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Research Progress and Key Technology Analysis of Lower Limb Rehabilitation Robots

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Abstract. In China, there is a large number of patients with lower limb movement disorders and limited medical resources, while the market for rehabilitation technologies is growing rapidly. The technology of lower limb rehabilitation exoskeleton robots has been successfully applied and shows significant development potential. Both domestic and international research on lower limb rehabilitation exoskeleton robots focuses on the design aspects of comfort, bionics, lightweight construction, and safety. Notable domestic and international companies and universities are committed to enhancing personalization and human-machine interaction experiences, reducing costs, and expanding application fields. A preliminary analysis of the forward and inverse kinematics of lower limb rehabilitation exoskeleton robots has been conducted to derive the kinematic equations and velocity Jacobian matrices, facilitating better optimization of the robot's control algorithms. Existing control algorithms are diverse, including position-based, force information-based, bioelectric signal-based, and intelligent control strategies, each with its own advantages and disadvantages. Among these, control algorithms that integrate artificial intelligence and other cutting-edge technologies hold the most promise. As the aging population continues to grow, this technology is expected not only to play a role in rehabilitation therapy but also to expand into other areas, such as assistive walking, along with the optimization of mechanisms and the evolution of control algorithms.

Keywords: Lower Limb Rehabilitation Robots, Exoskeleton Robots, Kinematic Analysis, Interactive Control.

1. Introduction

In 2011, China had 85.02 million people with disabilities[1], including 25.18 million with severe disabilities and 59.84 million with moderate or mild disabilities. Medically, spinal cord injury is a significant cause of paralysis, as the spinal cord is part of the central nervous system and controls limb movement. Currently, this type of injury cannot be restored through surgical intervention. According to the "2023 Report on the Quality of Life and Disease Burden of Spinal Cord Injury Patients in China"[2], there are over 3.74 million spinal cord injury patients in the country, with 90,000 new cases each year. As the population ages and living standards improve, the number of people with mobility impairments is sharply increasing, affecting their normal lives. According to the "2024 Report on Aging in China," the proportion of people aged 65 and older will continue to rise over the next 70 years, leading to a growing number of individuals with mobility challenges. China also has the highest incidence of strokes in the world. According to the "2023 Report on Stroke Prevention and Treatment in China", there are

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12.42 million people aged 40 and above currently living with stroke, and the affected population is becoming younger. Approximately 40 million elderly individuals are gradually losing their ability to walk. This large number of people with impaired mobility requires a significant number of rehabilitation therapists; however, the number of rehabilitation professionals in China is limited and unevenly distributed, and the workload for rehabilitation doctors is high. Therefore, new methods are needed to change this situation.

With the emergence of robots, people are gradually replacing human labor with machines for certain tasks. Robots can perform repetitive mechanical work with high intensity and, compared to humans, exhibit greater accuracy and efficiency. For patients with impaired motor functions, a range of specialized robots has also been developed. Lower limb rehabilitation exoskeletons can alleviate the burden on rehabilitation therapists, improve the efficiency and effectiveness of rehabilitation training, and collect real-time data to assess training outcomes[3]. The annual demand for lower limb rehabilitation training equipment reaches as high as 350,000 units, yet the current market offers fewer than 20,000 units[4]. Research on exoskeletons in China began only after 2003, and in recent years, the market for exoskeleton robots in China has grown rapidly. The market size increased from 3 million yuan in 2016 to 440 million yuan in 2021, achieving a compound annual growth rate (CAGR) of 171.19%. It is projected that by 2028, the market size for exoskeleton robots in China may reach 2.4 billion yuan, with an expected CAGR of about 50% from 2023 to 2028, indicating significant development potential.

2. Current Research Status of Lower Limb Rehabilitation Robots

2.1. Domestic Research Status

A team of researchers from the School of Artificial Intelligence at the University of Chinese Academy of Sciences has developed a lower limb rehabilitation robot. This robot employs a novel method for measuring human-machine interaction forces, significantly enhancing the safety and effectiveness of gait training (Figure 1(a))[5]. The National Key Laboratory of Robotics and Systems at Harbin Institute of Technology published the latest research on lower limb orthopedic rehabilitation robots on ELSEVIER. This new lower limb exoskeleton, named J-Exo, is designed to assist the elderly in climbing stairs and squatting. Inspired by elderly individuals' use of canes, the leg actuators of this exoskeleton utilize a linear telescoping mechanism to accommodate wearers of different heights (Figure 1(b))[6]. The research at Beihang University focuses on a lower limb rehabilitation robot system based on brain-inspired Central Pattern Generators (CPG) (Figure 1(c))[7]. Fourier Intelligent's exoskeleton robot, the Fourier X1, represents an innovation in Fourier's product line. It is reported that the pricing aims to reduce costs to 1/3 to 1/5 of similar foreign products. In terms of intelligence, it incorporates an AI system to identify and analyze user intent. Moreover, its wearable product weighs less than 18 kilograms, whereas similar foreign products weigh at least 20 kilograms (Figure 1(d))[8].

