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Lower Limb Rehabilitation Robots in Stroke Rehabilitation: An Overview of Systematic Reviews

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Abstract:
Stroke is one of the causes of permanent disability in adults. The varying degrees of functional impairment in stroke patients not only reduces the quality of survival but also adds to the economic burden on families and society. Rehabilitation in hospital and at home is an important intervention for stroke patients to return to life. As the incidence of stroke and disability rates increase each year, the need for post-stroke rehabilitation is becoming increasingly significant. With the impact of the COVID-19 pandemic, it has become increasingly difficult for stroke patients to travel to rehabilitation hospitals for regular rehabilitation. The use of lower limb rehabilitation robots to assist in the telerehabilitation of stroke patients is gaining importance in clinical applications. This paper reviews the clinical studies of the lower limb rehabilitation robot in improving motor and balance functions, gait and functional independence in stroke patients in three separate areas, with the aim of providing a reference for the development of scientific and efficient telerehabilitation services for stroke.

Keywords:
Lower Limb Rehabilitation Robot, Stroke, Home-Based Telerehabilitation

1. Introduction

As a relatively high incidence cerebrovascular disease, stroke is caused by a sudden rupture of a blood vessel in the brain, or by a blockage of a blood vessel that prevents blood from flowing to the brain. Stroke is the second leading cause of death and disability in the world, with over 13 million new cases of stroke each year [1,2]. As China's population ages, stroke is becoming the leading cause of death in China [3]. The incidence of stroke in China is increasing at an annual rate of 8.7%, and the number of people affected is rising year by year, with approximately 80% of survivors having varying degrees of functional impairment. With the rapid development of modern treatment techniques, stroke mortality has decreased significantly, but post-stroke rehabilitation poses additional challenges for rehabilitation workers. Depending on the size and extent of damage to specific parts of the brain, stroke patients will experience varying degrees of functional impairment, including physical impairment [4], cognitive impairment [5], swallowing impairment [6] and even mental impairment. Although it is not possible for modern clinical treatment techniques to reverse damaged nerves, targeted rehabilitation care can be provided to patients to effectively restore their physical functions and improve their quality of life. Appropriate hospital and home-based rehabilitation throughout the prognostic process is an important intervention for stroke patients to return to life [7].

Nonetheless, short-term hospitalisation does not meet the rehabilitation needs of most stroke patients. Due to the high cost of treatment and lack of transport, most stroke patients do not have access to appropriate long-term professional rehabilitation, especially for patients in remote areas and with lower limb dysfunction. There are regional differences in the level of rehabilitation care and a lack of specialist rehabilitation staff, resulting in most stroke patients in developing countries not being able to access appropriate rehabilitation treatment. Assisting stroke patients with home-based telerehabilitation is one of the ways to solve these problems [8].

Telerehabilitation (TR), a derivative of telemedicine, is a technology that provides online rehabilitation services to patients at home based on a combination of communication, computer and information processing technologies [9]. In the middle of the last century, many countries started to apply telerehabilitation systems to provide rehabilitation guidance services to patients with dementia, elderly people in the community and stroke patients, covering many areas such as cognitive rehabilitation, language rehabilitation, swallowing rehabilitation and hand function rehabilitation [10]. Telerehabilitation for stroke includes web-based video guidance technology, virtual reality technology, telerehabilitation training robots and the Internet of Things for home rehabilitation [11]. Most of the rehabilitation training for motor dysfunction in stroke patients is characterised by high intensity, high repetition and task-oriented training, and in recent years the lower limb rehabilitation robot is often used for telerehabilitation.

