Clinical Application of Flexible Lower Limb Exoskeleton in Neurorehabilitation

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Abstract. The number of patients with neurological diseases has been continuously increasing worldwide. Among them, stroke and spinal cord injury have become the main causes of long-term disability, leading to neurological disorders. Lower limb functional disorders caused by nerve injury seriously affect the quality of life of patients. Rehabilitation exoskeletons have emerged as a new type of assistive tool and have attracted widespread attention in the field of stroke rehabilitation due to their unique advantages. As a new type of exoskeleton robot that has emerged in recent years, flexible lower limb robots can effectively solve the problems of large volume and weight, poor compliance, and excessive constraints of traditional rigid exoskeleton robots, and have become one of the important directions in the field of robot-assisted rehabilitation. This article systematically reviews the clinical application research of flexible lower limb exoskeletons in the field of neurological rehabilitation, and summarizes the progress in the clinical efficacy evaluation of their application in the rehabilitation of stroke, spinal cord injury and other diseases. Studies have shown that this device can significantly improve lower limb motor function, gait stability and activities of daily living by assisting patients in early weight-bearing walking and promoting neural plasticity. However, there are still problems such as inconsistent evaluation standards and insufficient long-term efficacy tracking. This article summarizes and analyzes the existing research results of flexible exoskeleton robots to provide a reference basis for subsequent clinical applications and technical optimization.

1 Introduction

Stroke and traumatic spinal cord injury are catastrophic diseases that affect the stability and safety of daily activities such as walking, and increase the incidence of falls [1-2]. Traditional rehabilitation training is conducted under the assistance of therapists and relies on manual training by one or more therapists. This not only increases the labor intensity of the therapists but also has high requirements for their technical proficiency, making it difficult to meet the different patients' needs for rehabilitation time, intensity, and frequency [3]. Lower limb exoskeleton robots have become clinical rehabilitation tools for patients with paralysis of the lower limbs caused by neurological diseases, stroke, or spinal cord injury [4]. As an emerging

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robot technology in recent years, flexible exoskeletons combine flexible drive and wearable mechanisms, effectively solving the problems of heavy weight, poor compliance, low efficiency, and poor wearing comfort of traditional rigid exoskeleton robots [5]. In the field of neurorehabilitation, robot-assisted therapy is increasingly being applied to enhance training effects. Moreover, therapeutic robots have the potential to precisely evaluate motor functions, thereby enabling the diagnosis of patient conditions, measuring treatment progress, or providing real-time feedback on movement performance to patients and physiotherapists [6]. Stroke and spinal cord injury and other neurological diseases cause walking disorders. Traditional rehabilitation has limitations such as reliance on human resources. Flexible lower limb exoskeletons optimize walking training in neurorehabilitation through technologies such as flexible drive, but the needs of different patients with nerve injuries vary significantly. Conducting clinical efficacy evaluations of them can verify the intervention value from dimensions such as neural function remodeling and gait correction, providing key evidence for the intelligent and personalized technological innovation in the field of neurorehabilitation.

This article summarizes the technical features of flexible lower limb exoskeletons. This study analyzed the specific applications of flexible exoskeletons in the rehabilitation of stroke and spinal cord injuries, including gait correction, promotion of neural plasticity, and recovery of motor functions. This study compared the technical logic and clinical effects of three representative products (ReStore, Yulong "Tengyun" series, EasyWalk X1), summarized the differences in short-term (gait score, walking speed) and long-term (daily living ability, neural function remodeling) therapeutic effects; explored the enhancement of rehabilitation accuracy through multi-technology integration, analyzed the potential of flexible exoskeletons in home-based rehabilitation and full-cycle training; and finally pointed out the current challenges and future directions for technological integration. This study provides theoretical basis and technical directions for subsequent research, promoting the intelligent and personalized development of the neurorehabilitation field.

