



# Research progress of ankle-foot rehabilitation robots

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## Highlights

- Three types of ankle-foot rehabilitation robots, categorized by structure, are designed to address different stages of rehabilitation training.
- The development of control methods for rehabilitation robots, including integration of multiple control methods, remains a key area of exploration.
- The combination of artificial intelligence algorithms and rehabilitation robots represents a significant and promising research direction.

## Abstract

With the development of medical-engineering integration technology and the growing clinical rehabilitation demands, intelligent rehabilitation robots have emerged as a prominent area of research in stroke rehabilitation. The application of exoskeleton rehabilitation robots holds significant potential to alleviate the pressure on rehabilitation resources in China. These robots offer high-intensity, high-repetition rehabilitation training for stroke patients, helping to restore limb motor function, improve daily living independence, and contribute to neuroplasticity. As such, they are becoming an essential treatment modality for patients with motor function disorders. In this review, we first categorize ankle-foot rehabilitation robots based on the interaction methods between the robot and the user, detailing their structural characteristics and application scenarios. Additionally, we classify existing control strategies, including admittance control, impedance control, electromyography control, trajectory tracking control, and Proportional-Integral-Derivative control, based on the rehabilitation needs at various stages of recovery. Each control method is summarized, and their current research status is analyzed. Besides, current research status of key technologies in rehabilitation robots, both domestically and internationally are also summarized in this paper. Finally, the key challenges in the development of ankle-foot rehabilitation robots and future research directions are discussed, providing a reference for the research and design of these robots.

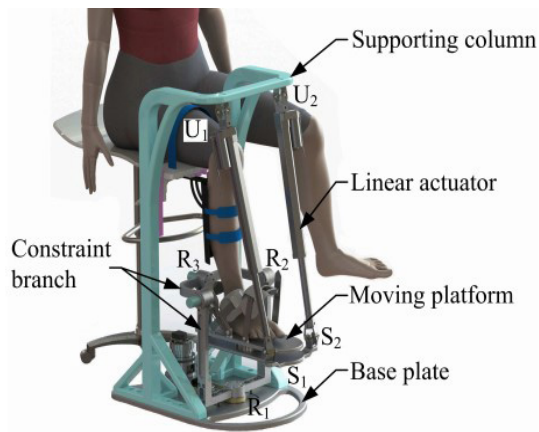
**Keywords:** Stroke rehabilitation, motor function disorder, control strategies, ankle-foot rehabilitation robot

## Introduction

Stroke, commonly known as a cerebrovascular accident, is an acute cerebrovascular disease characterized by high incidence, high mortality, and high disability rates [1]. Research indicates that stroke is the second leading cause of death globally and the primary cause of adult disability. Among stroke survivors, approximately 80% experience varying degrees of limb dysfunction, with hemiplegia being the

most common [2, 3]. This leads to a loss of independence in daily activities and severely impacts the quality of life [4]. According to data from Seventh National Census in 2020, China has 264 million people aged 60 and above, accounting for 18.73% of the population, highlighting the significant aging trend in China [5]. Aging brings about various health issues, including a decline in limb function, which causes inconvenience for many elderly individuals. Besides stroke, neurological diseases such as





**Figure 1. Wearable parallel robot.** This figure is cited from [18].

multiple sclerosis and spinal cord injuries also result in limb dysfunction, necessitating targeted rehabilitation measures to improve motor function [6].

Clinical studies show that 90% of stroke patients can regain the ability to walk and live independently with effective rehabilitation treatment, while only 6% can achieve this without rehabilitation [7]. Restoring limb motor function is the primary goal of stroke rehabilitation [8]. Stroke patients often experience a range of motor impairments, such as reduced muscle strength and abnormal muscle contraction timing [9, 10]. However, the brain's plasticity allows for personalized rehabilitation treatment and training for patients with motor dysfunction. Early intervention with rehabilitation treatment for stroke patients with hemiplegia yields better outcomes. Exercise therapy, a key component of rehabilitation, can promote neural recovery, improve limb motor function, and enhance daily living abilities [11].

For stroke patients, traditional rehabilitation primarily involves one-on-one passive training administered by physicians. The effectiveness of this approach is largely dependent on the physician's skill level, and maintaining consistent training intensity can be challenging. This training model is time-consuming, labor-intensive, and involves a prolonged rehabilitation process. Moreover, it lacks quantitative and objective assessment, making it difficult to optimize training parameters for the best treatment outcomes. Furthermore, rehabilitation therapists mainly rely on their experience to assess the patient's limb condition and formulate rehabilitation plans, lacking precise detection methods to evaluate the patient's limb motor state, which hinders timely adjustments to the rehabilitation treatment plan [12]. A significant contributor to

ankle dysfunction is the central nervous system damage, which requires targeted stimulation to promote the recovery of motor and sensory functions [13]. During physical therapy, patients gradually regain ankle joint range of motion, build muscle strength, and restore motor function [14].

