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Drive Mode of Lower Limb Rehabilitation Exoskeleton Robot: Safety and Comfort

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Drive Mode of Lower Limb Rehabilitation Exoskeleton Robot: Safety and Comfort

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Abstract. As an important auxiliary tool in modern rehabilitation medicine, lower limb rehabilitation exoskeleton robots provide innovative rehabilitation methods for patients with lower limb motor dysfunction by integrating mechanical engineering and intelligent control technology. This paper systematically analyzes the three mainstream technical solutions of pneumatic drive, motor drive, and hydraulic drive, and focuses on their safety and comfort performance in clinical applications. Studies have shown that different drive modes have their characteristics. Pneumatic drive shows unique advantages in human-computer interaction with its bionic compliance characteristics. Motor drive achieves good motion coordination through precise control. The hydraulic drive performs well in power output. At the same time, the study also reveals the technical challenges of various drive modes in noise control, weight distribution, and other aspects. Based on the analysis results, this paper further looks forward to the future development trend of exoskeletons in the direction of lightweight, intelligent, and personalized, and provides an important reference for the technical selection and performance optimization of rehabilitation exoskeletons.

INTRODUCTION

The lower limb rehabilitation exoskeleton robot is an intelligent rehabilitation device that combines mechanical engineering, biomechanics, and artificial intelligence technology. It aims to help patients with lower limb motor dysfunction caused by stroke, spinal cord injury, brain trauma, and so on to restore their walking ability. Since the fifth census in 2000, the number of the elderly in China has doubled by 2020. The number of people over the age of 60 has increased by more than 134 million in the past 20 years, with a growth rate of 103.15%, accounting for an increase of 8.5 percentage points. The population over the age of 65 increased by more than 102 million in 20 years, with an increase of 115.96%, an increase of 6.54 percentage points [1]. At the same time, China will officially enter the aging society by the end of 2022, and it is expected to enter the severe aging society by 2035 [2]. However, although exoskeleton robots have made significant progress in terms of safety and comfort, for example, the ONYX Lower Body Exoskeleton of Lockheed Martin in the United States adopts a bionic design, which can reduce the energy consumption of soldiers in marching and improve endurance and comfort [3]. Ekso Bionics' rehabilitation exoskeleton, EksoNR, has been used for gait training of stroke and spinal cord injury patients, and its adaptive control strategy can adjust the assistance force according to the patient's motor ability. [4]. The Soft Exosuit developed by Harvard University uses high-strength functional textile materials (such as nylon ribbon and carbon fiber rope) instead of traditional metal frames to avoid skin abrasion, joint compression, or local blood circulation restriction that may be caused by hard exoskeletons and summarize the problems existing in existing studies [5].

Therefore, this paper focuses on the safety and comfort of the driving mode of the lower limb rehabilitation exoskeleton robot and evaluates the safety and comfort of three different driving modes.

SUMMARY OF EXISTING RESEARCH

Mainstream Driving Method

At present, the lower limb rehabilitation exoskeleton robot mainly uses the following three drive systems: pneumatic drive, servo motor with ball screw drive, and hydraulic drive.

The characteristics of these three driving methods are analyzed in Table 1:

TABLE 1. Characteristics of three driving modes

Driving mode	Advantages	Limitation	applicable scene
electric motor	The motor drive has fast response speed and high control accuracy (position error $<0.1^\circ$), Easy digital integration, and supports complex motion mode.	The volume and weight of the motor are large when the torque demand is high.- Rigid transmission may lead to human-robot interaction.	It is suitable for precision rehabilitation training and daily assistance.
pneumatic drive	Pneumatic drive power-to-weight ratio is high, good compliance Simple structure, low cost, no risk of electric shock.	Gas compressibility leads to delayed response (typical response time 100-300 ms), air compressor dependence, high noise, and low control accuracy.	It is suitable for lower limb rehabilitation with a light load and smooth movement.
hydraulic drive	The hydraulic drive provides high power and is suitable for dealing with heavy-load systems.	Hydraulic devices are bulky (tubing, pumping stations), complex to maintain (leakage risk), consume high energy, and are noisy.	It is suitable for lower limb rehabilitation applications that need to handle high loads.

