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Research on the progress of neurorehabilitation

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Abstract. With the intensification of global aging problems, the incidence of central nervous system diseases such as stroke is getting higher and higher. At the same time, the number of disabled people has also increased. Amputation and neurological diseases are important causes of disability, and neurorehabilitation is an important method for restoring the nervous function and autonomous movement ability of the disabled. At present, neurorehabilitation methods commonly used in clinical treatment mainly include: wearing prosthetic limbs, functional electrical stimulation (FES) therapy, rehabilitation robots, and so on. The prosthetic limb refers to an artificial device used to replace the function of a lost limb. Many advanced technologies are being used to improve the motion control of prosthetics to achieve natural movement. FES is a technique that can improve physiological function or treat diseases by stimulating nerves or tissues through current, and has become one of the important means to promote nerve regeneration and restore motor function. Rehabilitation robots are the equipment that uses mechanical devices and advanced control technology to assist rehabilitation treatment and functional recovery. This article mainly discusses the current research progresses of prosthetic limbs, EFS and rehabilitation robots, so as to promote the development of neurorehabilitation.

Keywords: neurorehabilitation, prosthetic limb, functional electrical stimulation, rehabilitation robots.

1. Introduction

The World Health Organization (WHO) reported that around 1.3 billion people globally are suffering from severe disability. This number is still increasing due to the rise in non-communicable diseases and the extension of people's life [1]. People with disabilities have worse health than others and are subject to many restrictions in their daily lives. The disability is mainly caused by functional impairment of the central nervous systems like spinal cord injury (SCI) and stroke. In 2013, a survey with national representativeness was conducted, which involved 480,687 adult participants beyond 20 years old. The survey result reflected that proportion of the stroke prevalence and incidence was around 1.11 percent (1114.8/100,000 persons) and around 0.24 percent (246.8/100,000 person-years), respectively [2, 3]. Each year, about 250,000 to 500,000 people around the world are suffered from SCI due to traffic accidents, falls, violence or other traumatic accidents [4]. Neurorehabilitation can help disabled people carry out daily activities more independently, and its importance is obvious.

Neurorehabilitation is an important non-pharmacological approach to the treatment of diseases that affect the nervous and neuromuscular systems, and to the optimization of patients' participation in society and quality of life. Its main component is the training of behavior adaptation [5, 6].

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Neurorehabilitation can be used to trigger sensorimotor stimuli under the combined effect of repeated movements and daily activities, which is favorable for the central nervous system to develop activity-dependent plasticity [7]. It involves a number of methods including prosthetic limbs, FES, rehabilitation robots, and so on.

A prosthetic limb is an artificial substitute for a person's missing limb to make up for its appearance and function [8]. Krausz et al. put forwards an accurate prosthetic hand control method which is achieved by incorporating gaze and electromyography (EMG) [9]. FES refers to organized and patterned neuromuscular electrical stimulation designed to produce coordinated limb or body movement [10]. It stimulates muscles through electrical signals, enabling the muscles that have lost nerve control to contract, thus restoring neuromuscular function. Case Western Reserve University in the United States has developed a microsystem that can receive signals from nerves when the bladder is full, and it can be connected to FES to control bladder activity [11]. The rehabilitation robot technology is an integrated technology that can be used to produce wearable mechanical devices through combination of sensing, computer science, information technology and control [12]. Atalante is a crutch-less exoskeleton developed by Wandercraft that already helps paraplegics achieve a stable gait [13, 14].

By reviewing previous studies, this paper summarizes some applications of prosthetic limbs, FES and rehabilitation robots in the field of neurorehabilitation, aiming to provide references for related research on neurological rehabilitation and promote research progress in this domain.

2. Artificial limb

Patients with severe trauma, infection, blood circulation disorders or tumors need to save their lives through amputation. Prosthetic limb refers to a device used to replace the missing limbs of the human body, such as arms and legs. It can be controlled by EMG and electroencephalogram (EEG) signals, helping amputees regain many functions in daily life, such as walking, grasping and so on. The number of above-knee amputees that need prosthetics around the world is estimated to be 6.7 million, 1.7 million and 700,000 in Asia (especially India and China), Africa and South America, respectively [15]. It can be seen that prosthetic limbs in developing countries are in high demand. In the past, prosthetics available to most people were less comfortable and had very limited functions. The past years have witnessed the application of increasing technologies to this field, and prosthetic technology has made significant advances, continuing to develop around the goals of improving the reliability of control, imitation and the comfort of patients [11].