In recent years, the development of medical-engineering integration technologies, such as the combination of robotics and medical theory, has provided new avenues for rehabilitation treatment. Research shows that rehabilitation robot technology plays a crucial role in training patients with limb dysfunction [15]. Intelligent rehabilitation robots help reduce the labor intensity of therapists, offer precise control over the complexity of motor task learning, promote the recovery of limb motor function, and enhance patients' daily living capabilities [16]. With the continuous advancement of intelligent rehabilitation robots, their standardization, intelligence, and humanization will improve, leading to faster recovery and better outcomes for patients [17].

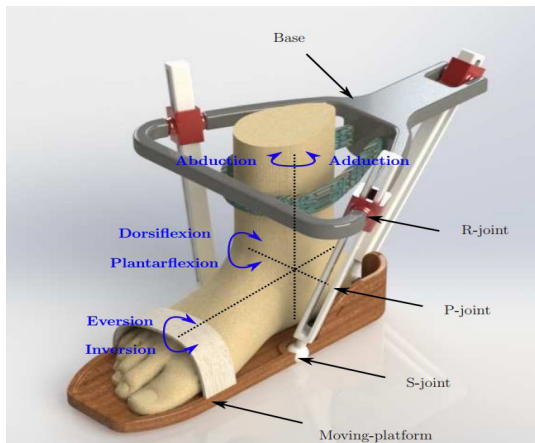
This review begins by classifying and comparing ankle-foot rehabilitation robots based on their interaction methods with the human body, explaining the application of various control methods in these robots. It also discusses their characteristics and research status. The review then enumerates the key technologies of rehabilitation robots and summarizes the challenges faced by ankle-foot rehabilitation robots, and discusses potential future development directions.

### **Classification of ankle-foot rehabilitation robots**

Ankle-foot rehabilitation robots can be classified based on several criteria. By drive method, they can be motor-driven, pneumatic-driven, or hydraulic-driven. By training method, they can be categorized into passive movement, active assistive movement, and resistive movement. In terms of actuator connection, they can be either serial or parallel. According to usage mode, they are classified into seated ankle-foot rehabilitation robots and recumbent ankle-foot rehabilitation robots. The most common structural classifications include platform-type, orthotic-type, and exoskeleton-type ankle-foot rehabilitation robots.

#### **Platform-type rehabilitation robot**

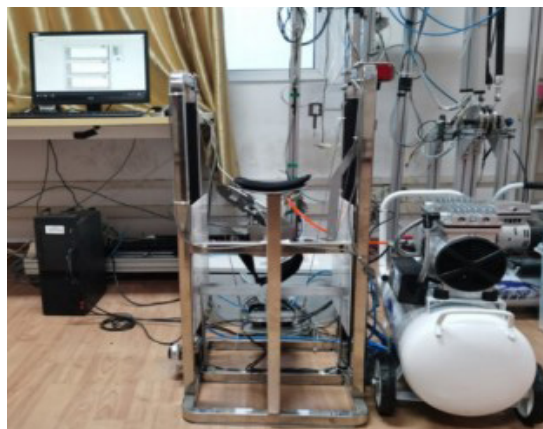
In the early stages of rehabilitation, muscle atrophy often weakens ankle joint movement. Plat-



**Figure 2. Parallel platform ankle foot rehabilitation robot.** This figure is cited from [19].



**Figure 3. 3-PRS (prismatic-revolute-spherical) parallel robot.** This figure is cited from [20].



**Figure 4. Pneumatic muscle-driven flexible ankle foot rehabilitation robot.** This figure is cited from [21].

form-type ankle-foot rehabilitation robots are designed to gradually increase strength training by adjusting the robot's resistance and load, thereby promoting the recovery and strengthening of damaged muscles and tissues. These robots are characterized by their adaptability and high precision, ensuring reliability and safety during the rehabilitation process.

Zuo et al. designed a new type of wearable robot with a parallel platform configuration (**Figure 1**) [18]. This robot features a simple mechanical setup with sufficient motion isotropy, transmission performance, and torque capability. Compared to ankle-foot rehabilitation robots with redundant actuators, this design uses a 2-UPS/RRR (universal-prismatic-spherical/revolute-revolute-revolute) parallel mechanism to simplify operation and control system development, effectively reducing manufacturing costs and the burden on therapists. Additionally, various safety measures were implemented, including a low-moving platform to minimize seat height and removable mechanical limits to restrict the robot's working space, protecting patients from secondary injuries. The robot is equipped with a multi-mode force/position data acquisition system, which collects kinematic and dynamic information to facilitate both active and passive rehabilitation training.