2 Flexible exoskeleton robot

The lower limb rehabilitation exoskeleton effectively maintains the joint range of motion of patients through various modes such as active movement, passive movement, impedance movement, and mirror movement, and gradually improves the gait of patients during rehabilitation training. In recent years, with the gradual maturity of control and manufacturing technologies, China has witnessed a variety of achievements in the research and development of rehabilitation exoskeleton robots. The development technology of lower limb rehabilitation exoskeleton with flexible joints has become mature [7]. The flexible exoskeleton robot mainly consists of four parts. The compliant exoskeleton suit generally uses lightweight and durable functional textiles to achieve good flexibility and flexibility. At the same time, elastic units are added at appropriate positions to make it more compliant. The lightweight drive system uses lightweight active drives (such as micro motors) to effectively reduce the weight of the wearer and combine passive components such as springs to achieve human-assisted movement. The motion sensing system includes force sensors, angle sensors, gyroscopes, etc., which can detect the movement of the wearer and the flexible device. The intelligent control system has intelligence and needs to respond promptly to the physiological information and movement information of the wearer [8]. Many flexible lower limb exoskeleton robots adopt Bowden cables for "cable drive", and the cable drive method can limit the interference of the flexible exoskeleton on the natural activities of the wearer[9].

3 Clinical application of flexible lower limb exoskeletons in neurological rehabilitation

3.1 ReStore System

ReWalk Robotics's ReStore exoskeleton suit is one of the few flexible devices approved for neurological rehabilitation in the international market, mainly targeting walking training for stroke patients. For stroke patients with hemiplegia, the ReStore system is particularly effective. These devices change the walking pattern of the user by providing parallel ankle-foot supination and foot dorsiflexion assistive forces to the damaged muscles. Unlike rigid exoskeletons that can move limbs powerfully without user input, the force generated by the exoskeleton must be synchronized with the user's movements to improve their walking ability. Multiple multi-center clinical trials within a short-term efficacy period show that after ReStore training, the Fugl-Meyer lower limb score of stroke patients increased by an average of 5-8 points, and the 10-meter walking speed increased by 0.2-0.4 m/s. Long-term efficacy studies show that patients using ReStore for more than 12 weeks have an increase of 15%-20% in daily living activity (ADL) scores, and some patients can achieve independent walking or reduce the dependence on walking aids. Its unique flexible design distinguishes it from traditional rigid exoskeletons, emphasizing active participation in training and promoting neurological rehabilitation. Through personalized, active synchronous gait training, it accelerates the recovery of motor function in stroke patients and improves their independence in daily life.

3.2 Yulong Flexible Lower Limb Exoskeleton Robot

The Yulong robot's flexible lower limb exoskeleton robot (such as the "Tengyun" series, which has been iterated to the third generation) has clinical applications in the field of neurorehabilitation, centered around the concept of "flexible drive enabling neural remodeling". It combines its lightweight, muscle-contracting imitation, and intelligent sensing technical features to achieve precise rehabilitation intervention for neurological diseases such as stroke and spinal cord injury. The driving method involves using high-intensity Bowden lines to simulate muscle contraction, with the force direction consistent with the anatomical position of human muscles (such as the quadriceps femoris and anterior tibialis muscles), providing natural assistance while also stimulating the reconstruction of the neural-muscle connection through "forced muscle movement" (in line with the principle of neural plasticity). In stroke rehabilitation for hemiplegia, for example, it addresses "circular gait" and "foot drop" by correcting hip joint flexion insufficiency and ankle joint dorsiflexion disorders through flexible assistance, restoring gait symmetry (after training, the difference in step length decreases from 50% to within 15%) [10]. The Bowden line drive simultaneously stimulates the affected muscles (such as the quadriceps femoris and gastrocnemius), combined with the synergistic effect of functional electrical stimulation (FES) (in some schemes integrated), enhancing muscle contraction ability and promoting neural pathway reorganization. In spinal cord injury (paraplegia/paraplegia) rehabilitation, for incomplete spinal cord injuries (ASIA B/C level), the "partial assistance mode" is activated (when the patient actively exerts force, the exoskeleton synchronously assists), strengthening the control ability of residual neural functions and increasing the possibility of future autonomous walking. The Yulong robot's future direction plans to integrate brain-computer interface (BCI) technology, exploring "thought-controlled assistance", further enhancing the precision of neurorehabilitation. It not only compensates for motor function deficiencies through mechanical assistance but also maximizes the potential for neural-

muscle self-repair through muscle contraction imitation and intelligent sensing. For neurorehabilitation, this "lightweight, conforming, and intelligent" characteristic is particularly suitable for long-term rehabilitation training and extension to home scenarios, providing a more sustainable rehabilitation solution for stroke, spinal cord injury, and other patients.

