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Research on the Development of Upper Limb Rehabilitation Robot Technology Driven by ECE

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Abstract: In the context of the continuous deepening of social aging, an increasing number of patients are suffering from upper limb dysfunction, and the rehabilitation treatment for patients' motor ability has become a major concern. This paper commences with the emergence of the upper limb rehabilitation robot and comprehensively summarizes and analyzes the research progress both domestically and internationally. Upper limb rehabilitation robots can be classified into different categories based on diverse classification methods. Based on feedback approaches, they can be divided into a rehabilitation robot system based on machine assistance (RA), a rehabilitation robot system predicated on functional electrical stimulation (FES), and a rehabilitation robot system founded on virtual reality (VR); in accordance with the motion intention recognition method, they can be categorized into rehabilitation robot system relying on electromyographic signals and rehabilitation robot system based on brain-computer interface. By integrating the existing advanced research technologies and addressing the attendant difficulties, this paper envisions the future development of upper limb rehabilitation robot and proffers ideas to facilitate its clinical transformation.

Keywords: Rehabilitation robot, Upper limb dysfunction, ECE, Wearable Systems

1. Introduction

In recent years, the exacerbation of population aging and the augmented frequency of traffic accidents have led to a year-on-year increase in the number of patients with upper limb dysfunction [1]. As an emerging intelligent rehabilitation device, the upper limb rehabilitation robot holds great potential in assisting patients to recover motor function and enhance the quality of life. Compared to traditional rehabilitation training, the rehabilitation robot exhibits superior efficient and stable training effects that can meet the individualized needs of patients, thereby emerging as a research hotspot at home and abroad in recent years [2].

Domestic and foreign scholars have progressively incorporated technologies such as functional electrical stimulation, virtual reality, electromyographic signals, and brain-computer interfaces in the research of rehabilitation robots, which has substantially enriched the training modalities of upper limb rehabilitation. Functional electrical stimulation can markedly enhance the efficacy of motor learning; virtual reality offers an immersive training environment for patients, augmenting their participation; electromyographic signals and brain-computer interfaces docode patient's intention and

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integrate it with the movement of the rehabilitation robot. The development of these technologies not only augments the scientific and effectiveness of rehabilitation training but also furnishes novel technical means for personalized rehabilitation.

Despite the remarkable achievements of the upper limb rehabilitation robot in clinical applications, its promotion still confronts certain challenges. Issues such as high equipment cost, complex design, and lack of universality impede the popularization of the rehabilitation robot. Moreover, addressing the wide variability among patients remains a key challenge. Developing more adaptive and intelligent robotic systems to precisely align with individual rehabilitation needs is a crucial future direction.

With the rapid advancement of artificial intelligence and sensor technology, the upper limb rehabilitation robot will possess broader application prospects in the future and provide more intelligent and efficient rehabilitation treatment regimens for patients. This paper explores the current progress of the upper limb rehabilitation robot in conjunction with the literature, and elaborates and dissects in detail from the perspectives of classification, characteristics, and existing deficiencies. The findings offer certain reference and inspiration for subsequent related research, promoting the development of upper limb rehabilitation robot technology, and rendering some assistance for the convenience of life of patients with upper limb dysfunction.

2. Classification and Research Status of Upper Limb Rehabilitation Robots

The earliest upper limb rehabilitation robot can be traced back to the 1990s. At that time, the neuroengineering technology was in its nascent stage, and the acquisition and recognition capabilities of neuroelectrophysiological signals were relatively feeble. Most of the early robots were designed to provided passive assistance to patients during training. In recent years, with the evolution of neurorehabilitation theory, researchers have been attaching greater significance to the initiative of patients in motor rehabilitation training. Based on feedback modalities, upper limb rehabilitation robots can be classified into machine-assisted systems (RA), functional electrical stimulation (FES)-based systems, and virtual reality (VR)-based systems. When categorized by motion intention recognition methods, they can be divided into systems relying on electromyographic (EMG) signals and systems based on brain-computer interfaces (BCIs).

2.1. Feedback Method

2.1.1. Machine Assistance

The rehabilitation robot system based on machine assistance can be principally subdivided into two types, namely, the end-effector type and the exoskeleton type, in accordance with the functional configuration of the robot system. The advantages of these robot systems lie in their ability to ensure the intensity, efficacy, and precision of rehabilitation training in comparison with traditional manual rehabilitation treatment.

(1) End-effector type

End-effector systems primarily actuate one end of the limb through the end-effector structure for the purpose of rehabilitation training. Typically constructed with general or serial link mechanisms, these systems support the upper limb’s terminal movement, allowing patients with motor dysfunction to engage in passive or active training along predefined trajectories to achieve rehabilitation goals.