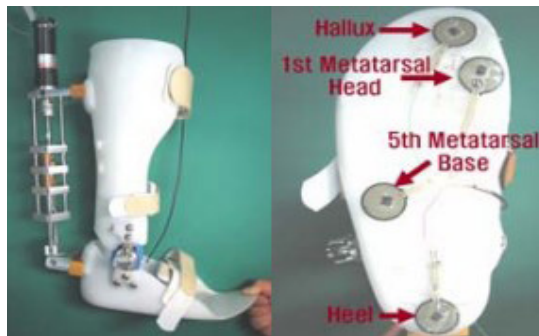
Nurahmi et al. developed a constraint-based 3-RPS (revolute-prismatic-spherical) parallel robot (**Figure 2**), which features a robot system with two operational modes based on the design of the base, moving platform, and working mode [19]. The robot's ability to perform translation and rotation movements was tested by parameterizing its pose workspace. The maximum inner circle diameter was used to track the maximum tilt angle in any azimuthal direction without triggering singularities. The robot employs a reconfiguration strategy to ensure that the moving platform operates effectively at any height.

Abu-Dakka et al. developed a platform-type parallel robot (**Figure 3**), which uses passive rehabilitation training targeting ankle inversion/eversion movements [20]. Based on dynamic motion primitives and iterative learning control methods, they designed motion trajectories and used recorded forces and motion paths to repetitively guide the patient through movements within predefined repetition counts. During the exercise, perceived forces are monitored, and necessary offsets are applied to the original trajectory to adjust and reduce measurement range. After completing the preset number of repetitions, the trajectory range is gradually restored until the patient can perform the initially designed exercise.

Lu et al. from Wuhan University of Technology designed a platform-type flexible ankle-foot rehabilitation robot (**Figure 4**) with multiple degrees of freedom, driven by pneumatic muscles [21]. The robot features a drive section and a



**Figure 5. Wearable robot ankle foot orthotics.** This figure is cited from [22].



**Figure 6. Single degree of freedom ankle foot orthotics.** This figure is cited from [23].



**Figure 7. Electric ankle foot orthotics.** This figure is cited from [24].

motion platform, ensuring alignment of the robot's and patient's ankle joint rotation centers. It mainly consists of a primary motion module, a power transmission module, and a support module, facilitating joint rotational movements for the patient. The power transmission module, driven by pneumatic muscles, connects to the motion platform via flexible cables and uses pulleys to change the direction of the driving forces, meeting the rehabilitation needs of the ankle joint. A telescopic rod in the robot's

mechanism adjusts the height of the thigh support plate to accommodate patients with different leg lengths.

#### ***Orthotic-type rehabilitation robot***

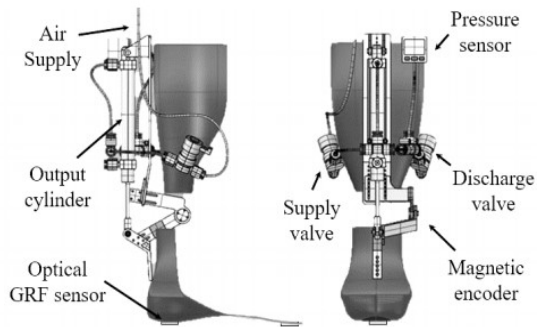
Orthotic-type rehabilitation robots are designed to closely fit the patient's ankle and foot, providing stable support and control. Their structure is designed to fit the anatomical model of the human body, ensuring both comfort and safety. By combining modern robotics technology with orthotic design, these robots assist patients in restoring ankle function and mobility, thereby enhancing rehabilitation outcomes.

Kwon et al. developed a lightweight and easy-to-wear ankle orthosis (**Figure 5**) [22]. It features a flexible 3D-printed frame and ankle support, which provides vertical support to prevent structural buckling. The device uses a bidirectional tendon drive to assist with plantarflexion and dorsiflexion movements. The robot also integrates a soft, wearable gait-sensing module that tracks the motion trajectory and pressure of both feet in real time, enabling feedback control. The system detects gait phases and accurately predicts timing, effectively promoting gait recovery and functional improvement in patients.

Hwang et al. designed an active ankle-foot orthosis (**Figure 6**) [23]. This device primarily consists of sensors, a controller, and actuators. The sensors use Force Sensing Resistor technology as switches to detect foot contact, with the output signals used to detect gait events and control the motor of orthosis system. A DC motor provides horizontal movement, and joint motion is adjusted by modifying the motor's speed and direction. The controller operates the actuator based on a defined control algorithm, enabling precise control over the dorsiflexion and plantarflexion movements of the ankle joint.

Sarma et al. designed and developed an electric ankle-foot orthosis (**Figure 7**) to improve ankle joint mobility in patients with foot drop and lower limb disabilities [24]. This orthosis, made of carbon fiber, includes a stepper motor that provides sufficient plantarflexion and dorsiflexion torque around the ankle joint. An Arduino controller manages the movement at the ankle joint. The motion capture system detects the body's movements during walking, and the motor-driven output voltage enables the motor to rotate, assisting in foot lifting and supporting patients in walking normally.