3.3 Siyi Intelligent's Yisheng Series

The Yisheng series of hand function rehabilitation robots by Siyi Intelligent combines flexible robot technology and neuroscientific theory, meeting the needs of the entire rehabilitation cycle, including passive training, assistance training, active game training, and resistance training [11]. These products promote the rehabilitation of brain nerve damage through movement relearning, reducing hand muscle tension, alleviating edema and stiffness, and accelerating the process of hand function rehabilitation [12]. The EasyWalk X1 lower limb soft exoskeleton can help solve walking difficulties for stroke patients, brain trauma, etc., optimizing gait, and enabling easier walking again. The medical version EasyWalk captures gait data through multiple sensors (foot pressure, accelerometer, gyroscope) in real time, combined with AI algorithms to identify gait cycles, providing personalized assistance for different stages (such as the stance phase and swing phase) to correct abnormal gait and establish normal movement patterns. For example, in the early rehabilitation of stroke patients, repetitive practice of flexion/extension movements helps patients restore ankle control and inhibit the formation of foot drop. Siyi Intelligent integrates brain-computer interface (BCI) with exoskeleton technology, using the patient's brain electrical signals for movement imagination to achieve "intention-driven" closed-loop feedback, further stimulating neural plasticity, especially suitable for patients with severely impaired motor functions.

4 Product Clinical Applications

4.1 Core Direction and Technical Logic of Clinical Applications

As shown in Table 1, all three focus on the recovery of walking function after nerve injury, especially for gait abnormalities caused by stroke, spinal cord injury, etc. (such as foot drop, circular gait), but their technical entry points are different: The core of ReStore is "synchronous collaboration", by providing ankle-foot assistive forces parallel to the damaged muscles, strictly following the rhythm of the patient's own movements, avoiding the drawbacks of rigid exoskeletons' "passive driving", allowing the assistance to form coordination with the patient's active force, thereby gradually correcting abnormal walking patterns. This "user-led + equipment-assisted" logic is more suitable for patients who still retain some active movement ability after stroke, and can improve walking efficiency by adjusting gait symmetry in the short term.

The Yulong "Tengyun" series focuses on "biological simulation drive", using the Bowen line to simulate the natural contraction trajectories of muscles such as the quadriceps femoris and anterior tibialis, with the force direction perfectly matching the human anatomical features. This design not only directly corrects problems such as insufficient hip flexion and ankle dorsiflexion disorders, but also stimulates the reconstruction of nerve-muscle connections by forcing muscles to participate in movement, conforming to the principle of neural plasticity, and is particularly targeted for patients with spinal cord injuries and other conditions requiring long-term neural remodeling.

The EasyWalk X1 highlights "intelligent personalization", relying on multiple sensors to capture gait data in real time, combined with AI algorithms to dynamically identify support phases and swing phases, and providing differentiated assistance as needed (such as enhancing backbending assistance in stair scenarios). At the same time, it integrates brain-computer interface technology, through a "motion intention - device response" closed-loop feedback, to build a "bridge" for neural remodeling for patients with severely impaired motor functions, covering the entire rehabilitation cycle from passive training to active resistance.

Table 1: Product Application Comparison

Product	Core direction	Technical logic
ReStore	Applicable to those with some residual motor ability after stroke, to improve abnormal gait	Synchronous collaboration, providing ankle and foot assistive forces in accordance with the movement rhythm, user-led + equipment-assisted
Youlong "Tengyun" Series	For those with spinal cord injuries or other conditions requiring long-term neural remodeling, improving abnormal gait patterns	Biologically-inspired drive, the Bowen line simulates the contraction trajectory of muscles, conforms to anatomical features, and stimulates the reconstruction of the nerve-muscle connection.
EasyWalk X1	Covering the entire rehabilitation period and assisting in the neural remodeling of individuals with severely impaired motor functions	Intelligent personalization, with multi-sensor + AI providing differentiated support, and integration of brain-computer interface to achieve closed-loop feedback.

4.2 Commonalities and Differences in Clinical Effects

In terms of therapeutic outcomes, all three treatments can significantly improve the walking function of patients. However, the emphasis on short-term and long-term effects is slightly different, as shown in Table 2.