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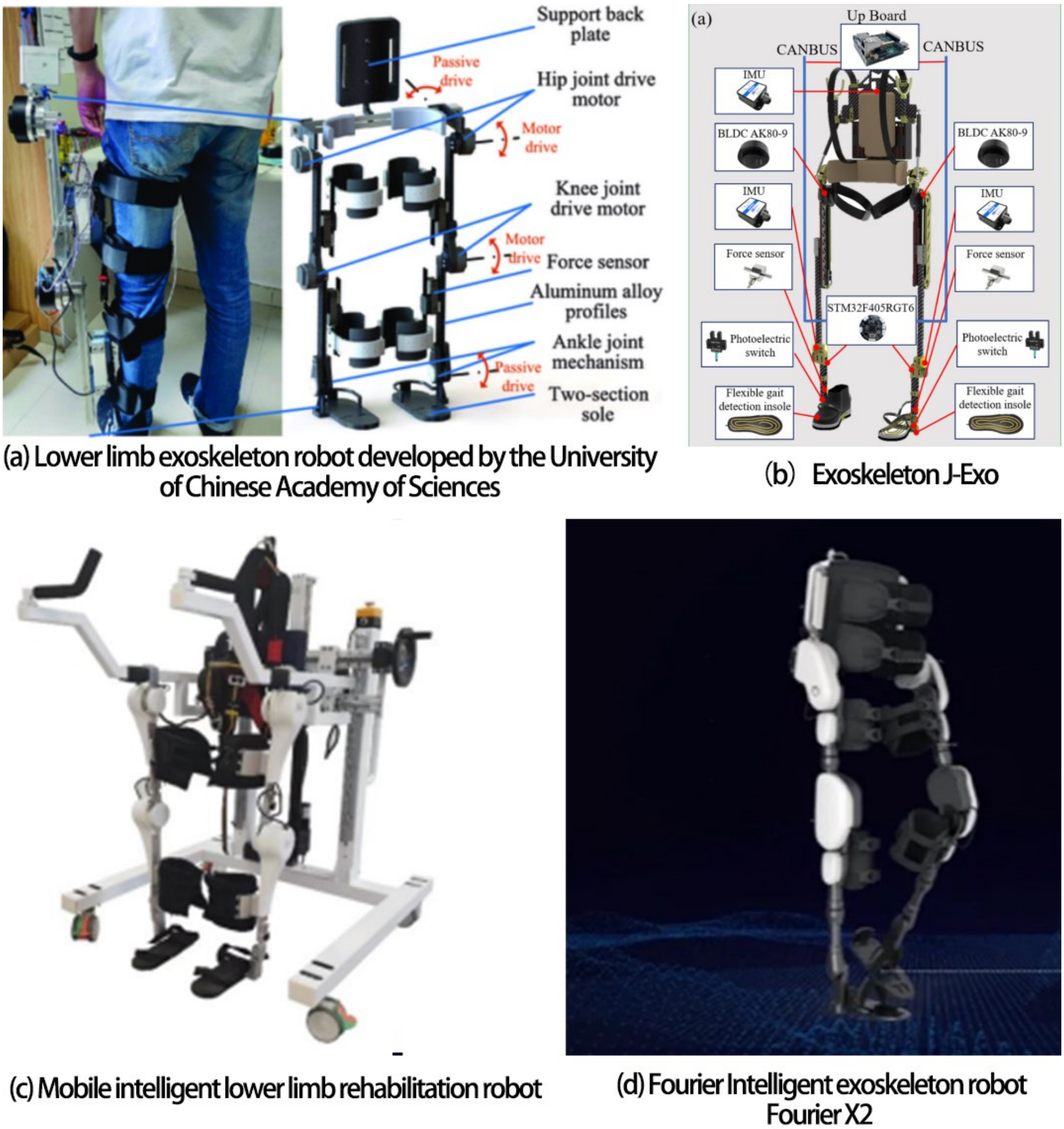

Figure 1. Domestic lower limb rehabilitation robots.

