

Engineering Application of Lower Limb Exoskeleton System in Clinical Rehabilitation

Xinyang Zhang *

School of Mechanical Engineering, Taiyuan University of Technology, Taiyuan 030000, China

* Corresponding Author Email: xinyangz813@gmail.com

Abstract. Spinal cord injuries and strokes can severely affect the function of the lower limbs, which in turn reduces people's quality of life. Lower limb function is an important part of daily life, and therefore, clinical treatment of these disorders is aimed at restoring the patient's ability to walk normally. Due to the great potential of lower limb exoskeletons in the clinical rehabilitation of these diseases, the number of studies on lower limb exoskeletons has increased a lot in recent years. However, there are some gaps between the current research and clinical practice of lower limb exoskeletons in the laboratory, and this paper provides some lower limb exoskeletons based on clinical rehabilitation practice to bridge the gap between theory and practice. This review article mentions the advantages and disadvantages of several different driving modes of lower limb exoskeletons, and focuses on the design of rigid electric drive lower limb exoskeletons and their role in clinical rehabilitation. This article compares the rehabilitation methods involved in the lower extremity exoskeleton with traditional treatment methods, and illustrates that the lower extremity exoskeleton can better assist patients in gait recovery in some cases.

Keywords: Exoskeleton, gait rehabilitation, limber.

1. Introduction

Spinal cord injury is a neurological disorder that often causes varying degrees of loss of motor function, resulting in the loss of the patient's normal ability to walk. At the same time, patients may also lose the sense of touch, temperature, and pain in the lower extremities. And due to long-term lack of exercise, the muscles of the lower limbs will gradually atrophy, and sometimes involuntary spasms will occur. Stroke is a cerebrovascular disease that may cause motor dysfunction such as paralysis or abnormal gait similar to spinal cord injury [1], loss of perception of sensation. These effects are often mitigated by long-term rehabilitation interventions with physical therapy, occupational therapy, and assistive devices. Training muscular dystrophic lateral sclerosis (ALS) is a progressive neurodegenerative disease characterized by gradual weakness and atrophy of muscles throughout the body.

Given the prevalence of these diseases and the challenges faced by patients, lower extremity exoskeletons can play a role. By mimicking their natural gait [2], the lower extremity exoskeleton system can provide gait support for these spinal cord injury patients, allowing them to walk normally and improve their quality of life. In turn, it can speed up the rehabilitation process of patients with spinal cord injury. For stroke patients, the lower extremity exoskeleton system can provide long-term, repetitive gait training and help them achieve a more symmetrical gait while walking [3], thereby promoting neurological remodeling and recovery of motor function.

However, although a large number of studies have designed a relatively complete lower limb exoskeleton, we can see that in the actual patients with the above cases can only achieve independent mobility in wheelchairs, rather than the lower limb exoskeleton designed in the laboratory, which shows that the lower limb exoskeleton is not widely used, which is not only because of the high cost, but also shows that the research of the lower limb exoskeleton is not really closely coordinated with the actual clinical practice.

The aim of this article is to systematically evaluate the existing documentation and analyze the rehabilitation effects of lower limb exoskeletons in clinical practice in different diseases. First, the advantages of lower extremity exoskeletons in spinal cord injury and stroke rehabilitation were

introduced [4, 5], and the potential role of lower extremity exoskeletons in muscular atrophic lateral sclerosis was explored [6].

2. Related Works

2.1. Lower Extremity Exoskeletons

In recent decades, many lower limb exoskeletons that are driven in different ways have been designed for various purposes, such as medical rehabilitation, industry and its manufacturing, military and rescue-, sports and training, and elderly care. In the process of these exoskeleton research, the design and research of exoskeletons in the field of medical rehabilitation are endless, because exoskeletons can be used as a key rehabilitation tool for occupational therapists and physical therapists. Especially in recent years, due to the popularity and maturity of 3D printing technology, the development progress of exoskeletons has been greatly promoted.

