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# *Design and Clinical Application Research of Ankle-Foot Rehabilitation Robot Systems*

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***Abstract:*** Ankle-foot rehabilitation robots have garnered significant attention due to their importance in assisting patients with rehabilitation training and enhancing treatment efficiency. This review systematically explores the current state of research on ankle-foot rehabilitation robots, covering structural design, control methods, and clinical application cases. Firstly, the article analyzes the advantages of rigid actuators in terms of control precision and the benefits of flexible actuators in adaptability, highlighting the potential of rigid-flexible coupled structures in improving rehabilitation outcomes. Secondly, it discusses the current control strategies for ankle-foot rehabilitation robots, including passive control, active control, and impedance control, and examines their applications at different rehabilitation stages. Finally, the article summarizes clinical application cases of ankle-foot rehabilitation robots and suggests that future research should focus on optimizing structural design, developing intelligent control algorithms, and promoting widespread clinical application of these robots to provide more personalized and efficient rehabilitation solutions.

***Keywords:*** Ankle-foot rehabilitation robot, Actuator, Control strategy, Clinical application.

## 1. Introduction

As concerns about health issues continue to grow and interdisciplinary fields of medical engineering rapidly develop, bio-robotics has become a focal point. In the interdisciplinary domain of medical engineering, the applications of bio-robotics are extensive. Exoskeleton robots not only enhance soldiers' combat capabilities and workers' efficiency but also assist humans in muscle training and rehabilitation. In areas such as surgical robots, rehabilitation robots, and wearable health devices, bio-robotics enhances treatment efficiency through precise operations, particularly showing great potential in aiding human bipedal walking and ankle joint rehabilitation training. Traditional rehabilitation methods often lack sufficient feedback and require a high level of expertise, while bipedal walking is critically important for humans [1]. Therefore, the ankle-foot rehabilitation robot has become an important research direction in modern rehabilitation engineering.

Ankle-foot rehabilitation robots can be classified into three categories based on the type of actuator: rigid, flexible, and rigid-flexible coupled. Rigid actuators are known for their high precision and are suitable for rehabilitation tasks requiring strict trajectory tracking, though they may lead to secondary injuries [2]. Flexible actuators, on the other hand, conform to the human body and provide greater safety, making them particularly suitable for the early stages of rehabilitation, though they are more

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challenging to control. Rigid-flexible coupled actuators combine the advantages of both, enhancing safety while maintaining control precision, and have become a future trend. In terms of control strategies, rehabilitation robots have gradually evolved from passive control to active control and impedance control to meet the needs of different rehabilitation stages. Common methods used in the early stages of rehabilitation include PID control, sliding mode control, and electromyographic signal control, while later stages often employ active control and task-oriented training strategies. From a clinical application perspective, ankle-foot rehabilitation robots have already demonstrated significant rehabilitation effects [3]. Research indicates that these robots are particularly effective in treating conditions such as stroke and foot drop. They not only accelerate functional recovery after the acute phase but also improve overall rehabilitation quality through personalized training programs. Future research should continue to optimize structural design and control algorithms to enhance the safety and effectiveness of clinical applications and promote their use in a broader range of clinical settings, providing patients with more personalized and efficient rehabilitation solutions.

This article aims to systematically review the current state of research on ankle-foot rehabilitation robots. The discussion will focus primarily on the three key areas illustrated in Figure 1: Actuators (structural design), Control Methods, and Clinical Applications. Actuators are the foundational components of ankle-foot robots, including different types of actuators such as Rigid Robots, Soft Robots, and Coupling Robots. Each type of actuator has distinct physical characteristics and design requirements, directly influencing the robot's control methods. In terms of Control Methods, system designers select appropriate control strategies based on the characteristics of the actuators, such as Passive Control, Active Control, and Human-Machine Interaction Control (HMI). These control methods determine how the robot interacts with the user and how it performs complex task movements. The choice and design of Actuators and Control Methods directly affect the robot's Clinical Applications. For example, Rigid Robots may be more suitable for scenarios requiring high stability, while Soft Robots are better suited for clinical operations that demand higher flexibility and comfort. Additionally, HMI control enables the customization of personalized treatment plans, further enhancing the effectiveness of clinical applications.