Kim et al. developed a pneumatic ankle-foot



**Figure 8. Pneumatic ankle foot orthotics.** This figure is cited from [25].



**Figure 9. Powered ankle exoskeleton robot.** This figure is cited from [26].



**Figure 10. Ankle exoskeleton robot.** This figure is cited from [29].

orthosis (**Figure 8**), which generates a sufficient amount of pressurized air using an enhanced compressor to power a unilateral ankle-foot orthosis, assisting dorsiflexion in patients with

foot drop [25]. A ground reaction force sensor detects different phases during the gait cycle, providing continuous analog output voltage. Throughout the gait cycle, the compressor activates according to the nominal rating, allowing the ankle to move freely during standing and enabling normal ankle joint movement.

### **Exoskeleton-type rehabilitation robot**

Exoskeleton-type rehabilitation robots are designed to closely fit the surface of a patient's limbs, with a structure designed to match the human body model. These robots can safely and comfortably couple with limb movements, allowing for smooth and controlled motion. Depending on the settings, exoskeleton robots can provide passive, active-assistive, or active training, catering to the various rehabilitation needs of patients.

Tamburella et al. developed a powered ankle exoskeleton (**Figure 9**), an autonomous wearable robot designed to assist with ankle walking functions [26]. The device uses a neuromuscular controller to adjust the assistance provided by the robot based on the subject's specific capabilities. The system features linear actuators for precise force control and employs encoders, along with knowledge of the kinematic structure, to estimate the transmitted torque, which is then used for feedback in the torque control loop. For subjects with spinal cord injuries, the controller can generate human-like joint torque without the need to adjust their biomechanical or reflex parameters [27, 28].

Orekhov et al. developed a lightweight ankle exoskeleton (**Figure 10**) designed to improve the mobility of patients with neuromuscular impairments [29]. The exoskeleton uses carbon fiber materials to reduce weight and enhance long-term functionality. Force is transmitted through actuators and Bowden cables, providing personalized torque based on the patient's needs. Equipped with torque sensors, the exoskeleton provides feedback to the control system, ensuring precise tracking. During assisted walking, the exoskeleton reduces the activity of the soleus muscle and increases the self-selected walking speed, improving the efficiency of exoskeleton-assisted walking.

Gasparri et al. designed an ankle exoskeleton for walking assistance (**Figure 11**) [30]. The exoskeleton uses proportional joint torque control to instantly adapt to the biomechanical needs of the ankle joint. By providing assistance in proportion to the needs of the biological joint, the device estimates the user's joint



**Figure 11.** Cable powered ankle exoskeleton robot. This figure is cited from [30].



**Figure 12.** Reconfigurable ankle rehabilitation robot. This figure is cited from [31].



**Figure 13.** Electric series ankle exoskeleton robot. This figure is cited from [33].

torque in real-time. The exoskeleton torque synchronizes with the muscle demands at the joint, intuitively and safely capturing the user's intent. The robot uses a motor-driven system

to assist with plantarflexion and dorsiflexion movements, with the ankle joint connected to a waist module via cables that transmit information.

Meng et al. designed a reconfigurable ankle rehabilitation robot (**Figure 12**) with an adjustable workspace capable of performing various types of ankle rehabilitation exercises [31]. The robot can be reconfigured by selecting different numbers of actuators, allowing for three single-degree-of-freedom movements, two-degree-of-freedom movements, and one three-degree-of-freedom movement. The adjustable design facilitates the interchangeability of the left and right feet. By changing the position of the sliders, the functional parts of the robot can be adjusted back and forth along the rails to accommodate users of different heights. The robot features a rotational center matching design, ensuring that the robot's rotational center closely aligns with the rotational center of ankle joint, preventing injuries during training. This robot meets the requirements for ankle rehabilitation training and offers practical usability [32].

Yeung et al. developed a portable ankle exoskeleton robot (**Figure 13**) with significant improvements in gait independence and walking speed [33]. The ankle joint is combined with a rotary motor and a torque amplifier, enabling both plantarflexion and dorsiflexion movements. In the power-assisted ankle robot mode, the device provides power to help patients with ground walking and stair training. It prevents foot drop through constant torque and calibrates in the dorsiflexion and plantarflexion directions as needed. In the swing control mode, the robot locks and unlocks the ankle joint during different gait phases, providing support to assist patients in their rehabilitation training.