2.1.1. Classification of lower limb exoskeletons

The lower limb exoskeleton can be divided into electric drive, hydraulic drive, pneumatic drive, mechanical spring drive and hybrid drive according to the drive mode. Each of these drives has its own advantages and disadvantages, but in the field of medical rehabilitation, electric drives are often the most commonly used option due to the need for precise control and adaptability. Hydraulic and pneumatic drives may also be used in some specific situations, but electric drives are the main choice because of their mature technology and wide range of applications.

2.1.2. Classification of electrically driven lower limb exoskeletons

In the design of the electric drive exoskeleton, we can see two different design concepts, rigid structure and flexible structure. Each of them has its own advantages and limitations, and is suitable for different fields.

The flexible exoskeleton is characterized by flexible structure, comfortable to wear, relatively light weight, and can adapt well to the shape and movement of the human body, reducing the restrictions on the natural movement of the human body. However, due to the characteristics of flexible materials, it is determined that it can not bear large loads, and at the same time has a short service life, and long-term use under high stress conditions, flexible materials are easy to wear and lose elasticity. Due to the influence of forces, flexible materials may be deformed, making it impossible to achieve high-precision operation.

Rigid exoskeletons are characterized by a robust structure that allows for precise control and, due to the high strength of the material, can carry heavy loads. These properties determine that the exoskeleton of this structure can maintain the stability of the structure during movement, reducing the risk of deformation. It is suitable for use in harsh environments and can work normally under high stress conditions for a long time. And as long as the size is customized, the rigid structure can accurately transfer the power of the electric drive to the wearer's joints and limbs, providing strong and effective assistance. However, most of the current rigid materials are heavier, which makes the overall weight of the rigid exoskeleton relatively large, and in some cases may make the human body bear a large load. Combining and comparing the design of two motorized exoskeletons, the lower limb exoskeleton is required during the rehabilitation process of spinal cord injury, stroke, and amyotrophic lateral sclerosis:

Strong support and stability to help them perform standing, walking and other rehabilitation exercises. Even in the case of complete loss of lower limb motor function, some basic movements can be achieved with a rigid lower limb exoskeleton.

For the precise control of the movement state, due to the structural characteristics of the rigid exoskeleton, combined with the current advanced control methods, the rigid exoskeleton can realize the personalized requirements of the patient to carry out precise control requirements, help the patient to gradually enhance muscle strength, and restore normal exercise ability.

Good durability, due to the use of high-strength materials, rigid exoskeletons usually have a long durability and can withstand long-term mechanical compliance as well as frequent use, and because these related diseases often require long-term rehabilitation, there are high requirements for durability.