The most paradigmatic example is the world's first (upper limb) rehabilitation robot, MIT-MANUS, developed by Professor Hogan of the Massachusetts Institute of Technology (MIT) in 1991. This system adopts a selective compliance assembly robotic arm (SCARA) serial five-link structure, and the terminus of the robotic arm possesses 2 degrees of freedom, which can assist patients in rehabilitation training of the shoulder and elbow joints in the horizontal plane [3].

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Professor Hogan was the first to propose the impedance control algorithm to enhance the compliance of human-robot interaction during the rehabilitation training process. This approach allows patients to complete passive rehabilitation along preset trajectories while benefiting from additional damping for muscle strength training. Based on MANUS, the MIT team subsequently added an auxiliary training device for the wrist joint, thereby realizing the rehabilitation training of five degrees of freedom of the shoulder, elbow, and wrist, and conducting preliminary clinical trials. As the progenitor of the upper limb rehabilitation robot, MIT-MANUS established a structural and algorithmic paradigm for subsequent research in rehabilitation robotics.

There have been copious studies on upper limb rehabilitation robots. In 2019, Sheng et al. developed a bilateral upper limb rehabilitation system based on an industrial robot (IRBRS), which is chiefly composed of two industrial robotic arms (UR10 and UR5), enabling the affected limb to synchronously replicate the movement of the healthy limb, thereby more efficaciously activating the damaged brain area and restoring the patient's motor function [4]. On this basis, Zhang et al. developed an end-effector type EULRR upper limb rehabilitation robot, which can concurrently conduct rehabilitation training on the three-dimensional space trajectory of both arms, enhancing the rehabilitation efficiency. Their research has compensated for the deficiency of the end-effector upper limb rehabilitation robot that could only conduct training in a specific plane, enabling the end-effector upper limb rehabilitation robot to assist patients with motor dysfunction in realizing the training of the three-dimensional space of the arm [5].

(2) Exoskeleton type

The exoskeleton-type upper limb rehabilitation robot is based on the principle of bionics and is designed with a mechanical structure that conforms to the physiological structure of the human upper limb. The system can precisely control each joint to realize single-joint independent movement and multi-joint compound movement and can provide direct assistance and recovery assessment at each joint of the human body.

Joel C. Perry et al. developed CADEN-7, a cable-driven lightweight exoskeleton-type upper limb rehabilitation robot system, which features seven single-axis external rotation joints. The flexible drive method is employed to avert excessive extension and unstable movement of the robot system to a certain extent. Its design merits include low inertia, high stiffness link, and reversible transmission [6]. Subsequently, Chen Chunda et al. developed a 4-degree-of-freedom upper limb exoskeleton robot actuated by pneumatic muscle actuators (PMA) to support shoulder and elbow movements. In contrast to the traditional serial manipulator design, the shoulder joint is configured as a ball-and-socket joint, and its design inspiration is derived from human anatomy [7]. When air is compressed into the PMA, the PMA contracts to generate a one-way tensile force through the cable, thereby rotating the support plate to drive the upper limb of the wearer to achieve rehabilitation exercise. When air is released from the PMA, the exoskeleton robot utilizes the weight of the upper limb to apply torque on these joints to restore its original configuration.

2.1.2. Functional Electrical Stimulation

Functional electrical stimulation (FES) is an efficacious method for reconstructing muscle activity. By applying low-frequency electrical pulses of specific intensity to targeted muscles or nerves, FES induces muscle contractions or mimics natural voluntary movements., This stimulation reactivates muscles, promoting the reactivation of muscles to achieve functional movement, and thus ameliorate or restore the motor function of the affected limb.

Lan et al. developed an electromyographic signal-driven functional electrical stimulation system, which aids patients with movement disorders in more effectively and flexibly accomplishing reaching and lifting movements in daily life [8]. Professor Ming Dong's team from Tianjin University integrated the brain-computer interface and functional electrical stimulation to develop a new

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artificial neural rehabilitation system and incorporated 32 patients with chronic stroke in a randomized controlled clinical trial. The results demonstrated that the new artificial neural rehabilitation system integrating the brain-computer interface and functional electrical stimulation can significantly improve the patient's motor function and neurological function. In comparison with the rehabilitation robot system based on machine assistance, the rehabilitation robot system based on functional electrical stimulation can augment the neural plasticity of the motor cortex and the excitability of the corticospinal tract and assist patients in recuperating upper limb muscle strength and motor function within a shorter time frame [9].

2.1.3. Virtual Reality

Virtual reality(VR) technology is a technological modality that utilizes a computer to synthesize a three-dimensional environment model and create and experience a virtual world. It is a system simulation that integrates multi-source information, interactive three-dimensional dynamic visual scenes, and entity behaviors, permitting patients to interact with the simulated multi-sensory environment [10]. It generates a virtual 3D environment through information technology, endowing users with a realistic sense of presence and multi-sensory experiences such as vision, hearing, and proprioception.