Through this logical structure, this article will delve into the interrelationships between these areas and use specific examples (such as the combination of Rigid Robots and HMI Control) to illustrate their practical impact on the clinical application of robots.

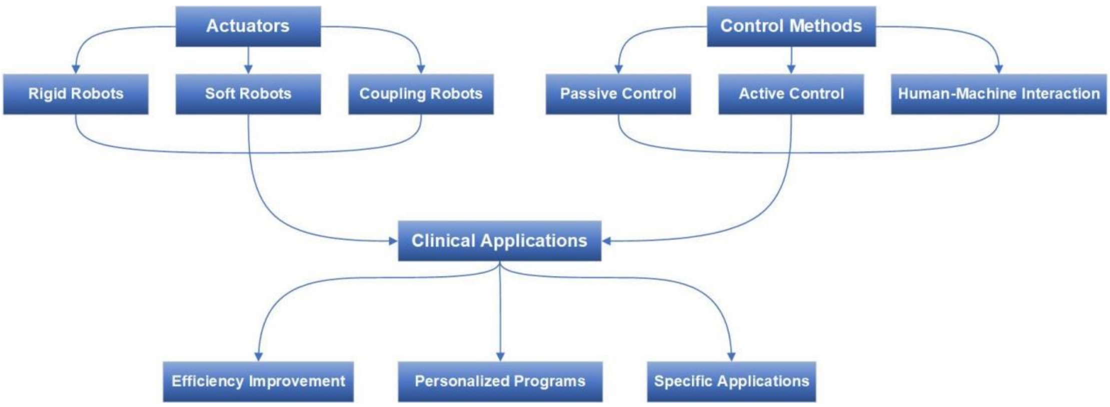


Figure 1: Flow Chart for Ankle-Foot Rehabilitation Robots.

## 2. Current Research Status on Ankle-Foot Rehabilitation Robot Structural Devices

In response to the vast demand for rehabilitation medical resources, and to address the relative shortage of rehabilitation therapists while establishing effective monitoring and feedback strategies for ankle joint rehabilitation, numerous research institutions worldwide have initiated studies on

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ankle-foot rehabilitation robots. This section primarily introduces and summarizes the current research status of the structural devices of existing ankle-foot rehabilitation robots. Depending on the type of actuators used in rehabilitation devices, ankle-foot rehabilitation robots can be classified into three categories: rigid ankle-foot rehabilitation robots, flexible ankle-foot rehabilitation robots, and ankle-foot rehabilitation robots based on rigid-flexible coupling mechanisms.

### 2.1. Current Research Status of Rigid Ankle-Foot Rehabilitation Robots

Traditional Stiffness Actuators (TSAs) are the primary components of conventional rehabilitation devices, known for their clear execution paths, high control precision, and consistent output force. However, they may cause secondary injuries to patients. Relevant research primarily focuses on enhancing human-machine interaction and improving control precision. Bian Hui et al. proposed a 2-RRR/UPRR parallel mechanism with a remote motion center, enabling the rotational center to coincide with the ankle joint center and allowing for real-time control [4]. Jianfeng Li et al. developed a 2-UPS/RRR parallel ankle rehabilitation robot prototype that, by considering the anatomical structure of the ankle joint, ensures the near-coincidence of the human-machine rotational center; they also built a force/torque information acquisition platform to enhance human-machine interaction [5]. Yanbin Zhang et al. designed an RR-RURU ankle rehabilitation robot mechanism that uses revolute pairs and universal joints, featuring non-coupled kinematic characteristics. This design enables smooth transitions in driving force during movement, with the mechanism exhibiting complete isotropy in the workspace under certain conditions [6]. Tong Wang et al. proposed a three-movement platform connection structure for dorsiflexion-plantarflexion, inversion-eversion, and internal-external rotation, allowing for personalized treatment according to the patient's specific conditions [7].