In recent years, the control technology of prosthetic limbs has developed rapidly. Machine learning and pattern recognition algorithms have been widely used in electronically controlled prosthetics, making the recognition and classification of EMG and EEG signals more accurate. In the study of EMG-controlled prosthetic hands, there are existing prosthetics that can accurately perform the expected actions of the subject based on the EMG signals. Nadjib et al. developed a gesture recognition system that controls the prosthetic hands by aid of EMG signals. This recognition algorithm is developed on basis of the deep learning technology that combines the convolutional neural network (CNN) and the long short-term memory (LSTM) network. They also examined the CNN-LSTM model on an open dataset "sEMG for Basic Hand movements Data Set", and the classification accuracy was as high as 98.88 percent. Additionally, this recognition model was experimented to control the prosthetic hand samples, which also reached a satisfactory result [16]. In the study of EEG prosthetics, Gao et al. proposed an EEG-based control of the will of the prosthetic leg to walk on different terrain. This approach enabled amputees to walk more naturally by directly manipulate the prosthetic leg via non-invasive brain signals (Figure 1). The prosthetic leg decoded three different motor imagery tasks and generated the corresponding motion commands, and then executed the gait trajectory which was generated by encoding the ground reaction force, thereby realizing more smooth walking. Through experiments on three healthy subjects who could walk on the floor, up and down stairs successfully on their own will while wearing the prosthesis, the researchers validated that this system was feasible and effective [17].

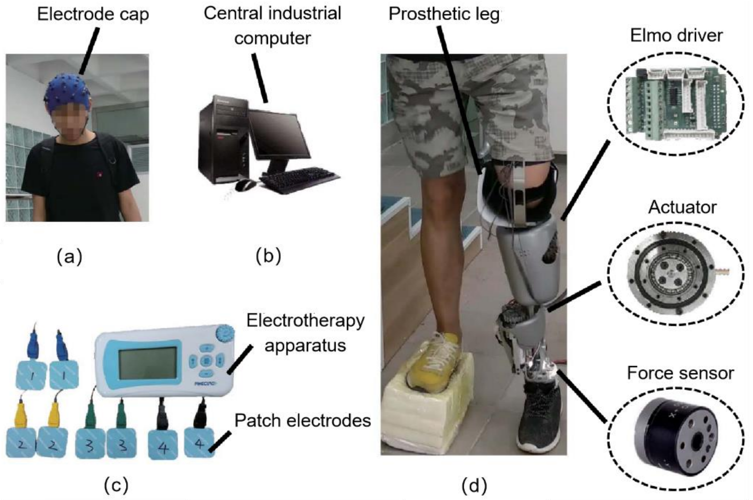

Figure 1. Demonstration of the designed system [17]. (a) Elastic and breathable electrode cap capable of recording the EEG signal; (b) Central industrial computer used to assess the EEG signal and convert the signal to control commands of the prosthetic leg; (c) Multifunctional electrotherapeutical apparatus used to generate current stimulations that are conveyed back to the cerebral cortex via the patch electrode; (d) the prosthetic leg for amputees to walk independently;

In addition, implanted electrodes are increasingly used for the control of prosthetic limbs. Mastinu et al. compared the grip performance of three subjects when using an osseointegrated prosthetic hand controlled by the surface EMG and the implanted epimysial EMG. The results showed that when grasping with osseointegrated prosthetic hand, implanted electrodes provided better controllability than the conventional surface electrodes. However, implanted electrodes did not increase the motor coordination, and the subject's natural grasping ability cannot be restored unless the function of tactile sensory feedback was added [18]. Implanting electrodes in the nerves provides amputees with a sense of touch and movement, giving lower-limb amputees confidence when walking [19]. Valle et al. implanted four transverse intraneural electrodes at the distal end of the tibial nerve in two subjects who had suffered amputations as a result of traumatic events. The researchers fitted the subjects with pressure sensors under their bionic legs and encoders on their knees. Readings from these sensors drove the subjects’ neurosensory feedback and conveyed continuous position and tactile information to the subjects’ prosthetic leg. The researchers then tested the completion conditions of two tasks by the subjects with and without neurosensory feedback, finding that the neurosensory feedback restored the subjects’ sensory flow information and enhance their ability to move [19].