In recent years, non-immersive VR-related research has been centered around enhancing the sense of immersion. Specifically, Korean scholars has developed a sports virtual reality game program. This robot system is integrated with traditional rehabilitation training, and a game program is designed and developed based on mobile phones and tablets. In the subsequent efficacy assessment, it was proved that the rehabilitation effect is superior to that of traditional rehabilitation training, with a high degree of satisfaction, and the training cost is also reduced [11].

Immersive VR conspicuously augments the user's sense of presence. By encompassing more sensory perceptions and diminishing the cognitive load required by the user in the virtual environment, the sense of immersion is significantly enhanced. It renders the user with the impression of being immersed in a virtual environment, facilitating easier interaction with the visual, auditory, and tactile stimuli in the virtual environment, thereby obtaining a multi-modal sensory experience comparable to the real world.

2.1.4. Existing Problems and Current Research Deficiencies

In the realm of machine assistance, both the end-effector type and the exoskeleton type upper limb rehabilitation robot systems are capable of providing patients with accurate, quantitative, and high-intensity motor rehabilitation training. However, their fundamental nature lies in driving the passive movement of the affected limb, which is prone to causing secondary damage to stroke patients with severe upper limb or hand spasm and harbors certain safety risks. Since the end-effector type upper limb rehabilitation robot places emphasis on the movement trajectory of the end effector of the hand, its sensors are often solely utilized to collect the position and force information of the end effector of the hand, and there is a paucity of effective feedback on the kinematic and mechanical information of other joints of the upper limb. Moreover, this type of robot is frequently employed to assist patients in training within a specific plane and is incapable of better realizing the joint movement in three-dimensional space. Particularly for the shoulder joint with multiple degrees of freedom, the number of degrees of freedom and the range of joint movement are highly circumscribed, resulting in the robot being challenged to simulate the movement trajectory of daily upper limb behaviors and unable to fulfill complex rehabilitation training requirements. Therefore, the future development of this type of upper limb rehabilitation robot should contemplate the direction of multi-joint control and expanding its movement range. The exoskeleton type lacks an external

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framework for support, rendering it arduous to install motors and sensors, and there are issues such as axis alignment and individual differences in limb size, which impose stringent requirements on the structural design and control compliance of the robot. Future designs should take into account the length of different upper limb joints and provide reasonable support. Each control strategy possesses its own merits, and the control strategy should be selectively combined and deployed in accordance with the application scenario to maximize the advantages of each control strategy and meet the needs of patients.

For functional electrical stimulation, it obliges patients to bear a substantial physical burden, and the rehabilitation effect is significantly influenced by treatment parameters such as current intensity, frequency, and duration. Additionally, it also demands that rehabilitation therapists possess certain anatomical knowledge to accurately stimulate the target muscle group [12].

For virtual reality, the complexity of system development represents a major obstacle. The construction of a virtual rehabilitation system entails the precise collaboration between hardware and software, which not only necessitates substantial investment but also demands profound professional knowledge. Concurrently, the interdisciplinary nature of rehabilitation research also poses additional challenges to this field.

2.2. Motion Intention

2.2.1. Electromyographic Signal

Electromyographic signal (EMG) is a bioelectrical signal that records the feeble electrical alterations generated during muscle contraction activities.

In 2021, Shi et al. of the Chinese University of Hong Kong [13] developed an electromyographic signal-driven flexible hand robot system. It primarily governs the soft elastic composite actuator (SECA) through the patient's finger extensor muscle (employed to control hand extension) and abductor pollicis brevis muscle (utilized to control hand closure). If the amplitude of the single-channel electromyographic signal of the corresponding muscle exceeds the preset threshold, the SECA is actuated to pressurize or depressurize, thereby realizing the extension and closure of the hand robot.

Subsequently, in 2022, Nam et al. of the Hong Kong Polytechnic University [14] developed an Exoneuromusculoskeleton upper limb rehabilitation robot system that amalgamates electromyography-driven, neuromuscular electrical stimulation, flexible pneumatic muscles, and exoskeleton technology. It regulates the flexion and extension of the elbow through the electromyographic signals of the biceps brachii and triceps brachii muscles, and governs the flexion and extension of the wrist and palm through the flexor carpi radialis and flexor digitorum profundus muscles, and the extensor carpi ulnaris and extensor digitorum muscles. If the amplitude of the electromyographic signal exceeds the preset threshold, the neuromuscular electrical stimulator and pneumatic muscles are triggered to impel the affected upper limb for rehabilitation training. They also conducted a clinical trial concurrently, and the results manifested that the autonomous motor functions of the elbow, wrist, and fingers of the patients were conspicuously enhanced after rehabilitation training.