Platform-type ankle-foot rehabilitation robots offer a wide range of motion and high safety by using a fixed base and a movable platform. These robots are suitable for patients at different stages of rehabilitation, as the platform can move in multiple directions to simulate natural ankle movements. Typically controlled by motors and sensors, platform-type robots allow for precise adjustment of the platform's movements. Orthotic-type robots, on the other hand, wrap around the patient's foot and ankle to provide external support and movement guidance. Compared to platform-type robots, orthotic devices have a limited range of motion but are lighter and can be adjusted according to the patient's specific needs, offering personalized rehabilitation training. Exoskeleton-type robots

**Table 1. Comparison of different types of ankle rehabilitation robots**

Type of Rehabilitation Robot	Advantages	Problems	Possible Solutions
Platform-Type	Providing a wide range of motion and high safety; easy to master and use; designed with comfort, enhancing patient experience	Accuracy limitations; difficult to control; limited application range; high demand for power and technical support	Introducing more precise sensors; increasing degrees of freedom; optimizing control algorithms
Orthotic-Type	Lightweight and portable; easy to customize; convenient for daily use; providing external support, reducing patient burden	Limiting patient mobility; unable to perform complex training; insufficient support for specific movements; inadequate support and power	Optimizing robot structure; introducing more efficient drive systems; increasing range of motion; developing additional support functions
Exoskeleton-Type	Highly adaptable; performing complex movements; offering high flexibility and power support; enhancing strength and facilitating rehabilitation	Complex design; heavy equipment; long wear times may cause fatigue; requiring substantial power support	Simplifying design; using lightweight materials; improving wear comfort; reducing fatigue; enhancing adaptability

are designed to accommodate various complex movement patterns to meet different rehabilitation requirements. They cover the patient's legs and feet, providing active motion support and using sensors and computer algorithms for precise motion control, offering additional force support to enhance rehabilitation training. Each type of rehabilitation robot has its own advantages and disadvantages, as shown in **Table 1**. Selecting the appropriate robot based on the patient's specific condition is key to achieving the best rehabilitation outcomes.

#### **Ankle-foot rehabilitation robot control methods**

Ankle-foot rehabilitation training is facilitated through the motion control system of an ankle-foot rehabilitation robot, with the specific control strategy chosen based on the rehabilitation goals. Based on different rehabilitation treatment needs, control strategies can be categorized into two types: active control and passive control. In active control, the robot provides appropriate assistance force and direction based on the patient's intentions and actual motor abilities, helping the patient complete the movement tasks. In passive control, the robot assists the patient by guiding them through a series of predefined rehabilitation exercises according to preset motion parameters. Passive control requires addressing issues such as uncertainties and disturbances that arise from the complex multi-joint structures of the robot and variations in load during movement.

#### **Admittance control**

In rehabilitation training, admittance control can adjust the robot's movement based on the forces exerted by the patient. Its primary goal is to control the robot's displacement based on

external forces, ensuring its movement aligns with the desired dynamic characteristics. This approach provides flexible support during rehabilitation exercises, accommodating the patient's individual needs.

Siviy et al. developed a controller consisting of two nested control loops [34]. The inner loop performs closed-loop control of the motor speed in the drive system, tracking the desired cable speed trajectory generated by the outer loop. The outer loop includes two feedforward compensators for changes in Bowden cable position caused by joint movement and the forces generated by exoskeleton deformation. Force errors are compensated by a feedback admittance controller. The effect of dorsiflexion on stroke patients' ankles was assessed, optimizing offline assistance and separating positive and negative enhancement forces. Mu developed an improved rotary orthosis for arm-swing walking. In passive mode, the robot system implements a closed-loop position control algorithm [35]. In active mode, the ankle joint mechanism uses an adjustable admittance control algorithm, allowing patients to adjust the range of ankle joint motion. The system uses a series of linear actuators installed in front of the ankle joint to facilitate natural arm swinging. Force sensors at the actuator's end provide real-time force information to adjust the admittance control algorithm. The orthosis facilitates early-stage patients in regaining walking ability after injury.

Ren et al. developed a wearable rehabilitation robot for early rehabilitation training in stroke patients [36]. This robot combines video game-based training with admittance control, providing real-time feedback and adjustments by detecting resistance torque at the ankle joint.

The training, which includes 12 feedback-assisted isometric torque generation exercises along with both passive and active movements, promotes neuroplasticity and motor control. Chen et al. from Suzhou University designed an ankle exoskeleton robot with force feedback admittance control, which enhances human-robot interaction (HRI) compliance during walking assistance [37]. This system uses a cable-driven mechanism that adjusts the tension of the Bowden cable to control the assistive torque at the ankle. Admittance control provides better human-robot compliance while meeting control requirements.

### ***Impedance control***

In rehabilitation robots, impedance control ensures that the end-effector's impedance characteristics match the expected dynamic relationship, providing the desired compliance. This method primarily adjusts the system's response to external forces by modifying the control signals to achieve the desired impedance characteristics.

Liu et al. from Henan University of Science and Technology designed a pneumatic muscle redundant parallel-drive ankle rehabilitation robot [38]. They employed a compliance control strategy for active rehabilitation training, providing precise assistance and resistance during rehabilitation process. Based on impedance control theory, the system achieves error-free force tracking through trajectory planning. The combination of the control strategy and error-free force tracking guarantees both safety and compliance during assistance and resistance training.