The exoskeleton rehabilitation robot is a wearable exoskeleton assistive device that can assist patients with walking impairment to walk and gradually restore normal gait, further promoting motor nerve recovery and improving the ability to perform activities of daily living. At the same time, the human-robot interaction technology of the rehabilitation robot helps patients to build up a flexible conscious response during rehabilitation exercises, enhancing the fun of rehabilitation and increasing patients' active participation [12]. In addition, the exoskeletal rehabilitation robot can assist the affected limb and the healthy limb to perform rehabilitation training together, which is conducive to strengthening the connection between the motor limb and the damaged nerve, thus inducing the normalization of the patient’s motor sensation and promoting the early recovery of the function of the affected limb [13]. This paper reviews the current application of lower limb exoskeletal rehabilitation robots in stroke rehabilitation, with the aim of providing a reference for the better use of telerehabilitation technology and the development of scientific and efficient stroke telerehabilitation services.

2. The Clinical Application of a Lower Limb Exoskeleton for Stroke

Lower limb exoskeleton rehabilitation robots have been gradually used since the 1980s for patients with motor dysfunction, particularly walking impairment due to neurological impairment. Combining exoskeletal technology and rehabilitation training, the use of exoskeletal rehabilitation robots for the rehabilitation of the limbs allows the exoskeletal robot to be controlled by the active will of the person, using the robot to drive the rehabilitation movements of the patient [14]. This telerehabilitation approach not only has the advantages of the traditional rehabilitation model, but can also solve many of the problems that exist in traditional rehabilitation training methods. The robot is able to reduce significant human costs and tirelessly meet the training intensity requirements of different patients; it can objectively record objective data on the position, direction and speed of the patient's limb during training, as well as the state of muscle strength recovery. The rehabilitation robot also frees the rehabilitation therapist from heavy training tasks, allowing him to focus on developing individualised treatment plans, analysing patient training data, improving the robot's functionality and optimising training content. In this paper, we review clinical research on the use of lower limb exoskeletal rehabilitation robots to improve motor and balance function, gait and functional independence in stroke patients.

2.1. Clinical Study of a Lower Limb Exoskeleton Rehabilitation Robot in the Motor and Balance Function of Stroke Patients

Motor and balance dysfunction caused by stroke seriously affects patients' independence in daily life and their ability to walk. Lower limb exoskeleton robots have a significant impact on balance and improve the quality of life of stroke patients. The lower limb exoskeleton system helps stroke patients to shift their body weight from the healthy side to the affected side, thus restoring a symmetrical gait pattern and improving balance [15]. It could be useful to promote mobility in persons with stroke owing to mechanisms of brain plasticity and connectivity re-modulation that are specifically entrained by the robotic device, as compared to conventional Rehabilitation. Lower limb exoskeleton robots can activate the lower limb muscles of stroke patients and provide better stability, promoting coordination of lower limb muscle activity, which in turn manifests itself in improved balance [16,17].

Figure 1. *Patient performing gait training with the HAL exoskeleton.*

Figure 2. *Patient performing gait training with the Lokomat system.*

Zheng et al [18] systematically reviewed the effects of rehabilitation robot-assisted training on balance function in stroke patients and showed that rehabilitation robot-assisted training significantly improved balance function in stroke patients, independent of the type of robot, whether it was combined with other interventions, and the duration and intensity of training. Yoshimoto et al [19] used the HAL (hybrid assistive limb), a rehabilitation robot developed at Tsukuba University in Japan, to assist stroke patients with high-speed gait training (20 minutes five times a week for five weeks). The results showed that the HAL-assisted high-speed gait training group had significantly higher Berg Balance Scale scores than the conventional physiotherapy group. Kim et al [20] found that Lokomat combined with conventional physiotherapy showed more significant improvements in static balance, dynamic balance and lower limb function compared to conventional physiotherapy alone. (Figure 1, Figure 2)

2.2. Clinical Study of a Lower Limb Exoskeleton Rehabilitation Robot in the Gait of Stroke Patients

Hemiplegic gait is a typical sequelae of stroke patients. Motor dysfunction in hemiplegic patients is mainly manifested by hypertonia of the flexor muscles in the upper limbs and extensor spasm in the lower limbs. Patients with mild hemiplegia tend to walk with the upper limb flexed and the lower limb straightened, with the paralysed lower limb walking in a half circle. Walking is an important part of the quality of daily life, so it is important to rehabilitate stroke patients to restore normal gait patterns.