2.2.2. Brain-Computer Interface

Brain-computer interface (BCI) records and decodes the neurophysiological signals engendered by the user's cerebral cortex activity, and following processing, transmutes them into signals recognizable by external devices such as computers to actualize interaction and control functions. It assists patients with neurological and muscular dysfunctions in interacting with the external environment and has emerged as a crucial technology in motor nerve rehabilitation. It has also been

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corroborated that the rehabilitation robot system based on the brain-computer interface is safe and efficacious for the rehabilitation of the upper limb motor function of stroke patients and can be harnessed in neurological rehabilitation. The acquired brain signals are fed back to the patient in alternative forms to induce and fortify the brain neuroplasticity of the patient, thereby aiding the patient in recuperating activity ability and subsequently enhancing the motor ability of the limb.

A Remsik et al. developed a system that potentially promotes neuroplasticity and Hebbian-based motor recovery by rewarding cortical activity associated with sensory-motor rhythms through diverse self-guided and assisted modes [15]. Subsequently, Carino-Escobar et al. developed a brain-computer interface upper limb rehabilitation robot system predicated on motor imagery (MI), which discerns the patient's active motion intention, actuates the hand exoskeleton to provide corresponding kinesthetic feedback, forms a closed-loop control pathway of intention-motion-sensation, and remodels the brain function through repetitive training [16].

2.2.3. Existing Problems and Current Research Deficiencies

For electromyographic signals, the hand robot imposes relatively high demands on the hand motor function of the included patients. For example, the presence of residual electromyographic signals in the driving muscles of the affected limb is adopted as an inclusion criterion, which considerably restricts the applicable population of the robot system; in terms of safety, long-term driving of the rehabilitation system by electromyographic signals is prone to inducing muscle fatigue, and simultaneous neuromuscular electrical stimulation can exacerbate muscle fatigue and augment the risk of injury to the affected limb.

For the brain-computer interface, the majority of the current brain-computer interface upper limb rehabilitation training robots are voluminous in size and costly to utilize. Future research can explore the installation of the brain-computer interface system in a more diminutive tablet computer to appreciably curtail the volume and investigate the issues of maintaining durability and high signal fidelity.

3. Future Directions

Future key progress in this field still needs to achieve breakthroughs in the following aspects. Firstly, improve the accuracy of human intention recognition. The feedback brought about by incorrect motion intention recognition may affect the rehabilitation effect of the robot system [16]. Researchers should focus on the methods of inducing, collecting, and decoding high-resolution electroencephalogram signals to achieve high-performance motion intention recognition, form correct and immediate feedback, so that patients can participate in the virtuous cycle of active rehabilitation with higher enthusiasm, and thus more effectively induce brain nerve remodeling. Secondly, the safety and comfort feedback of the rehabilitation robot system design should be fully discussed during the laboratory research and development stage. The hand exoskeleton robot system can provide high-intensity, quantitative, and highly repetitive motor rehabilitation training for hemiplegic patients, but it has certain safety hazards for patients with high hand muscle tone or flaccid paralysis. Future research should further develop flexible, lightweight, and portable auxiliary robot systems; standardize the stimulation frequency, duration, and other treatment parameters of functional electrical stimulation; develop coupling systems of various types of rehabilitation robots, etc., to further improve the safety and comfort of the robot system [17]. Finally, realize the clinical research and transformation of the rehabilitation robot system. Currently, there is a huge rigid demand for rehabilitation training. Facing the increasingly severe situation of stroke prevalence in China and the backward situation of intelligent rehabilitation assistive tools, future research should further standardize the design of clinical trial protocols, carry out multi-center cooperative clinical

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research, expand the sample size, and accelerate the innovation and transformation of intelligent medical rehabilitation equipment.

4. Conclusion

This paper combines the literature to conduct research on the upper limb rehabilitation robot driven by ECE. Using the feedback method, the paper devides upper limb rehabitation robots systems base into machine assistance (RA), electrical stimulation (FES), and virtual reality (VR).. Additionally, it classifies these systems based on motion intention recognition methods into those driven by electromyographic signals and brain-computer interfaces, analyzing their respective representative types.

The goal of rehabilitation training is to help patients improve their functional impairments to the greatest extent, enhance their self-care ability in daily life, and return to their families. In terms of task guidance, rehabilitation should focus on daily living activity requirements, with training tasks designed to enhance adaptability. From a structural perspective, the robot's design should align with the physiological structure of the limb, conform to the movement characteristics, physical characteristics, and training space requirements of the patient, and be able to adapt to the individual differences among patients. The intelligent upper limb rehabilitation robot system can be used as an effective means to replace traditional rehabilitation therapists. However, most of the systems remain in the laboratory research and development or clinical verification stage. Significant challenges need to be addressed before these systems can achieve widespread clinical application and commercialization, including the insufficient number of existing experimental samples and the lack of strong empirical research. Future research should combine clinical practice to conduct empirical research to make up for the deficiencies of current research.

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