2.1.3. Summary of the exoskeleton of the lower limb with rigid electric drive

Some lower limb exoskeleton designs was shown in the Figure 1

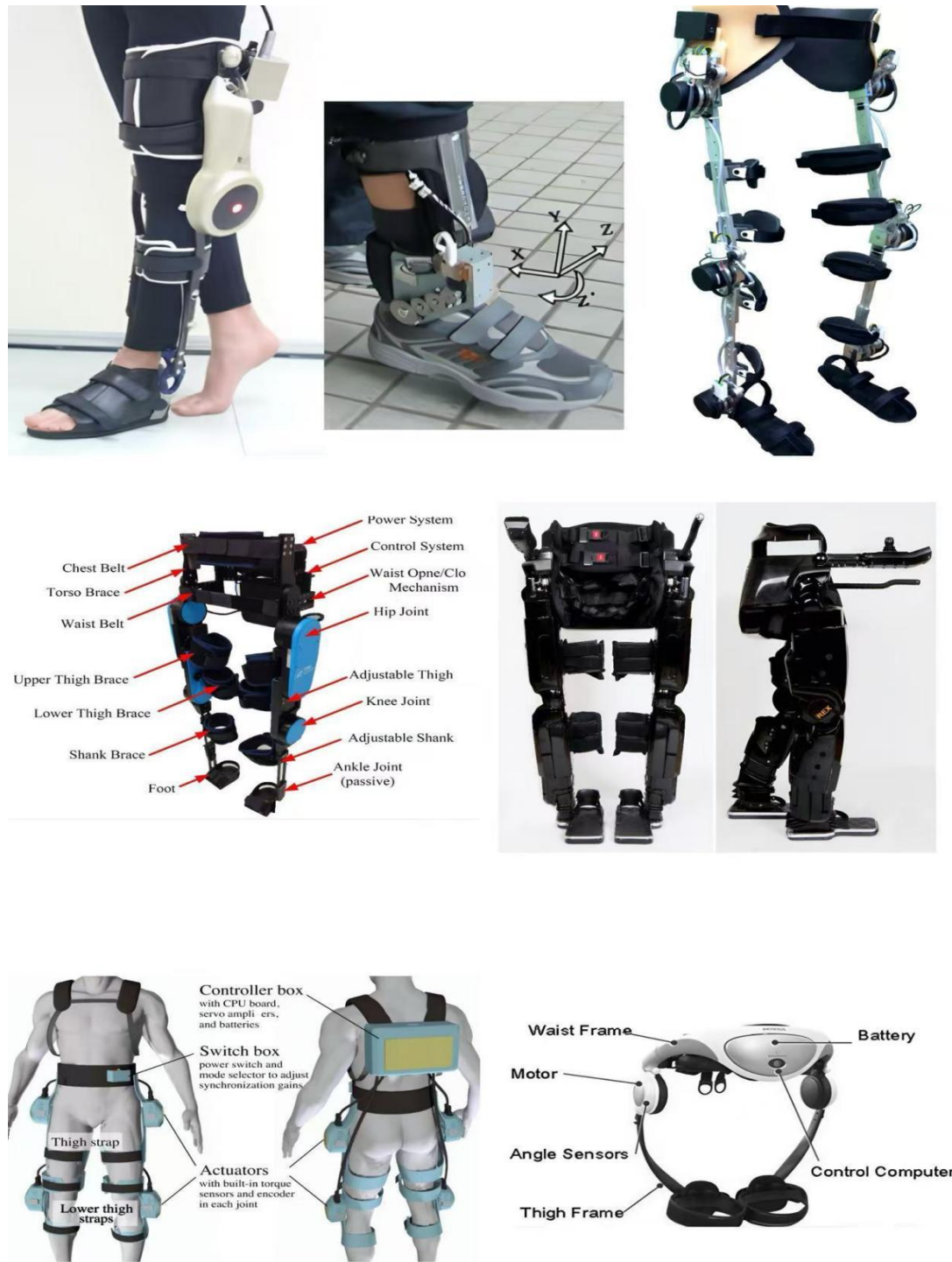


Fig 1. Some representative lower limb exoskeletons [2, 3, 7-11].

This review summarizes seven studies published by different authors over the design of rigid electrically driven lower limb exoskeletons and details their characteristics. These exoskeletons are used for specific diseases in the medical field, with four exoskeletons designed to help stroke patients rehabilitate and three exoskeletons for spinal cord injury patients. See Table 1 for detailed information on exoskeleton characteristics.