3. Functional electrical stimulation

The central nervous system of stroke or SCI patients is unable to produce required motor commands and/or is unable to transmit the required motor commands to the peripheral nervous system to govern muscle activity. This disabled these patients to perform functions or move their body parts to realize operations like grasping, standing, sitting, walking or urinating. However, if muscles, the nerves innervating the muscles, soft tissues and joints are intact, electrical stimulation can stimulate the muscles that drive the joints to contract, thereby producing joint movement. Such process is neuromuscular electrical stimulation (NMES). Organized and patterned NMES that is designed to produce coordinated limb or body movements is the so-called FES [10].

FES technology was initially used to develop neural prostheses for permanent replacement of impaired functions, such as bladder urination. Nowadays, the FES technology is increasingly used for the purpose of restoring the autonomic movement function and the neuromuscular function like walking, grasping and sitting. It is used for a short-term purpose, as a transition to the autonomous function in the long run [10]. In rehabilitation engineering, FES is often used in the treatment of diseases such as stroke, SCI, and multiple sclerosis.

The mirror neuron system based action observation training (AOT), as a supplementary treatment of stroke, can effectively improve stroke patients’ movement function [20]. At the same time, brain-computer interfaces (BCI) with FES systems are expected to facilitate rehabilitation by promoting motor learning after stroke occurs [21]. EEG-based BCI detected the event-related synchronization in the sensorimotor oscillatory rhythm related to action observation (AO) or motor imagery, and this also drove the BCI. The technique is able to help stroke patients to rehabilitate their motor functions [22]. Kim et al. investigated the combined impact of AOT and brain-computer interface BCI-based FES having a real-time feedback function on the restoration of the upper limbs’ movement function. In the study, participants completed 18 motion-observing tasks related to daily life. If the attention level of the participants rose to the attention limit value and they can imagine the correct movement, they would trigger the FES that stimulated the wrist extensor muscles that controlled the movement of the upper limb. According to the results, the upper limb of the BCI-based FES group showed a remarkably better performance compared with the control group. This suggested that during the implementation of the AOT associated with the subjects' daily lives, the combination of BCI and FES can improve the rehabilitation efficacy [22].

Selfslagh et al. studied the effect of non-invasive, brain-controlled FES on motor rehabilitation in paraplegics. They used a BFNR (BMI, surface FES, NeuroRehabilitation) protocol to enhance recovery in SCI patients through four key elements: muscle activation through surface FES, balance control based on body weight regulation, motor sensory feedback from a movable tactile device and real-time decoding of movement commands (Figure 2). Through the application of EEG-based BCI, combination of robot walking trails and assisted walking training, and continuous visual feedback, this training protocol induced significant levels of neurological recovery, including improved muscle response, reduced muscle fatigue, increased muscle volume, and improvement in walking function, further enhancing the nerve function recovery of serious SCI patients under clinical treatment [23].

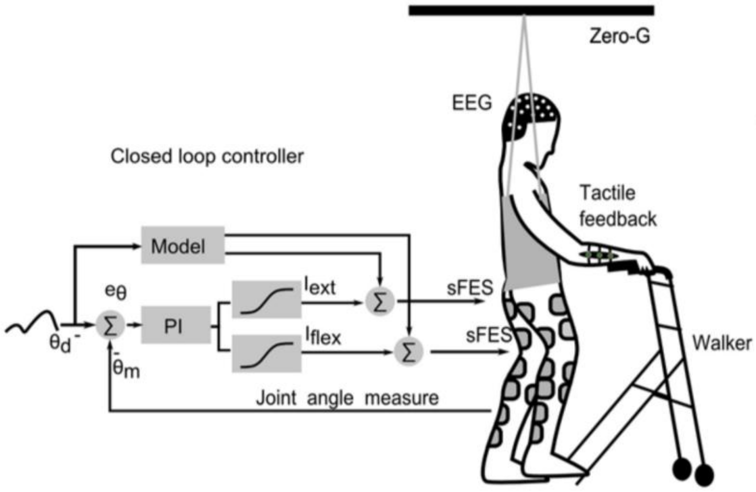

Figure 2. BFNR experimental setup [23].