Liu et al. developed an ankle rehabilitation platform to assist patients with ankle joint movements [39]. It consists of two symmetrical three-degree-of-freedom robotic platforms, with the robot's rotational center aligned with the patient's ankle joint center. This design allows patients to train the affected ankle joint by replicating the movements of the healthy ankle joint. The platform offers three training modes: constant-speed exercise, constant-torque impedance exercise, and conscious exercise. In constant-speed mode, the platform matches the input value. In constant-torque impedance mode, adjusting the torque threshold enables strength training for the ankle joint. In conscious mode, one side of the platform moves within the motion range. These modes support early neural rehabilitation for hemiparetic patients.

Perez-Ibarra developed an adaptive impedance control robot that is wearable and reversely driven [40]. It supports dorsiflexion, plantarflexion, inversion, and eversion within the normal range of motion. The robot's impedance control stiffness parameters are adjusted according to the patient's engagement level, guiding the patient through exercises with a game-based approach. The adaptive strategy allows for greater kinematic variability in the patient's movements. By monitoring the patient's performance during the game, the level of robotic assistance can be dynamically adjusted throughout the exercise.

### ***Electromyographic (EMG) signal control***

EMG signals provide rich information about human movement and accurately reflect neuromuscular activity. Using EMG signals as a control source for robots offers a promising control approach, as it enables the detection of movement intentions and the analysis of movement trajectories to and trigger control actions accordingly [41].

Researchers from the Shenyang Institute of Automation, Chinese Academy of Sciences, led by Zhang, developed an ankle rehabilitation robot based on adaptive control using EMG signals [42]. This robot assists patients in performing dorsiflexion and plantarflexion movements. The design simplifies the control process using a limit-based EMG model, while data-driven control methods address the uncertain dynamic characteristics of the robot system. By leveraging the antagonistic relationship between the tibialis anterior and the gastrocnemius muscles during ankle movements, the robot correlates the type of ankle movement with the contraction of individual muscle groups. The adaptive control algorithm ensures safety in HRI.

Ao et al. developed an EMG-driven Hill-type neuromuscular skeletal model [43]. This robot, featuring a single-degree-of-freedom powered exoskeleton, assists in ankle dorsiflexion. It can estimate ankle torque in real-time and accurately reflect changes in joint angles and muscle dynamics. Compared to linear proportional models, the Hill model improves predictions of joint torque at different joint angles. Patients using the Hill neuromuscular skeletal model expend less physical effort and exhibit smoother movements, as it reduces muscle co-contraction during the task, leading to more efficient rehabilitation.

Zhuang et al. designed an ankle rehabilitation robot based on EMG signal-guided admittance

control [44]. This system consists of an EMG signal-driven musculoskeletal model, an admittance filter, and a position controller. Both the EMG signal-based admittance control scheme and open-loop control scheme improve the range of ankle motion in stroke patients. Proportional-derivative controllers enhance the stability of human-robot cooperation. The admittance control method provides stable and smooth tracking trajectories for assistive rehabilitation, making it suitable for implementation in portable assistive devices for robot-assisted walking.

### **Trajectory tracking control**

Trajectory tracking control ensures that a robot's end-effector accurately follows a pre-defined trajectory, achieving high-precision movement control. The primary objective is to make sure the robot moves along a specified path while maintaining the expected speed and acceleration. During actual movement, real-time monitoring of the robot's position allows for the computation of error between the actual and desired trajectories.

Zhao et al. proposed a proportional-derivative control method based on deep deterministic policy gradient, which enhances the trajectory tracking accuracy of exoskeleton robots to ensure effective patient rehabilitation [45]. A degree of freedom was implemented at the robot's ankle joint to achieve dorsiflexion and plantarflexion movements. The gravity-compensated proportional-derivative control serves as the primary controller, effectively tracking the joint angles of the rehabilitation exoskeleton robot and enabling high-precision tracking control of joint angle trajectories.

Bae et al. designed a rehabilitation robot that employs trajectory tracking control as the main control method [46]. This method determines position control for each axis and utilizes force sensors on the footplate to measure ground reaction forces, compensating for vertical pelvic movements. Feedforward and feedback torque calculations drive the torques, with a feedforward torque compensation control module adjusting position, speed, and acceleration. Adjustments to the gravity compensation torque further improve control capabilities, and encoder feedback allows for real-time error tracking, aiding in the production of a standardized gait pattern for patients.

Jamwal et al. developed a parallel ankle rehabilitation robot, featuring a fixed platform and a moving platform connected by four linear

flexible actuators [47]. The robot's optimal trajectory is generated by minimizing joint reaction torques and muscle-tendon unit tensions. Adjustments to the predetermined correct position errors, ensuring the robot moves in the opposite direction of these errors. Modifying the reference path can reduce the forces applied by the rehabilitation robot, and speed limits on path adaptation help maintain system stability.