Table 1. Main technical aspects of the exoskeletons.

exoskeleton	Actuator	sensor	Control methods	Gait pattern	weight	The user's weight range (kg)	The user's height range (cm)	Continuous use time	peculiarity
H2 [2]	electric	JA, JT, IT, FF	Orbital interaction	Button	12	100	145–195	6	–
KAF O [7]	electric	JA, JT	orbit	–	3	100	150-190	4	–
SM A [8]	electric	JA, JT	Orbital interaction	Motion intent	2.7		140-200	1	–
Yeu ng [9]	electric	FF, Acc, Ori	–	Foot lift of	1	–	–	5	The battery is mounted on the waist
REX [10]	electric	–	orbit	Joystick	38	100	146–195	1	Joystick and three-button keypad
ITRI [3]	electric	–	orbit	Button	20	–	–	–	–
cura ca [11]	electric	JA, JT, IT	Orbital interaction	Motion intent	5.8	–	–	–	–

2.2. Review of Clinical Methods

After spinal cord injury and stroke, especially in cases that affect the lower limbs, patients will experience significant discomfort as well as deficits in motor function, which seriously affects their normal life. The main goal of lower limb rehabilitation is to restore normal walking ability as well as improve the strength of the lower limbs, and only when these goals are achieved can the patient perform activities of daily living, such as walking, climbing stairs, standing, etc. This article describes the importance of less responsiveness in stroke patients and discusses the significance of changes in gait speed for patients [12]. Depending on the person's clinical manifestations, doctors usually take different rehabilitation measures. Common methods include gait training, strength and endurance training, range of motion (ROM) and stretching, and functional electrical stimulation.

Gait training is designed to restore the patient's ability to walk, improve the coordination and balance of the lower limbs, and can reduce the risk of falls to a certain extent, promoting blood flow throughout the body.

Strength and endurance training, which enhances the strength and endurance of the lower limbs, allows patients to carry out long-term rehabilitation training and reduces fatigue. At the same time, it can enhance the stability of the lower limbs, and the improvement of muscular endurance also helps to promote other rehabilitation exercises.

Range of motion (ROM) and stretching are designed to maintain the range of motion of the joint and to prevent muscle contractures. Strokes and spinal cord injuries can cause muscle stiffness, which can be largely relieved by stretching, promoting muscle and joint flexibility.

Functional electrical stimulation uses electrical stimulation to activate the paralyzed muscles and maintain their normal function.

Rehabilitation is a combination of treatments that are tailored to each patient's individual wishes and the development of the disease to ensure the effectiveness of the treatment.

During rehabilitation, many patients with spinal cord injuries and strokes require adaptive devices such as orthoses, splints, and more. Most of the purpose of these devices is to prevent joint contractures, enhance muscle function, and help restore mobility. For example, functional electrical stimulation can be used in conjunction with gait training equipment to stimulate muscles for standing and gait training [13].

2.3. Exoskeleton vs. Conventional Means

Lower limb exoskeletons and traditional rehabilitation methods have their own advantages and application environments. In the recovery process of stroke and spinal cord injury, this work found that there are some obvious and important differences between the two by reading the relevant literature.

2.3.1. Patient populations of applications

During the recovery process, the rehabilitation needs of patients vary depending on the degree of injury to the lower extremities.

The applicable group of traditional rehabilitation methods:

Patients with moderate to mild lower extremity functional impairment: Traditional rehabilitation methods are well suited to this population, which usually has some ability to move autonomously. After a stroke or spinal cord injury, their lower limb function is impaired, their muscles are atrophied, their coordination is reduced, but they are not completely unable to exercise. Traditional rehabilitation methods such as gait training, strength and endurance training, functional electrical stimulation, etc., can effectively promote the recovery of muscles in this group of people, and realize that they can easily complete various activities in daily life more quickly.

Patients with the ability to move on their own: Traditional rehabilitation methods rely on the active participation of the patient himself. For such patients who have the ability to move independently, appropriate gait training and strength and endurance training can be used to strengthen and tolerate the muscles to improve the speed of recovery.

Patients with early rehabilitation from stroke and spinal cord injury: In the early stages of treatment, the primary goal of rehabilitation at this stage is to maintain the range of motion of the joints, maintain the activity and strength of the muscles, and prevent further deterioration. With the help of a team of therapists, such patients will first undergo appropriate rehabilitation exercises such as physical therapy and gait training to gradually recover and lay the foundation for the next stage of treatment. Applicable groups for lower limb exoskeletons: Compared with traditional rehabilitation methods, lower limb exoskeletons are more suitable for some more severe patients. Spinal cord injury and stroke [14, 15].