Classification of Existing Research

At present, motor drive, pneumatic drive, and hydraulic drive are the three main technical routes, each with different advantages and limitations. The motor drive system uses electric motors (such as brushless DC motors, servo motors) to convert electrical energy into mechanical energy, and drives the exoskeleton joint movement through reducers and transmission mechanisms (such as synchronization belts, ball screw). Its control is based on sensor feedback (such as encoder, force sensor, IMU), and PID, adaptive control, and other algorithms are used to achieve accurate adjustment. Pneumatic actuation relies on compressed air to drive cylinders or pneumatic muscles. The pneumatic muscle expands radially and contracts axially when it is inflated to simulate the motion of biological muscles. The pressure and flow are adjusted by a proportional valve, and the compliance control is realized by combining a pressure sensor. The hydraulic drive drives the hydraulic cylinder or hydraulic motor through high-pressure oil (pressure up to 20 MPa) to produce linear or rotary motion. The motor pump set provides power, the servo valve regulates the flow and direction, and the force and displacement sensors realize closed-loop control.

Given the existing research, this paper classifies the drive system, specific type, and motion gait of the lower limb exoskeleton robot. For example, the lower limb hydrotherapy rehabilitation robot of the University of Electronic Science and Technology of China and the integrated motion assistance robot of Tianjin University are both in the form of wheelchairs to assist treatment, ensuring sufficient safety. The running table lower limb exoskeleton robot of Guangxi University of Science and Technology realizes the function of reducing the leg pressure of rehabilitation personnel through the construction of the running table skeleton [6]. The rope drive model of Beijing University of Aeronautics and Astronautics (BUAA) ensures the comfort and safety of the drive [7]. The rest of the drive systems are shown in Table 2 below.

TABLE 2. Lower limb rehabilitation exoskeleton robot

document	Type of drive system	concrete type	Realizable action	testing personnel
[8]	Servo motor with rod drive	wheelchair	Walking, stretching	Not marked
[9]	Servo motor with rod drive	wheelchair	Walking, stretching	One healthy person
[7]	Servo motor with rope drive	Wearable Device	extension, flexion	Four healthy people
[6]	Servo motor with rod drive	treadmill	Walking	One medical dummy
[10]	Servo motor with rod drive	Bridge bed type	extension, flexion	One healthy person
[11]	pneumatic drive	Wearable Device	Walking, squatting, and standing up	Not marked
[12]	pneumatic drive	treadmill	Walking, stretching	One healthy person
[13]	hydraulic drive	Wearable Device	Walking, and standing up	Not marked

COMPARISON OF SAFETY AND COMFORT

Security Comparison

The pneumatic drive is characterized by a low risk of high pressure, with a low working pressure range between 0.3 and 2MPa, and no burn risk when leaking. High compliance is another characteristic of pneumatic actuation. Pneumatic muscles can cushion the impact and reduce the risk of secondary injury to patients, but there are hysteresis nonlinear problems, and low control accuracy may affect the stability of motion. The motor drive has the characteristics of high stability, and the wheelchair itself is well balanced without additional support. The absence of movement risk is the advantage of the motor drive, and the patient does not need to actively control the balance. Lightweight design is also one of its features; the rope has no rigid structure, reducing the risk of collision. Tight tension control is necessary, as loosening or breaking of the rope may lead to loss of control. The joint limit design is a motor-driven safety measure, and the rotation range of the hip and knee joints of the exoskeleton is limited to avoid over-stretching or compressing the patient's limb. Overload protection is driven by servo motors, which can urgently stop or reduce the output force when abnormal resistance is detected. The hydraulic drive adopts a high-pressure system; the working pressure is more than 10MPa, and there is a risk of leakage. Regular maintenance is required to ensure the tightness. The emergency stop response time is less than 30ms, and the overload protection mechanism is perfect. The security comparison of the final pair with the three driving methods is shown in Table 3 below.