Ai et al. from Wuhan University of Technology developed a pneumatic muscle-driven flexible ankle rehabilitation robot [48]. They implemented an adaptive backstepping sliding mode control method to address nonlinear characteristics and uncertainties in the human-robot rehabilitation process. This approach can estimate external disturbances online, enhancing the robustness of the control method and allowing real-time adjustments to control outputs, achieving high trajectory tracking accuracy. This control method reduces oscillations, thereby minimizing further harm to patients.

### **Proportional-Integral-Derivative (PID) control**

PID control provides precise control of a system by adjusting control parameters to track a set target. It is characterized by its adjustable dynamic properties and does not rely on the model of the controlled object. Adjusting the system parameters can yield satisfactory control effects.

Nhon et al. proposed a resonant method based on PID control, which uses an interval type-2 fuzzy self-tuning PID controller to improve system control accuracy [49]. Compared to traditional PID controllers, fuzzy PID controllers demonstrate superior stability and robustness against external disturbances and exhibit faster response speeds. Type-2 fuzzy logic is particularly effective for managing complex and uncertain systems. Fuzzy logic controllers apply fuzzy set theory to manage uncertainties and nonlinearities in the system, allowing for more adaptable control strategies.

Wang et al. from Northeastern University designed a 3-SPS/S (spherical-prismatic-spherical/spherical) parallel ankle rehabilitation robot, combining fuzzy inference systems with traditional PID control to develop a fuzzy adaptive PID controller that enhances control system accuracy [50]. The robot's control module generates algorithmic control quantities based on feedback deviations to control the system. The trajectory generation module computes the movement trajectories of each limb based on the desired pose, while the sensing module

**Table 2. The advantages and disadvantages of different control methods**

Control methods	Advantages	Disadvantages
Admittance control	Provides compliance, enables precise force control, and adapts to constantly changing external forces or disturbances.	Requires precise parameter selection for effective performance and may struggle to maintain stability in high-stiffness scenarios.
Impedance control	Provides stable force feedback, and allows for easy integration of force and position control by adjusting impedance parameters.	Performance may be less agile in environments with large external forces or significant dynamic changes; requires high-performance actuators.
Electromyographic signal control	Provides immediate muscle activity feedback, enabling quick response to user intentions and adaptability to varying muscle activity patterns and enhancing flexibility.	Susceptible to noise and interference; muscle fatigue can alter electromyographic signals, potentially affecting system stability and control performance.
Trajectory tracking control	Improves overall system accuracy by reducing errors and deviations; accommodates various task requirements with customizable trajectories.	Requires complex computations and real-time processing; high computational loads may delay system response and depend on the accuracy.
Proportional-integral-derivative control	Effectively reduces steady-state errors and offers good robustness through adjustable proportional, integral, and derivative parameters.	May require additional adjustments or extended control strategies for time-varying or complex dynamic systems.

gathers information such as the platform's position and speed.

Lb et al. from East China University of Science and Technology developed a hybrid active-passive ankle prosthesis, which uses a combination of series and parallel springs to meet the impedance requirements at different ankle positions during walking [51]. Series springs adjust the impedance dynamically, while parallel springs serve as energy storage components. The prosthesis controller collects joint angle and torque data and uses a finite state machine to determine the gait phase of the ankle joint, outputting appropriate angles or torques. Different controllers are selected based on the detected gait to meet the complex movement needs of the ankle joint. Cui et al. from Shanghai Jiao Tong University designed a flexible ankle rehabilitation robot, which uses soft actuators, calf, and foot fixtures that are 3D-printed for lightness and practicality [52]. The robot's symmetrical pneumatic soft actuators enable dorsiflexion and plantarflexion movements. PID control methods are used to manage the robot's drive angles, with a feedback closed-loop control system constructed based on hardware devices, such as posture sensors, to achieve ankle rehabilitation training [53].

The signals generated by the human body are transmitted to the robot, allowing the selection of a control strategy based on rehabilitation needs. Each control method offers unique characteristics, as summarized in **Table 2**.

## Key Technologies in Ankle-foot rehabilitation robots

### HRI technology

HRI technologies enable efficient and natural interactions between humans and robots, primarily achieved through control systems, feedback mechanisms, and artificial intelligence. By leveraging the robot's strong capabilities in perceiving, acquiring, and processing biological and environmental information, and combining the human brain's exceptional decision-making ability in unfamiliar and complex situations, HRI enables a complementary advantage between humans and robots. In rehabilitation robots, HRI technologies are mainly implemented through the monitoring of physiological signals and force and position information [54].

Shi et al. developed a rehabilitation robot based on a HRI dynamics model [55]. The adaptive controller in the robot system can handle uncertainties in the stiffness coefficients of the robot's parameters and force models. A three-dimensional equivalent spring model is used to represent the interaction forces between the human and the robot, simulating the torque applied by the robot to the body. The robot addresses the limitation of recognizing patients' movement intentions due to their limited voluntary control during rehabilitation, thereby improving patient comfort.