2.2. International Research Status

The ReWalk robot from Israel is primarily designed to assist patients with lower limb paralysis in standing and walking again. ReWalk is the first exoskeleton device that uses tilt sensors for autonomous walking. Its unique mechanism allows users to initiate walking by leaning their upper body forward and to achieve continuous walking by repeating this process. The ReWalk system consists of a wearable exoskeleton with joints, a series of sensors, and a control system that provides power support for knee and hip movements. Its powerful central processing system and high-precision sensors continuously detect subtle changes in center of gravity and adjust movement accordingly, mimicking the user's natural gait and providing an appropriate walking speed. This technology enables even quadriplegics to walk independently with the system, giving them the sensation of using their own legs (Figure 2(a)) [9].The HAL (Hybrid Assistive Limb) wearable robot from Japan is designed for easy donning and can be used by various patients. It offers different shoe sizes and can be adjusted based on waist size and stride length. Through various detailed adjustments, HAL provides a sense of safety by enveloping the patient’s body, facilitating rehabilitation training. During training, each patient has independent data management, allowing them to intuitively understand rehabilitation outcomes and further optimize training plans through a dedicated system platform. HAL utilizes active training; while walking still relies on the assistance of the robotic exoskeleton, the control comes not from the machine itself but from signals emitted by the patient's brain. By stimulating neural pathways, it gradually reconstructs the connection between the brain and muscle movements, achieving independent walking (Figure 2(b))[10]. The EksoNR exoskeleton robot from Ekso Bionics in the United States is one of its flagship products. This device has received 510(k) approval from the U.S. Food and Drug Administration (FDA) and is used for the rehabilitation of patients with multiple sclerosis (MS). It was approved for stroke and spinal cord injury rehabilitation as early as 2016 and received indications for acquired brain injury (ABI) in 2020. It is the first device in its category to obtain stroke indications and is the only exoskeleton with ABI indications, pioneering rehabilitation treatment for MS patients (Figure 2(c))[11].