The patient gains protective support from the weight support system and is kept stable using a walker. The simulation model is used as the basis for feed-forward current stimulation, and it includes the gait phase and the reference motion curve. After computing the commands of the proportional integral action controller, the model converted them to the feedback current for the musculus extensors and flexors. Finally, by combining the feed-forward current and the feedback current, the actual current value exerted on the electrodes can be produced.

In addition, Street et al. used data from standard clinical practice to determine the effectiveness of FES in treating foot drop of multiple sclerosis (MS) patients. Foot drop refers to the decreased ability of the foot to lift off the ground due to dorsiflexion and valgus weakness when an MS patient was walking, which lead to unstable gait and a higher risk of falling. FES may be a possible treatment as it can stimulate the peroneal nerve and further activate the dorsal flexor muscle. The findings showed that among the participants that received FES treatment, 95 percent of them kept or even improved the functional walking category [24] no matter what kind of category they had at the beginning of the experiment. This indicates that FES may be applicable to various types of patients of different functional walking categories. 71% of treatment responders had clinically meaningful changes, indicating that FES had a significant effect on actual ability to perform daily activities, which may help improve the overall well-being and life quality of the majority of patients [25].

4. Rehabilitation robots

As the aging of society is becoming increasingly severe, people are more and more concerned about their own health. The upper and lower limb dysfunction caused by SCI has also brought great inconvenience to the life of the patients. In clinical rehabilitation treatment, rehabilitation robotics has gradually attracted people's attention, and has made great progress. As rehabilitation robots can provide controllability of movement and reliability of measurement, therapists and neuroscientists can apply them to neurorehabilitation to solve the difficulties in this field. On the one hand, they can produce repetitive high-quality and multiple types of exercise, thereby improving the rehabilitation intensity and treatment effect. On the other hand, they also provide a human-computer interaction that can objectively measure progress, and they themselves can regulate changes in the interaction by changing the control parameters [26]. Research has found that the rehabilitation robots can partially or completely restore the damaged function as they can provide repeated exercises for the damaged function and stimulate neuroplasticity [27, 28]. According to the different parts of rehabilitation, there are two types of rehabilitation robots, i.e. the upper limb rehabilitation robots and the lower limb rehabilitation robots.

As for the upper limb rehabilitation robots, EMG signals, as a direct reflection of human motion intention, can be used to control robotic prostheses and exoskeletons. Despite recent advances in algorithms controlled by EMG, there is still a need to develop more suitable algorithms to exoskeletons and prosthetic limbs more naturally. To examine the myoelectric control algorithm, Ruiz-Olaya et al. developed a flexible, 6-degree-of-freedom prototype robot using the low-cost Arduino technology. This work tentatively establishes a MATLAB/Simulink-based cost-effective robot platform for assisted/rehabilitative upper limbs for the disabled. This platform can be used to design and evaluate the novel myoelectric control algorithm and incorporated into the rehabilitation apparatuses [29]. The development and integration of multi-disciplines have promoted the exoskeleton for hand function recovery to gain great progress. Wang et al. developed ReHand which is a new exoskeleton specially designed to rehabilitate stroke patients’ hand functions and facilitate their daily lives. ReHand can accurately assist each finger of the hand to stretch or withdraw conveniently. They also designed an under-actuated linkage-slide mechanism for the linkage structure to ensure its rotating center coincide with human joint’s rotating axis, which reasonably simplifies the structure of ReHand and makes it more compact and lighter. In addition, it can be jointly used together with the voice control mode, EMG signals and other control approaches. Tests on stroke patients with upper limb motor dysfunction showed that these patients responded well to the exoskeleton intervention, with significant improvements in hand function after 20 training sessions [30].