2.2.1. Research Based on Kinematic Analysis Methods

Kinematic analysis is a scientific method of studying the temporal and spatial patterns of limb movement during walking. Time-space measurements are commonly used in scientific research, with gait speed, stride frequency, stride length, stride length and foot deflection angle often used as parameters of walking ability. Walking dysfunction in stroke patients is mainly reflected in a significant slowing of gait frequency, stride length and speed, prolonged support time on the affected side and a significant asymmetry in the time-space parameters [21]. Weight loss support is essential for gait rehabilitation. The exoskeleton robot weight loss support system improves trunk stability and allows functional walking training for stroke patients with low muscle strength early in the course of the stroke, significantly improving gait speed and walking endurance. In addition, the weight loss support system helps to prevent the development of abnormal movement patterns by avoiding compensatory and spasticity induced by excessive weight bearing on the limb. The exoskeleton robot system can provide normal gait training patterns and adjust hip and knee range of motion in real time during exercise, which can effectively improve the time-space asymmetry of hemiplegic gait and promote the balance function rehabilitation of stroke patients [22].

Klaske et al [23] compared the Lokomat (developed by Hocoma Switzerland) assisted walk test with a running table walk test in 10 stroke patients over 3 months of age and in 10 healthy controls. The running test showed a significant reduction in single-support phase time on the affected side compared to the healthy side, confirming the temporal asymmetry of gait in stroke patients, while the difference in single-support phase time between the legs was significantly reduced in the Lokomat-assisted walking test, indicating that the Lokomat improves the abnormal gait pattern of stroke patients and facilitates the recovery of walking function. Buesing et al [21,24] conducted several trials of SMA (a wearable exoskeleton stride management assist system) assisted training and functional task specific training (FTST) with a lower limb exoskeleton robot for patients in the post-stroke period. The results showed no significant difference between the SMA group and the FTST group after training, and that SMA training achieved the same training effect as FTST. Stroke patients showed effective improvements in walking speed and motor endurance, and significant improvements in several gait parameters, such as increased gait speed, increased stride frequency, increased bilateral stride length, increased stride length, reduced swing time on the hemiplegic side and reduced double support phase time. The shortening of the swing time on the hemiplegic side indicated an improvement in the patient's temporal asymmetry, and the shortening of the double support phase time indicated a reduction in the patient's balance dysfunction. (Figure 3)

Figure 3. *Honda Stride Management Assist (SMA) Device.*

2.2.2. Research Based on the Muscle Activity Analysis Methods

Electromyography is capable of collecting electrical signals of muscle activity and processing features such as amplitude, frequency and integrated EMG values for muscle activity analysis. Androwis [25] conducted a muscle activity analysis of the lower limbs of patients with acute stroke using the Ekso exoskeleton robot-assisted walking and level walking developed by Ekso Bionics, USA. It was shown that although the level of muscle activation in the healthy and affected leg differed between the two walking conditions, the temporal sequence and trend of muscle activity was similar and patients were able to retain voluntary neuromuscular activity while using the lower limb exoskeleton robot. The lateral and rectus femoris muscles of the affected leg of stroke patients walking with Ekso assisted walking more closely resemble the muscle activity pattern of normal gait. The lower limb exoskeleton robot provides support for the lower limb joints during the stance phase, reducing compensatory muscle activation, improving muscle coordination and reducing the metabolic cost to the body; it ensures adequate ankle dorsiflexion during the swing phase by providing a smooth movement trajectory that activates the anterior tibial muscles in a stable movement environment, reducing foot drop during the swing phase and increasing ankle joint stability. The normal gait pattern provided by the lower limb rehabilitation robot effectively inhibits abnormal hypertonia and spasticity of the lower limb extensor muscles on the hemiplegic side, increases the excitability of the flexor muscle groups and improves foot drop and pronation deformity [26]. (Figure 4)