### 2.2. Current Research Status of Flexible Ankle-Foot Rehabilitation Robots

Flexible actuators, such as Pneumatic Muscles, offer advantages including close conformity to the human body, good compliance, and high energy efficiency. These actuators can adapt to varying environments and loads, making them particularly suitable for rehabilitation tasks requiring high safety. Hailing Huang et al. designed a 3-DOF parallel mechanism driven by four flexible cables, taking advantage of the motion characteristics of the ankle joint and the benefits of a flexible cable-driven parallel mechanism. This mechanism achieves spatial 3D rotation by controlling the cable lengths [8]. Louis N. Awad et al. developed a soft exosuit that, through the interaction of functional textile anchors and cable transmitters, improved the walking ability of stroke patients [1]. Jie Zuo designed a pneumatically actuated parallel-driven ankle rehabilitation robot capable of adapting to different patients' needs through a multi-input, multi-output parallel control algorithm, and introduced a disturbance observer to compensate for parallel coupling interference [9]. Xiao Cui et al. designed and manufactured a symmetrical pneumatic soft actuator using silicone rubber liners and various fabrics, combining it with soft actuators via 3D-printed fixtures and carbon fiber tubes to perform ankle-foot rehabilitation exercises [10].

### 2.3. Current Research Status of Ankle-Foot Rehabilitation Robots Based on Rigid-Flexible Coupling Mechanisms

To combine the advantages of both rigid and flexible actuators, future ankle-foot rehabilitation robots are expected to develop towards rigid-flexible coupling. These mechanisms integrate the high control precision of rigid actuators with the safety and adaptability of flexible actuators. Jinliang Li et al. designed a lower limb exoskeleton rehabilitation robot, and through rigid-flexible coupling analysis and simulation, validated the rationality and accuracy of its structure, laying the foundation for

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dynamic studies [11]. Guilian Wang et al. designed a symmetrical micro-positioning platform with a rigid-flexible coupling structure, composed of three sets of parallel symmetrical flexible drive mechanisms (with wedge-shaped structures in the middle of flexible hinges) and a rigid platform, verifying the motion characteristics and load-bearing performance of this platform [12]. Xiangfeng Zeng et al. developed a three-degree-of-freedom ankle rehabilitation robot that combines pneumatic muscles and servo motors, ensuring the coordination of multi-axis movements and improving patient comfort and rehabilitation quality [13].

## 3. Current Research Status of Ankle-Foot Rehabilitation Robot Actuation Methods

Efficient actuation methods can optimize the structure and functionality of robots, enhance safety and reliability, provide more personalized rehabilitation solutions for patients, reduce energy consumption, and extend service life, thereby lowering long-term usage costs. The following content introduces and summarizes the current research status of actuation methods for ankle-foot rehabilitation robots.

### 3.1. Research on Control Algorithms for Ankle-Foot Rehabilitation Robots

In the research of control algorithms for ankle-foot rehabilitation robots, key areas of exploration include the application of PID control and composite control strategies, pneumatic muscle actuation with adaptive control, and impedance control strategies. The primary goal of these studies is to improve the control precision and adaptability of rehabilitation robots, effectively addressing potential nonlinear disturbance issues during rehabilitation, and providing diverse training modes to support the different stages of rehabilitation.

The application of PID control and composite control strategies in ankle-foot rehabilitation devices aims to overcome common nonlinear disturbances during rehabilitation through precise control methods, enhancing the stability and effectiveness of treatment. César H. Guzmán-Valdivia et al. designed a single-degree-of-freedom ankle-foot rehabilitation device incorporating aquatic therapy, using PID control to ensure constant temperature in the hot water recirculation system, effectively aiding in rehabilitation [14]. Lan Wang et al. addressed the issue of ankle rehabilitation devices being easily disturbed by nonlinear factors (including partial load torque disturbance, friction disturbance, and idle disturbance) during training. They designed a platform-based three-degree-of-freedom ankle-foot rehabilitation device and proposed a feedforward-feedback composite control strategy, which limits the impact of nonlinear disturbances within an acceptable range. This strategy was validated for its effectiveness in the inversion/eversion mechanism through the dSPACE/MATLAB/Simulink platform [15].