In the study of lower limb rehabilitation robots, Vaida et al. discovered a blank spot in the field, that is, most of the lower limb robot rehabilitation apparatuses are designed upright, so they are not suitable for the severely disabled patients who are unable to stand. Therefore, they systematically developed a novel robot and fixed it to the bed of a patient to facilitate movement exercises of lower limb joints such as ankles, knees and the hip. In the design process, they first analyzed the movement ability of the healthy participants to determine the movement amplitude of the limb joints like the ankles, knees and hips, and then they designed the robot system by using the test data. In addition, they conducted initial evaluation on the robot system through numerical simulations to determine its ability in conducting motor actions. The results showed that the design scheme is technically feasible. Then, they conducted various clinical tests to assess the medical applicability of the robot system through a prototyped RAISE robotic system [31]. Organizations have make great contribution to the

the research of lower limb exoskeleton rehabilitation robots and some of them have even developed mature products and technologies (Figure 3). The wearable device exoskeleton can be fixed to the body's limbs and provide strength and movement support according to the movement intention of the patient. Designed with 4 degrees of freedom for movement, the medical exoskeleton HALML05 is used to assist gait training of SCI patients and others who suffer from musculoskeletal or neural disabilities[32]. It can accurately measure muscle activity by collecting data of plantar force, the EMG sensor and the joint angle, thereby determining which stage of the user's walking mode they are in. This device is also equipped with several modes that support different control approaches such as myoelectricity, auxiliary torque, and so on [14].

Figure 3. A patient is using Ekso GT exoskeleton for rehabilitation [14, 33].

Despite the widely validated effectiveness, robot-based rehabilitation has not been extensively used by patients in their daily lives due to the high costs. In the future, low-cost rehabilitation robots that can reduce the supervision of therapists will be developed to reduce patients’ financial burden on rehabilitation [34].

5. Conclusion

This article reviews the research status and new progress in the fields of prosthetic limb, FES and rehabilitation robots, focusing on their application in neural rehabilitation. Neurorehabilitation aims to improve the independence of persons with disabilities by promoting neuroplasticity and optimizing the rehabilitation treatment process. Prosthetic limbs can partially or completely replace the lost limb function, help amputees to recover walking, grasping and other functions, and is an important means to enable disabled people to return to society. By using advanced prosthetic control technology, patients can regain functions such as movement and sensation, improving quality of life. By stimulating nerves and muscles, FES helps patients with central nervous system diseases recover motor function, improve sensory perception, and promote neuroplasticity, providing an effective support for the rehabilitation of nervous system damage. Rehabilitation robots help patients restore motor function, enhance muscle strength and coordination by providing precise, personalized rehabilitation training. Advanced rehabilitation robots can provide reliable support and real-time feedback to facilitate the remodeling and repair of the nervous system.

Despite great progress on the research on neural rehabilitation, there are still some problems to be resolved. For example, the prevalence of prosthetics is still low, and the comfort of them needs to be improved. Today, as the rapid proto-typing technology (RPT) and the additive manufacturing technology (AMT) have been gaining fast development, the 3D printing technology applied to the healthcare industry is also gradually mature, which can create more affordable, comfortable and personalized prosthetics for patients [35]. In addition, FES treatment has only yielded statistically significant results in stroke patients and incomplete SCI patients. With the continuous progress of FES technology, its application scheme will be continuously optimized. In the future, FES treatment has the potential of developing into a major rehabilitation strategy for amputees. Besides, most of the current rehabilitation training using robots requires one-to-one interaction with a therapist and can only be carried out in places like treatment centers. With the development of tele-rehabilitation, patients will be able to recover effectively in their homes in the future.

The prosperous artificial intelligence technology will promote the development of more accurate and rational algorithms that can facilitate the development of prosthetic limbs, FES and rehabilitation robots. In the future, neurorehabilitation will become increasingly intelligent and personalized, and the quality of life of disabled people will be greatly improved.

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