Patients with severe lower limb weakness or even paralysis: For these patients, traditional rehabilitation methods may not provide adequate support and precise gait control, especially in this case, the lower extremity exoskeleton. Due to its material and structural properties, the rigid lower limb exoskeleton has high strength and support, enabling patients to stand and walk, and to achieve multiple and precise gait training, which plays a vital role in restoring lower limb function and promoting cardiovascular health.

2.3.2. Healing effect

In the course of rehabilitation for patients with stroke and spinal cord injury, there are significant differences in the effectiveness of traditional rehabilitation methods and the use of lower extremity exoskeletons [15, 16]. However, their effectiveness depends on the severity of the patient's condition, the degree of cooperation of the patient himself, and the intensity of training. In contrast, the use of lower extremity exoskeletons to help patients recover has a more obvious advantage. As a new type of rehabilitation tool, the exoskeleton can stop providing stable and suitable auxiliary force during use, helping patients to carry out boring repetitive gait training, thereby promoting nerve plasticity and speeding up the rehabilitation process. Compared with traditional rehabilitation methods, the use of more mature lower limb exoskeletons plays a more critical role in gait symmetry, uniform gait

speed and equal stride length. In practical clinical application, the rehabilitation team will determine a personalized solution based on the actual situation of the patient, usually traditional rehabilitation methods and the cooperation of exoskeleton equipment, so as to maximize the rehabilitation effect. The introduction of flexible materials and structures, such as soft robotics, can provide more natural locomotion capabilities and reduce the limitations of rigid structures.

3. Discussion

3.1. Existing Issues

Based on the extensive review of the current clinical and lower limb exoskeletons, for now, there are still problems such as small sample size, insufficient widespread dissemination, and immature technology, and there are obvious limitations.

Patients are unable to act as they would like when using it. One. With a lower number of degrees of freedom, most motorized exoskeletons are primarily focused on supporting anterior-posterior movements of the hip, knee, and ankle joints, as this is a key need for gait rehabilitation and walking assistance. Adding more degrees of freedom, such as lateral or rotational motion, can significantly increase design complexity, control difficulty, and cost. Two. Unable to accurately identify the patient's intentions and provide timely feedback. a. We can improve this problem by improving the connections between the joints, such as using more advanced spherical connections that allow for more directional movement. b. The introduction of flexible materials and structures, such as soft robotics, can provide more natural locomotion capabilities and reduce the limitations of rigid structures. c. Increase the accuracy of the identification system.

Lack of perception of the current environment and inability to adjust the movement of the exoskeleton of the lower limbs according to the environment. Stability in the event of interference via Robust Markov Torque Controller [17]: a. Add contextual perception sensors, such as accelerometers and gyroscopes, pressure sensors, distance sensors (such as lidar or ultrasonic sensors), and contextual perception equal. b. Develop more intelligent control algorithms that can adjust the movement trajectory of the exoskeleton in real time to bring it closer to the natural gait.

3.2. Solution

Improvement plans for relevant content [18]: Hardware improvements: An elastic rotary actuator is designed to introduce a spring between the motor shaft and the mechanical joint, so that the connection between the patient and the exoskeleton is softer, the impact load is effectively relieved, and the device allows a certain degree of compliance throughout the movement recovery process, that is, it can be adjusted appropriately according to the actual movement of the patient, improving freedom. Elastic rotary actuators was shown in the Figure 2.