In the short term, the multi-center data of ReStore is the most intuitive. After training, the Fugl-Meyer lower limb score of stroke patients increased by an average of 5-8 points, and the 10-meter walking speed increased by 0.2-0.4 m/s, demonstrating a rapid optimization of gait efficiency; while Yulong "Tengyun" excels in gait symmetry, which can reduce the step length difference of stroke patients from 50% to within 15%, directly addressing the core issue of "circling gait"; EasyWalk X1, by inhibiting foot drop, can quickly improve the walking safety of patients and reduce the risk of falls caused by insufficient ankle control.

In the long term, all three treatments can promote the improvement of patients' daily living abilities: for patients who have used ReStore for more than 12 weeks, the ADL score increased by 15%-20%, and some can reduce the dependence on walking aids; Yulong "Tengyun" through continuous muscle-like contraction stimulation, has a more significant enhancement of residual nerve function in patients with spinal cord injury, improving the possibility of independent walking; EasyWalk X1, with its full-cycle training mode, helps patients transition from passive training to independent walking, and is particularly suitable for long-term rehabilitation scenarios in the home environment.

Table 2: Comparison of Product Clinical Effects

Product	Short-term clinical outcome	Long-term clinical effect
ReStore	The lower limb score of Fugl-Meyer increased by 5 to 8 points, the 10-meter walking speed increased by 0.2 to 0.4 meters per second, and the efficiency of the gait was optimized.	The ADL score increased by 15% - 20% after 12 weeks, and the dependence on walking aids decreased.
Youlong "Tengyun" Series	The stride length difference has been reduced from 50% to within 15%, improving the "circling gait"	Strengthen the residual neural functions of patients with spinal cord injuries and enhance their ability to walk independently
EasyWalk X1	Prevent foot drop, reduce the risk of falls, and enhance walking safety	Comprehensive cycle training, facilitating the transition from passive training to independent walking, suitable for home-based rehabilitation

4.3 Trends in Clinical Application

Based on the practical experiences of these three devices, the application of flexible exoskeletons in the field of neurorehabilitation is developing several key trends.

Flexible technology has become a breakthrough point. Compared with traditional rigid exoskeletons, the lightweight and biologically-inspired design of flexible systems significantly improves the patient's wearing compliance, addressing the clinical pain point of "heavy equipment making training difficult to sustain", and providing the possibility for long-term rehabilitation.

Whether it is ReStore's action following, Youlong's muscle contraction imitation, or EasyWalk X1's AI dynamic adjustment, the core lies in making the device assistance highly coordinated with the patient's own movement intention - avoiding "replacing movement" and instead activating the patient's active participation through an "assistance-guidance" mode, which is the key to promoting neural remodeling.

The integration of multiple technologies such as BCI (Brain-Computer Interface) and FES (Functional Electrical Stimulation) (like the BCI integration in Youlong's plan and the BCI closed-loop system already implemented by Siyi) enables the device to upgrade from "mechanical assistance" to "neuro-mechanical synergy", not only improving the external gait but also deeply activating the repair potential of the central nervous system, providing a new rehabilitation path for patients with severe functional impairments.

Overall, the clinical application of these three devices validates a core logic: Neurorehabilitation flexible exoskeletons are not only "walking assistance tools", but also "neural remodeling catalysts" - through precise, coordinated, and continuous intervention, the damaged neural-muscular system gradually rebuilds its function through active participation, ultimately achieving the rehabilitation progression from "being able to walk" to "walking well" and then to "independent living".

5 Conclusions

The flexible lower limb exoskeleton has achieved remarkable results in clinical applications of neurological rehabilitation, providing effective rehabilitation methods for patients with lower limb dysfunction. However, in the field of lower limb medical rehabilitation exoskeleton robots in China, efforts should be focused on addressing issues such as insufficiently intelligent control algorithms, weak energy supply and endurance, and high costs. Based on this, multiple clinical application studies should be conducted and a complete clinical medical rehabilitation effect evaluation system should be established. In the future, the flexible lower limb exoskeleton may be combined with technologies such as virtual reality and remote medical care to provide patients with more convenient, efficient, and personalized rehabilitation services, becoming an important treatment tool in the field of neurological rehabilitation, helping more patients regain the ability to walk and return to normal lives.

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