Klaske [23] compared muscle activity during the gait cycle in stroke patients and healthy subjects with the aid of Lokomat and during running table walking and found that some of the muscles of the lower limb were significantly more active in stroke patients during running table walking, with increased activity of the affected biceps femoris in the single support phase and increased activity of the lateral femoris in the mid-support and swing phases. There was overcompensation of muscle groups and uncoordinated muscle activity during running table walking training. However, lower limb muscle activity was significantly lower in the Lokomat-assisted walking test and this was more pronounced in stroke patients. The guiding force provided by the exoskeleton robot can limit the degree of active participation, with higher guiding force potentially reducing the user's active muscle participation and too low guiding force not ensuring that the patient follows a normal gait trajectory. This on-demand assistance can effectively avoid unnecessary movement restrictions on the lower limb by the robotic exoskeleton system. The Lokomat assisted walking training is therefore personalised with a guide force to ensure active participation and coordinated walking training to improve the gait of the stroke patient. In addition, muscle activity is influenced by other device parameters, such as the walking speed of the exoskeleton robot, in addition to the guiding force, and more in-depth research is needed on how to adjust the individualised parameters to achieve the best training results for stroke patients [28].

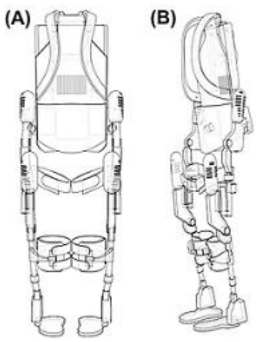

Figure 4. *Frontal and Oblique view of the EksoGT.*

2.3. Clinical Study of a Lower Limb Exoskeletal Rehabilitation Robot in Functional Independence of Stroke Patients

Walking is an important factor in the daily activities of stroke patients, and gait speed is an important indicator of walking ability. By increasing gait speed in stroke patients, lower limb exoskeleton robot-assisted training can improve walking ability, lower limb motor function and balance, and further increase functional independence. Belas [29] et al. randomised 15 stroke patients more than 1 year after onset into a rehabilitation therapist-assisted gait training group and a Lokomat-assisted gait training group for a period of 5 months. The results showed an improvement in the Functional Independent Measure (FIM) in both groups compared to the pre-training period, but there was no significant difference between the two groups. However, Taveggia et al [30] randomised 28 recovering stroke patients to a trial group (Lokomat-assisted walking training) and a control group (conventional walking training) for 5 weeks and found that only the experimental group had a significant improvement in FIM scores at the end of the training and that the experimental group still had higher FIM values than before treatment at follow-up at month 3 after the training. The above studies confirm that the lower limb exoskeleton robot has a definite effect on improving functional independence in stroke patients, even better than conventional walking training, but that this positive effect is maintained for a longer period of time after the training has been stopped needs further study.

3. Discussion

The lower limb exoskeleton rehabilitation robot has been widely used clinically as an efficient method of telerehabilitation training. From the patient's perspective, the use of a lower limb rehabilitation exoskeleton robot for telerehabilitation can correct abnormal gait and effectively improve the overall motor function of stroke patients. From the rehabilitation therapist's point of view, the Lower Limb Rehabilitation Exoskeleton Robot frees the rehabilitation therapist from heavy training tasks and saves a lot of manpower and time costs. It allows rehabilitation therapists to focus on developing individualised treatment plans, improving the robot's functionality and optimising training content, increasing the quality and efficiency of the specialist's work and improving the quality of patient survival. From a societal perspective, it can reduce the cost of rehabilitation services due to the uneven distribution of rehabilitation resources, address the imbalance in the distribution of rehabilitation resources in different regions, further optimise rehabilitation resources, and enable more stroke patients to enjoy high-quality rehabilitation services. However, the exoskeleton rehabilitation robot still has some shortcomings, such as expensive equipment, complex structure and inconvenient operation. With the new generation of rehabilitation medicine, artificial intelligence, new energy and control technology, the lower limb exoskeleton rehabilitation robot will be more dexterous, intelligent, portable, lightweight and personalised in the future, and will carry out more efficient stroke telerehabilitation services.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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