Du et al. proposed an adaptive HRI control strategy for rehabilitation robots [56]. Based on

a dynamic model, they extract surface electromyographic signals and plantar pressure features to identify movement intentions. The developed HRI information fusion model enables real-time planning of the robot's movement trajectory. An adaptive fuzzy controller enables trajectory tracking and implements adaptive HRI control for the robot.

### **Sensor technology**

Sensor technologies play a crucial role in ensuring the adaptability and safety of rehabilitation robots. Sensors and perception devices are strategically integrated into various parts of the robot to collect data on physiological state, movement, joint velocities, and torques. The accuracy of this data directly impacts the stability and performance of the entire robotic system. Currently, multi-sensor perception systems are employed to integrate signals for more accurate gait information [57]. These systems track body posture, predict movement intentions, and monitor the physiological state of patients during rehabilitation, providing objective data for clinicians.

Yang et al. designed a rehabilitation robot based on force-torque sensing and teaching, which allows for personalized and diverse rehabilitation training for different patients [58]. A six-dimensional force sensor is installed at the ankle end to detect external contact forces. By implementing a compliance control algorithm and analyzing the robot's pose matrix, inverse kinematics modules are used to determine the joint angles, enabling the robot to follow the desired trajectory. Gao et al. developed a multi-functional rehabilitation robot capable of sitting, lying, and standing. Angle sensors are installed on the backrest and seat to measure the real-time inclination angles at the control terminal [59]. A six-dimensional force sensor at the foot collects torque information from the patient's foot, aiding clinicians in understanding the patient's condition better. Proximity sensors in the leg extension module offer non-contact detection, contributing to enhanced safety and performance during rehabilitation exercises. Zhang et al. designed a rehabilitation robot based on motion injuries [60]. The control system includes torque sensors at the output end of the motor drivers, which provide force feedback information during active training. This facilitates real-time adjustment of impedance values, improving the effectiveness of the rehabilitation process.

Muro-de-la-Herran utilized inertial sensors in gait analysis, primarily to measure angles and

assess patient conditions throughout the entire gait cycle [61]. A wearable rehabilitation exoskeleton robot developed by the University of Twente in the Netherlands uses motors to drive the ankle joint movements, enabling paraplegic patients to walk without obstacles, maximizing comfort and adaptability [62]. The robot is equipped with a multi-control strategy system that adjusts overall walking control based on shifts in the body's center of gravity, which occur due to forward and lateral tilting during walking. The accuracy of the control is monitored using encoders and gravity sensors on the device.

Sensor technology plays a crucial role in detecting and transmitting subtle signals, making judgments based on the collected data to ensure that rehabilitation robots perform appropriate actions. This technology is advancing towards greater intelligence and efficiency. In human-machine interaction, software is becoming increasingly user-friendly, with new technologies enhancing the interactivity between humans and machines. Future software will significantly improve its practicality, leading to better patient experience.

### **Conclusion and Outlook**

Rehabilitation robot provides a significant technological avenue for alleviating current healthcare challenges and enhancing training levels, offering substantial social value. Rehabilitation robots show promising prospects in the recovery of stroke patients, significantly improving upper limb, lower limb, and cognitive functions. Compared to traditional rehabilitation training, rehabilitation robots offer more stable and controllable training, ensuring optimal rehabilitation intensity and efficiency. They not only provide scientifically effective rehabilitation training to accelerate patient recovery but also address the shortage of rehabilitation therapists.

Current advancements in rehabilitation robotics reveal a range of promising technologies, each with distinct advantages and challenges. End-effector robots have simple structures and are easy to manufacture but suffer from kinematic mismatches with limb joints, limiting their ability to control multiple joints simultaneously and restricting their range of motion. Although exoskeleton rehabilitation robots offer good compliance, comfort, and portability, they lack external rigid frameworks, making the installation of motors and sensors challenging, and limiting their functional diversity and support capabilities. Future research may focus on com-

binning rigidity with flexibility. Regarding control strategies, current systems utilize a variety of methods, often in combination, to harness the strengths of each approach and address the weaknesses of individual techniques. Future research is expected to increasingly adopt hybrid control methods.

Currently, the structure of rehabilitation robots mainly consists of traditional materials such as metals and alloys, which results in larger sizes that impacts patient comfort, thereby affecting rehabilitation therapy. The shift towards lightweight materials will improve comfort and structural efficiency. Rigid joint-based rehabilitation robots have limited movement and cannot achieve continuous deformation. The use of flexible materials such as elastomers can effectively absorb impact energy, representing an important direction for future development. A advancements in artificial intelligence, when combined with rehabilitation robots will make patient rehabilitation training more intelligent and safer, representing a key trend in future developments. Research into rehabilitation robots holds significant social implications and broad application prospects.

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