The research on pneumatic muscle actuation with adaptive control strategies aims to solve nonlinear problems through innovative control methods, improving the trajectory tracking precision and anti-disturbance capabilities of rehabilitation robots. Qingsong Ai et al. designed a two-degree-of-freedom parallel compliant ankle rehabilitation robot driven by pneumatic muscles. To address the nonlinear issues of pneumatic muscle actuation, they proposed and validated an Adaptive Backstepping Sliding Mode Control (ABS-SMC) method. From a control strategy perspective, Qingsong Ai et al. utilized the Lyapunov function and virtual control to establish new backstepping sliding mode control, adaptive backstepping sliding mode control, and stability analysis. Experimental results showed that ABS-SMC outperformed traditional methods in trajectory tracking and effectively reduced chattering and secondary injury to patients, also providing better anti-disturbance capabilities [16].

Impedance control strategies, through the application of various training modes, can effectively assess and support the different stages of rehabilitation for patients with neurological disorders.

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Prashant K. Jamwal et al. used a parallel pneumatic muscle-driven three-degree-of-freedom ankle rehabilitation robot to develop and implement impedance control-based training strategies. The robot operated in four training modes: position control, zero-impedance control, nonzero-impedance control with high compliance, and nonzero-impedance control with low compliance. These modes demonstrated the effectiveness of impedance control schemes in assessing the disability level of patients with neurological disorders at different stages of rehabilitation [17].

## 3.2. Ankle-Foot Rehabilitation Robot Control Training Strategies

The control training strategies for ankle-foot rehabilitation robots are diverse, tailored to different rehabilitation needs and patient conditions through various control methods and training modes. The following provides a detailed introduction to some of the main strategies.

Passive and Active Training Strategies combine different control methods and training modes to meet the specific movement requirements during the patient's rehabilitation process, effectively promoting the recovery of ankle-foot function. Tongyang Sun et al. designed a platform-based three-degree-of-freedom ankle-foot rehabilitation mechanism and proposed passive training and active training, as well as neural system training methods based on subjective awareness and objective training. They used PID, WB LPMS sensors, and other tools to propose and experimentally verify the control algorithms corresponding to these two driving strategies. In passive training, position control and force control correspond to passive control and active control, respectively. Subjective awareness training is based on the patient's awareness to move the healthy side, thus driving the training device on the affected side. Objective training uses electromyography and functional electrical stimulation to stimulate the calf muscles, promoting their movement [18].

Task-Oriented Training Strategies aim to enhance the practical effects and adaptability of rehabilitation training by simulating specific tasks that patients need to accomplish in daily life, using various control methods. Rachel B. Tabor et al. introduced an impedance control strategy based on an adaptive control architecture, integrated into treadmill training, with a focus on improving the biomechanics and dynamic stability of the patient's gait. The study showed that this task-oriented training excelled in improving the swing angle and dorsiflexion angle of the affected ankle. Compared to extensive exercises focusing only on the affected joints, this task-based training method demonstrated superior outcomes in restoring functional dorsiflexion and push-off [19]. Xiao Li et al. designed and analyzed an exoskeleton robot system for upper limb rehabilitation, employing a task-oriented training strategy. In terms of control strategy, this study applied a hybrid strategy based on adaptive control and feedback control through a multi-degree-of-freedom robotic mechanism combined with a biomechanical model, aiming to simulate specific tasks that patients need to accomplish in daily life. This strategy helps patients undergo rehabilitation training in real-life tasks, thereby improving the functional effectiveness and adaptability of the rehabilitation [20].