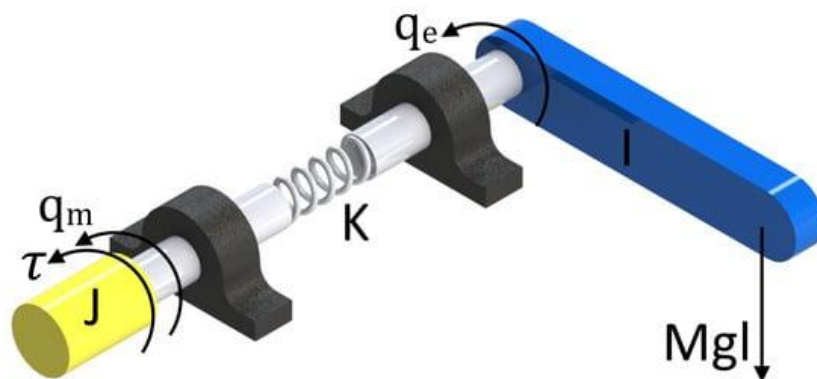


Fig 2. Elastic rotary actuators [18].

Algorithm improvements: The algorithm identifies the user's movement intent by analyzing electromyography (EMG) and plantar pressure (Baropodometry) sensor signals. After preprocessing,

feature extraction, and classification, these signals are converted into specific motion commands that drive the exoskeleton to perform corresponding actions.

The performance of traditional fixed gain control strategies decreases when the human dynamics change, so a better representation of the human dynamics is needed. Therefore, we can propose a robust Markov torque controller to help improve the impedance to maintain a stable interaction with the environment.

The process can be divided into (see Figure 3):

Data acquisition: Input: Real-time collection of human motion data and exoskeleton state data through sensors (such as force sensors, position sensors, acceleration sensors, etc.) on the lower limb exoskeleton robot. Output: A collection of raw data, including force values, positions, accelerations, and more.

Data preprocessing: Process: Preprocessing operations such as filtering and denoising the collected raw data to improve data quality. Output: A collection of preprocessed data.

Interference detection: Procedure: Use preset algorithms or thresholds to detect interference on the preprocessed data to determine whether there are abnormal signals or interference. Decision point: Did interference be detected? Yes: Go to the Interference Identification and Classification step. No: Continue data collection.

Interference identification and classification. Procedure: Combined with the gait phase recognized by the Markov chain model, the type and intensity of the detected interference were identified and classified. Output: Interference type, intensity, and current gait phase information.

Impact assessment. Procedure: According to the type and intensity of interference, as well as the current gait phase information, the degree of impact of interference on the robot-assisted rehabilitation effect of lower limb exoskeleton was evaluated. Output: Impact assessment report.

Resistance strategy selection. Procedure: Based on the impact assessment report, the appropriate resistance strategy was selected in combination with the robust Markov impedance control method. Possible strategies include adjusting control parameters, switching control modes, enabling alternate control algorithms, etc. Output: Selected resistance strategy and its implementation parameters.

Resistance measures were implemented. Procedure: According to the selected resistance strategy and its implementation parameters, adjust the control algorithm and parameters of the lower limb exoskeleton robot to implement resistance measures. At the same time, the status of the system is monitored in real time to ensure the effectiveness of resistance measures. Output: Post-implementation system status data.

Effect verification and feedback. Procedure: The system state data after the implementation of resistance measures were validated to evaluate whether the robot-assisted rehabilitation effect of the lower limb exoskeleton was restored or improved. Based on the results of the validation, the resistance strategy can be adjusted or data collection and monitoring can be continued. Output: Validation report and feedback.

End of process. The process is terminated when the interference has been eliminated and the robot-assisted rehabilitation effect of the lower limb exoskeleton is stable. If the interference persists or the assisted rehabilitation effect is not fully recovered, the feedback is repeated back to the "data collection" step to continue processing.

Notes: Throughout the process, it is important to ensure the accuracy and real-time nature of data collection, as well as the accuracy of interference detection and identification. The selection and implementation of resistance strategies need to be flexibly adjusted according to the actual situation and the type of interference.

