems is expected to gradually decrease. Technological innovation, such as improvements in chip - manufacturing processes and software - algorithm optimizations, can enhance the performance of intelligent rehabilitation products while reducing hardware costs. Mass production can also lead to economies of scale, further lowering production costs[60].

On the policy front, the government and relevant departments can introduce supportive policies to promote the popularization of intelligent rehabilitation technologies. Financial subsidies can be provided for medical institutions to purchase intelligent rehabilitation equipment. Additionally, intelligent rehabilitation services can be included in the scope of medical - insurance reimbursement. These measures can reduce the economic burden on patients and promote the wide application of intelligent rehabilitation technologies.

For BCI technology, cost - reduction is also a crucial development direction. Continuous optimization of interface - device design, development of new materials and manufacturing processes, and improvement of component - integration levels can effectively reduce the manufacturing cost of BCI devices. Promoting cooperation between different research institutions and enterprises can achieve resource sharing and complementary advantages. This cooperation can accelerate the industrialization process of BCI technology and further reduce costs through economies of scale, making the technology more accessible to a wider range of patients.

CONCLUSION

Intelligent technologies have already had a profound impact on rehabilitation diagnosis and treatment within the framework of the International Classification of Functioning, Disability and Health (ICF). From the historical evolution, we can observe a continuous progression from basic assistive devices to highly integrated intelligent systems. Current applications, despite facing various challenges, have demonstrated the significant value of these technologies.

Looking ahead, the future development of intelligent technologies in rehabilitation diagnosis and treatment is filled with opportunities. Technological integration and innovation will lead to more advanced and efficient rehabilitation solutions. The expansion of application scenarios will enable more patients to benefit from intelligent rehabilitation services. Talent cultivation and cooperation will provide strong intellectual support for technological development. Standardization and regulation will ensure the healthy and orderly development of the industry. Cost - reduction and popularization will make intelligent rehabilitation technologies more accessible.

In particular, as a frontier technology, BCI technology has great potential in the field of rehabilitation diagnosis and treatment. Although it currently faces some challenges, with continuous technological breakthroughs and the joint efforts of all parties, it is expected to play an increasingly important role in the future. It will bring new hope and possibilities for patients with severe disabilities, enabling them to regain a higher degree of autonomy and a better quality of life.

By effectively addressing these challenges and seizing development opportunities, intelligent technologies will play a more central and decisive role in rehabilitation medicine. They will comprehensively improve patients' physical and mental health as well as their social participation, ultimately realizing the ICF's goal ofenhancing the quality of life for people with disabilities and health related conditions. This will not only promote the development of the rehabilitation medicine industry but also make important contributions to the well being of society as a whole, leading to a more inclusive and healthy social environment.

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