# 4. Current State of Clinical Application Research on Ankle-Foot Rehabilitation Robots

Although ankle-foot rehabilitation robots still face challenges in clinical application, their broad prospects bring new possibilities for future rehabilitation therapy. These robots significantly improve rehabilitation quality by enhancing rehabilitation efficiency and shortening recovery time, especially during the critical phase of functional recovery after the acute stage. Their structural design and control strategies—such as rigid, flexible, and rigid-flexible coupled actuators, along with different control strategies—directly influence rehabilitation outcomes and patient experience. Through these technologies, rehabilitation training can be standardized and personalized, while also reducing costs and alleviating the economic burden on patients. This section will summarize the current research

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status of clinical applications of ankle-foot rehabilitation robots, combining studies on structural devices and driving methods.

### 4.1. Clinical Application Effects of Flexible, Rigid, and Rigid-Flexible Coupled Designs in Ankle Rehabilitation Robots

Mingming Zhang et al. developed a compliant ankle rehabilitation robot (CARR) for the treatment of foot drop, where its flexible actuators provide precise trajectory tracking control using Festo Fluidic Muscles (FFM) to guide the ankle joint of foot drop patients to the specified position. Clinical trials demonstrated that this robot showed excellent results during the early stages of rehabilitation, effectively reducing patient discomfort and lowering the risk of secondary injury, highlighting its potential for widespread application in foot drop treatment [21]. Rigid-structure actuators perform outstandingly in rehabilitation training requiring high precision control. Anindo Roy et al. developed a three-degree-of-freedom ankle rehabilitation robot, which, through reverse driving and low mechanical impedance design, focuses on helping patients restore their ankle joint's range of motion (ROM). Clinical tests showed that this robot effectively improved ankle joint stiffness during mid-to-late rehabilitation through precise torque control, proving its practicality in rehabilitation training [22]. The ARBOT rehabilitation robot designed by Jody A. Saglia et al. combines the advantages of rigid-flexible coupled design, utilizing a 3UPS/U parallel platform structure and admittance control technology to meet the needs of patients at different rehabilitation stages [23]. This robot adjusts resistance and support force effectively through auxiliary control algorithms, particularly showing high practicality in active patient exercises, offering greater flexibility in providing personalized rehabilitation solutions in different clinical scenarios [24].

### 4.2. Personalized Design of Ankle-Foot Rehabilitation Robots: Optimization in Design and Clinical Application

Jianjun Zhang et al. proposed the concept of an "Ankle-Foot Comfort Zone" and developed a UR-equivalent model of the ankle joint and a three-degree-of-freedom parallel ankle rehabilitation robot by measuring ankle-foot movement data using surface markers. They experimentally verified the coupling of ankle-foot movements and proposed evaluation metrics for the ankle-foot comfort zone, providing a theoretical foundation for optimizing the design of ankle-foot rehabilitation robots and laying the groundwork for their practical application in clinical settings [25]. Renyu Yang et al. developed the Voluntary and Assist As Needed (VAAN) controller, which enhances patient interaction through a visual feedback interface and conducted clinical experiments. The experiments indicated that as the level of disability increased, the trajectory tracking error also increased, but the VAAN controller improved rehabilitation efficiency through precise adjustments. This controller can dynamically adjust according to the actual needs of the patient, with personalized adjustments of control strategies being crucial for improving rehabilitation outcomes, especially in patients with higher levels of disability [26]. Haoyong Yu et al. designed a gait rehabilitation robot that uses a new compact series elastic actuator, integrating control designs such as human-machine interaction compensation, friction compensation, and disturbance observers. In experiments, this robot demonstrated precise torque tracking control capabilities, particularly in zero-force control and assistive force control tests. The experimental results showed that this actuator could provide precise assistive torque to human joints, indicating its potential for clinical application in gait training for stroke patients. The design of this actuator plays a critical role in enhancing the accuracy and efficiency of rehabilitation training, further demonstrating the importance of new control strategies in clinical rehabilitation [27].