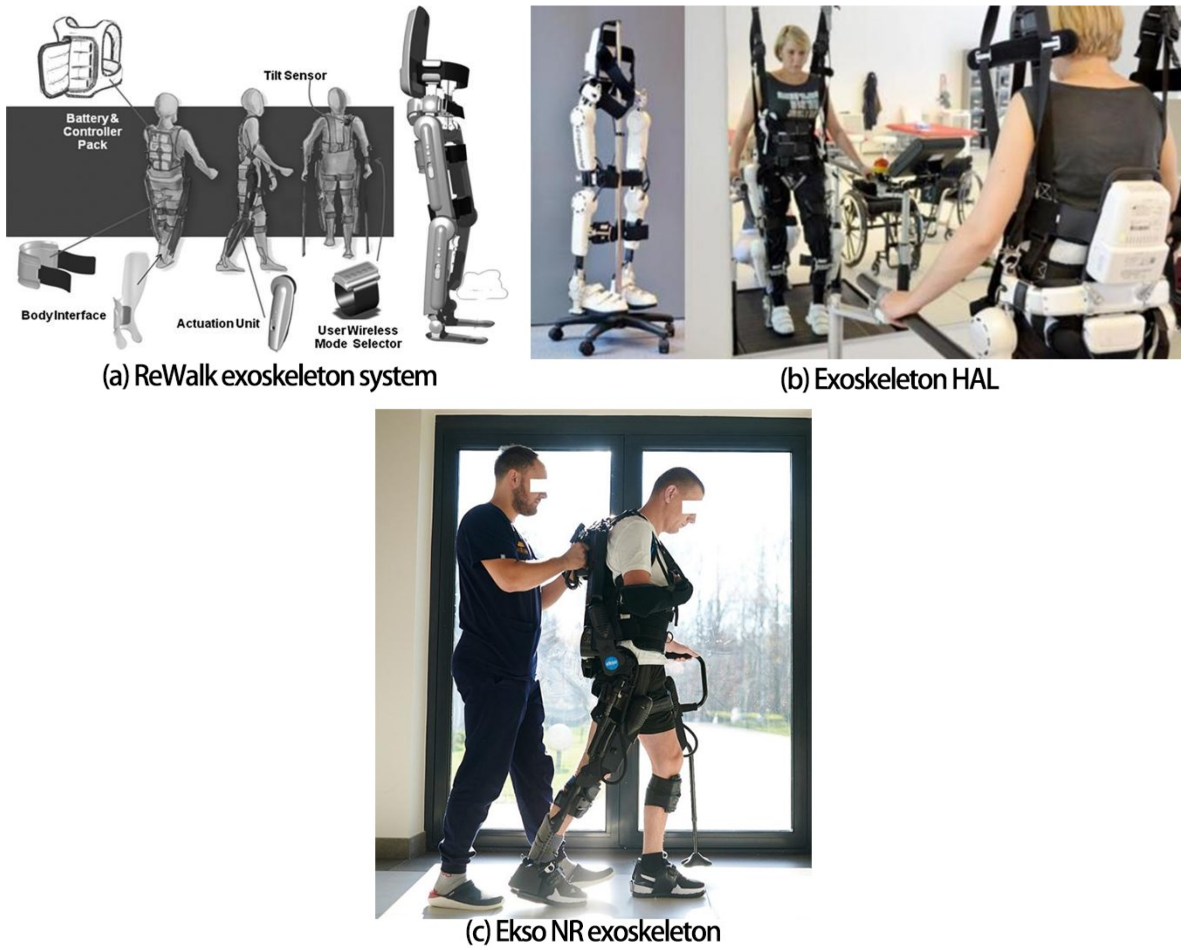

Figure 2. International lower limb rehabilitation robots.

3. Structural Design Features of Exoskeleton Robots

Exoskeleton robots exhibit strong adaptability to the human body and environment, minimal human-machine interference, high biomimicry, and comfortable wearability. They are constructed from lightweight, high-strength, flexible, non-toxic, and environmentally friendly materials, ensuring safety. While ensuring functionality and safety, the structural design of exoskeleton robots aims to simplify by eliminating unnecessary components and redundant structures. Furthermore, by optimizing layout and connection methods, the overall weight and energy consumption of the device can be further reduced. The design incorporates degrees of freedom tailored to different needs, length adjustments for various body types, and buffer designs to minimize energy consumption, ensure safety, and extend the lifespan of the equipment. Safety features include physical connections between humans and machines, information interaction, traditional mechanical structures combined with biomimetic design for joints, and emergency protection mechanisms. These mechanisms are critical to preventing injuries to operators due to unforeseen circumstances during use. For example, if the device detects an abnormal state or receives an emergency stop signal, it must quickly cut off the power source and lock all joints to ensure user safety.

In the study of lower limb rehabilitation exoskeleton robots, most hip and knee joint assistive robots are primarily based on two-link robotic structures. The simplicity of two-link robots makes them convenient for analysis, so the following section will conduct kinematic analysis based on the two-link robot model.

4. Kinematic Analysis of Exoskeleton Rehabilitation Robots

Lower limb rehabilitation exoskeleton robots can be viewed as systems composed of joints and links. Therefore, during research, they can be abstracted and simplified. When studying the motion of exoskeleton robots, the joint positions and the end-effector positions are two crucial parameters. Formulating these parameters allows for better optimization of control and improves the effectiveness of the robots. Among lower limb exoskeletons, the two-link robot is the most representative model.

4.1. Forward Kinematics Analysis

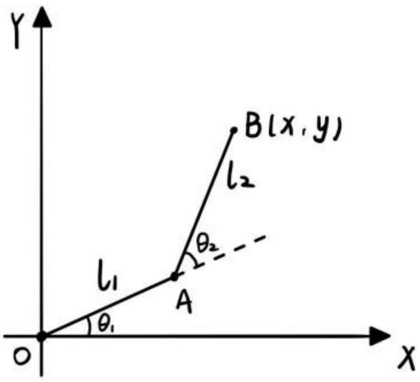

Figure 3. Kinematic Diagram of the Lower Limb Exoskeleton Robot.

The two-link robot can be abstracted as shown in Figure 3, where points A and O represent two joints, l_1 and l_2 are the links, and θ_1 and θ_2 are the joint variables.

When the joint angles are known, the end-effector position (x, y) can be calculated.

$$\begin{cases} x = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ y = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \end{cases} \tag{1}$$

4.2. Inverse Kinematics Analysis

In certain situations, when the robot's end-effector position (x, y) is known, it is also necessary to calculate the joint angles of the robot. This process is crucial for understanding how the robot adjusts its joint angles based on the target position, which can enhance control efficiency, optimize robot design, and support real-time control. The two-link robot can be abstracted as shown in Figure 4.

Using the forward kinematics formulas, the values of θ_1 and θ_2 can be derived.

$$\theta_2 = \arccos \frac{x^2+y^2-l_1{}^2-l_2{}^2}{2l_1 l_2} \tag{2}$$

$$\theta_1 = \arctan \frac{y}{x} - \arccos \frac{l_1{}^2+x^2+y^2-l_2{}^2}{2l_1\sqrt{x^2+y^2}} \tag{3}$$

4.3. Velocity Jacobian Matrix of the Two-Link Robot

By applying the forward kinematics to determine the relationship between the end-effector position and the joint angles θ_1 and θ_2, differentiating Equation (1) with respect to time, we can derive the mapping relationship between the robot's joint angles and positions. This allows us to express the relationship between the joint velocities and the end-effector velocities for the two-link robot.