Effect verification and feedback are important links to optimize the process and improve system performance, and it needs to be taken seriously and the strategy should be adjusted in time. If the interference persists or the system performance is not fully restored, the cycle continues back to the Monitor & Detect step.

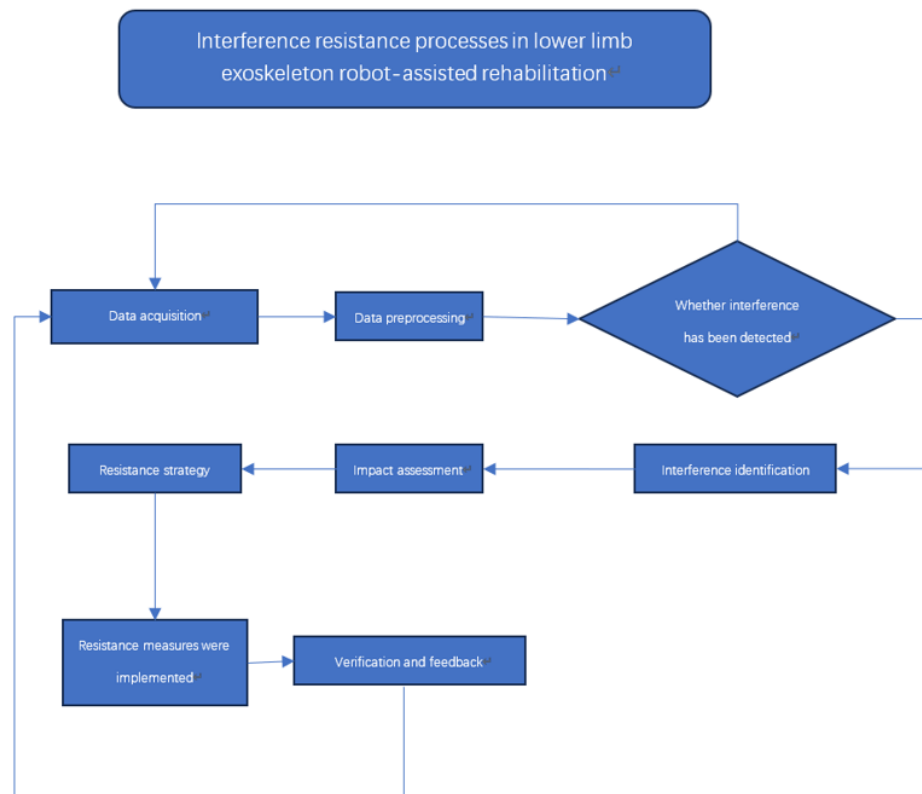


Fig 3. Interference resistance processes in lower limb exoskeleton robot-assisted rehabilitation (Photo credited: Original).

4. Conclusion

In this article, this study delve into the intricate design of electrically powered rigid lower extremity exoskeletons and explore their profound clinical implications, aiming to enhance the walking capabilities of patients. Since the inception of the concept of lower limb exoskeletons over two decades ago, there has been extensive design iteration and rigorous clinical validation. The wearable lower limb exoskeleton has emerged as a pivotal tool in the rehabilitation process for individuals suffering from spinal cord injuries and those who have experienced strokes. These devices have shown remarkable potential in aiding patients to regain mobility and independence in their daily lives.

Despite the significant progress made, the current generation of lower limb exoskeletons is not without its limitations. Some of the notable drawbacks include a limited number of degrees of freedom, which can restrict the natural range of motion, and a relatively bulky design, which may hinder comfort and ease of use. However, the article suggests that these issues are not insurmountable. Solutions are within reach, as discussed in the article, through the enhancement of the mechanical structure, which could lead to more flexible and lightweight designs, as well as the refinement of the control algorithms that govern the exoskeleton's movements. These advancements could potentially lead to exoskeletons that are more intuitive and responsive to the user's needs, thereby further improving the quality of life for those who rely on these devices for mobility assistance.

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