TABLE 3. Comparison of security

Security Index	electric motor	pneumatic drive	hydraulic drive
Emergency response time	<50ms	~100ms	<30ms
Overload/Fault protection	Current/position limitation	Pressure limit	Pressure relief valve protection
environmental suitability	Electromagnetic interference should be prevented	Moisture-resistant and no risk of electric shock	Leakage prevention is required.
Physical risk	Mechanical jamming	The pneumatic pipeline has fallen off.	Oil leakage and high temperature

Comfort Comparison

The application of different driving modes in rehabilitation exoskeletons presents their own unique comfort characteristics. The design of the pneumatic muscle in the pneumatic drive system adopts the biological principle, and

its lightweight and fitting structure can simulate the natural movement mode of human muscles, bringing a high degree of comfort to the user. This mode of actuation has good adaptability and can meet the needs of patients with different body sizes, but due to the inherent hysteresis characteristics of the pneumatic pressure system, it may affect the smoothness and naturalness of the movement to some extent. The motor drive system shows a variety of comfort performance according to the specific application scenario. Although traditional wheelchair-type actuation provides stable mobility support, long-term use may lead to lower limb muscle atrophy and joint stiffness problems in users due to the completely passive working mode. The rope drive system reduces the overall weight and improves the wearing flexibility through the lightweight design, but the rope fixation site may cause local compression discomfort.

In contrast, bed and table motor drive systems are more optimized for comfort, including the use of a parallel four-bar shank support structure to distribute pressure and the use of soft materials to wrap at key contact points. Combined with the precise PID three-closed-loop control algorithm, the system can achieve smooth and natural joint motion. MATLAB simulation shows that the motion parameters are highly matched with the human gait, and the sudden stop and start phenomenon is effectively avoided. The hydraulic drive system brings some comfort challenges while providing a strong driving force. The high rigidity of the system makes the impact generated during movement more obvious, and the heavy weight of 6-8 kg increases the burden on the user. Therefore, the comfort comparison of the driver is shown in Table 4 below.

TABLE 4. Comparison of Comfort Levels

Comfort index	electric motor	pneumatic drive	hydraulic drive
sports coordination	precise trajectory tracking	Gentle and natural	Obvious rigidity
Joint adaptability	Possible restrictions on activities	Strong adaptability	Poor adaptability
level of noise	55-65dB	<40dB	75-85dB
weight distribution	Concentrate on the motor at 3.5-5 kilograms	Evenly weigh 2.5-4 kilograms	The heaviest one. It is approximately 6 to 8 kilograms.

Future Research Directions

Future research can explore the use of lightweight materials and novel manufacturing processes to optimize the structural design of exoskeletons to reduce weight and improve comfort. For example, Li Litao proposed the use of carbon fiber materials to reduce the weight of exoskeletons in his research [14]. Future research can explore the application of artificial intelligence and machine learning techniques in the control system of the exoskeleton to improve its adaptive ability and the fluency of human-computer interaction. For example, Luo Dingji et al. proposed a trajectory tracking control method based on deep learning, which significantly improved the motion accuracy of the exoskeleton robot [15].

Future research could explore personalized customization of exoskeletons based on patient-specific conditions such as height, weight, and gait characteristics. For example, Xiao Chunjie proposed a personalized control algorithm based on patient gait data in his study, which significantly improved the adaptability and comfort of the exoskeleton robot [15]. In his research, Meng Jinglu proposed a personalized exoskeleton design method based on patients' gait data, which significantly improved the rehabilitation effect [8].

CONCLUSION

As a fusion product of modern rehabilitation medicine and engineering technology, the lower limb rehabilitation exoskeleton robot has shown great potential in helping patients with motor dysfunction to restore their walking ability. This paper reveals the key features in terms of safety and comfort through a systematic comparison of three mainstream driving modes: pneumatic, motor, and hydraulic. It is found that different driving methods have their own advantages. Pneumatic driving has outstanding performance in human-computer interaction safety due to its bionic compliance characteristics. The motor drive achieves excellent motion coordination and trajectory accuracy through a precise control algorithm. A hydraulic drive in response to high load demand to show irreplaceably strong power output.

In terms of safety, the data show that the motor-driven emergency response mechanism (<50ms) and multiple protection strategies (current/position limitation) make it the preferred option for high-risk patients; However, the low operating pressure range of 0.3- 2MPa driven by air pressure significantly reduces the leakage risk. The comfort

evaluation shows that the pneumatic driven distributed contact design (40% pressure reduction) and lightweight feature (2.5-4kg) are more suitable for long-term wear requirements, but the noise pollution (75-85dB) and weight burden (6-8kg) of the hydraulic system are still technical bottlenecks to be broken. For future research direction, the learning and personalized customization of artificial intelligence is an important research direction.

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