Starting from the known end-effector position, we can express it in matrix form:

$$\begin{bmatrix} dx \\ dy \end{bmatrix} = \begin{bmatrix} -l_1 \sin\theta_1 - l_2 \sin(\theta_1 + \theta_2) & -l_2 \sin(\theta_1 + \theta_2) \\ l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) & l_1 \cos(\theta_1 + \theta_2) \end{bmatrix} \begin{bmatrix} d\theta_1 \\ d\theta_2 \end{bmatrix} \tag{4}$$

Let

$$J = \begin{bmatrix} -l_1 \sin\theta_1 - l_2 \sin(\theta_1 + \theta_2) & -l_2 \sin(\theta_1 + \theta_2) \\ l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) & l_1 \cos(\theta_1 + \theta_2) \end{bmatrix} \tag{5}$$

This can be simplified into the formula $dM = Jd\theta$, differentiating with respect to time on both sides:

$$v = J(q)\omega \tag{6}$$

5. Control Strategies for Lower Limb Exoskeleton Robots

With over 60 years of development, control methods for lower limb exoskeleton robots can be broadly categorized into four types: 1. Position-based control, 2. Force information-based interaction control, 3. Bioelectrical signal-based interaction control, and 4. Intelligent control. Position-Based Control is the simplest method, which involves precise gait planning to guide the exoskeleton robot’s movements, enabling it to assist patients in physical activity. Force Information-Based Interaction Control monitors the interaction forces between the user and the robot to control its actions. Compared to position-based control, it offers greater compliance. However, variations in force require precise real-time monitoring, necessitating the deployment of numerous sensors. Bioelectrical Signal-Based Interaction Control captures electrical signals generated by the body during movement or preparatory actions to predict motion. It effectively addresses system lag issues, but the accuracy of electrical signal measurement and feature extraction still needs optimization. Intelligent Control integrates artificial intelligence to better manage nonlinear systems, enabling adaptive control of the robot. It allows for iterative learning and continual optimization of control algorithms.

6. Conclusion

This paper investigates the conditions of domestic patients with mobility impairments, analyzing the causes of lower limb dysfunction and the value of lower limb rehabilitation exoskeleton robots for these patients. To clarify the market demand and development trends for lower limb rehabilitation exoskeletons, a survey of the domestic market was conducted, summarizing the research background. To identify the technological features of lower limb rehabilitation exoskeletons, existing domestic and international models were researched and analyzed, focusing on cutting-edge technologies. Simplifying the models of these exoskeletons is crucial for studying their kinematics and control strategies. This paper reasonably simplifies the complex mechanisms of lower limb rehabilitation exoskeletons, retaining key joints and components. The forward and inverse kinematics were then analyzed, deriving the mapping relationship between joint angles and the end effector position. The inverse kinematics

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addresses the problem of calculating the required joint angles for a given end position, providing a theoretical foundation for precise control. Subsequently, the velocity Jacobian matrix was derived, which describes the linear relationship between joint velocities and end effector velocities, playing a significant role in motion planning for lower limb rehabilitation exoskeletons. The analysis of the velocity Jacobian matrix reveals the speed transmission characteristics of lower limb exoskeletons under various motion states. Finally, the paper summarizes existing control strategies for lower limb exoskeletons, ranging from basic position control to intelligent control strategies that incorporate artificial intelligence for adaptive iterative learning.

As the aging population in our country becomes increasingly serious, the number of individuals with lower limb dysfunction will continue to rise. This technology will undoubtedly make significant contributions to rehabilitation treatment and assisted walking. Lower limb rehabilitation exoskeleton robots combine multiple fields, including medicine, artificial intelligence, automatic control technology, and sensing technology. With the continuous maturation of artificial intelligence, intelligent control strategies that integrate various approaches will be a key trend. In the future, lower limb rehabilitation exoskeletons will be better at accurately interpreting human movement intentions, allowing for tailored rehabilitation strategies and control drives for different patients. Human-machine interaction will become more coordinated, minimizing the risk of secondary injuries to users and enhancing patient experience. Future designs of lower limb rehabilitation exoskeletons will emphasize lightweight construction to reduce costs while continuously improving structural strength and lifespan. Modular designs will increase control precision and eliminate unnecessary components, facilitating further development, maintenance, and repairs. Although lower limb rehabilitation exoskeletons may not yet fully replace traditional treatment methods for patients with mobility impairments, their unique advantages will position them as a leading force in rehabilitation therapy in the future.

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