### 4.3. Personalization and Daily Integration of Wearable Ankle-Foot Rehabilitation Technology in Clinical Applications

Louis N. Awad et al. developed a flexible wearable ankle-foot rehabilitation robot that uses functional fabric anchors and a cable transmission system to transfer the mechanical power generated by the actuator to the patient. Through clinical trials, Awad and colleagues evaluated the effectiveness of this device in restoring patients' gait mechanics and energetics. The results indicated that this wearable device not only significantly improved patients' walking function but also offered higher comfort and ease of use. This demonstrates the broad application potential of wearable devices in rehabilitation, particularly in their integration into daily life [1]. Bruce H. Dobkin et al. explored the application of mobile health technology (mHealth) in rehabilitation therapy, utilizing wireless ankle accelerometers and the MDAWN platform to monitor patients' lower limb activities. By analyzing data from international research institutions, the study assessed key indicators such as patients' daily walking speed. The experimental results showed that feedback enhanced patients' activity levels and rehabilitation exercises, proving the potential of mobile health technology to improve rehabilitation outcomes [28].

Table 1: Examples of Clinical Applications of Ankle-Foot Rehabilitation Robots.

| Researchers | Age (mean ± std) | Time from Stroke | N (exp/ctrl) | BCI Intervention Method | Control Group | Intervention Time (total sessions) | Outcome Measures |
|---|---|---|---|---|---|---|---|
| Mingming Zhang et al. | 61 (45-76) | 12 m | 3 (1/2) | CARR | Sham | 6 w, 3 d/w | DP, ROM, Muscle Strength |
| Anindo Roy et al. | 54 ± 10 | 10 m | 10 (5/5) | Robot-Assisted Therapy | Conventional | 8 w, 2 d/w | Ankle Stiffness |
| Jody A. Saglia et al. | 34 ± 5 | N/A | 5 (3/2) | ARBOT | MI only | 4 w, 2 d/w | EMG, ROM, Muscle Activation |
| Jianjun Zhang et al. | 40 ± 6 | 7 m | 4 (2/2) | New Evaluation Index | Sham | 12 w, 2 d/w | Comfort Zone, Ankle Motion |
| Renyu Yang et al. | 55 ± 8 | 24 m | 7 (5/2) | VAAN Controller | MI only | 6 w, 3 d/w | MVC, ROM, Muscle Activation |
| Louis N. Awad et al. | 49 ± 12 | 72 m | 9 (5/4) | Wearable Exosuit | Sham | 8 w, 3 d/w | Gait Mechanics, Energy Efficiency |
| Haoyong Yu et al. | 30 ± 7 | 9 m | 3 (2/1) | Series Elastic Actuators | Sham | 4 w, 2 d/w | Torque Tracking, Gait Training |
| Bruce H. Dobkin et al. | 57 ± 11 | 18 m | 16 (8/8) | Wireless Monitoring | Control | 12 w, daily | Daily Activity, Lower Limb Function |

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## 5. Conclusion

This study provides a comprehensive review of ankle-foot rehabilitation robots, focusing on the current state of rigid, flexible, and hybrid structures, control methods, and clinical applications. Rigid structures, known for their high precision and stability, can provide a clear motion path during rehabilitation but may pose a risk of secondary injury due to the high output force. Flexible structures, with their high adaptability and good conformity to the human body, can offer safer support in complex rehabilitation scenarios, although they are more challenging to control. Hybrid structures that combine the advantages of both rigid and flexible designs are becoming the direction for future development of rehabilitation robots, ensuring both precision and safety.

In terms of control methods, ankle-foot rehabilitation robots have evolved from simple passive control to more complex strategies such as active control and impedance control, supporting various stages of rehabilitation from guided movement to autonomous movement. The optimization of these control strategies has enabled the robots to better meet the needs of different patients, thereby enhancing rehabilitation outcomes. Furthermore, these robots have already shown good results in clinical applications, particularly in improving rehabilitation efficiency, shortening recovery time, and providing personalized treatment plans. However, challenges remain, such as the need for lighter robot designs, further optimization of control algorithms, and more precise patient feedback systems. Future research should focus on further optimizing the design of hybrid structures, developing smarter control algorithms to enhance human-robot interaction, and strengthening research on the application of robots in various clinical scenarios. This will promote their wider clinical application and provide patients with more personalized and efficient rehabilitation solutions.

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