Progress in
Medical Devices

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REVIEW ARTICLE

Review of key technologies in ankle rehabilitation robots

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Received May 24, 2025; Accepted July 25, 2025; Published March 24, 2026

DOI: 10.61189/730741lcujht

Abstract

Ankle rehabilitation robots represent an important branch of rehabilitation robotics, offering significant potential to improve the quality of life for patients with ankle dysfunction caused by stroke, sports injuries, and other conditions. This review first outlines the anatomy and range of motion of the ankle joint, compares conventional rehabilitation approaches with robot-assisted therapy, and highlights the clinical significance of ankle rehabilitation robots. It then systematically examines current research progress from two core perspectives: mechanical structure design and control strategies. In mechanical design, the performance characteristics of series versus parallel mechanisms are compared, the advantages and limitations of actuation methods such as electric motors and pneumatic artificial muscles are analyzed, and the application contexts of platform-based and wearable robots are discussed. In control strategies, the discussion covers motion control and human-robot interaction, beginning with fundamental position, velocity, and trajectory tracking control, and extending to intention-level and cognitive interaction. Finally, based on current research and clinical needs, future ankle rehabilitation robots are expected to evolve toward greater flexibility, intelligence, and universality, providing a theoretical foundation for future studies.

Keywords: Ankle rehabilitation robot, Mechanical design, Control strategy, Human-Robot interaction

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Highlights

- As a primary weight-bearing joint, the ankle is highly susceptible to injury, while neurological disorders such as stroke can further impair its motor function, leading to long-term gait disturbances.
- Rehabilitation robots can be platform-based or wearable: platforms aid early-stage motion restoration, while wearable designs focus on gait retraining.
- Control systems must prioritize motion accuracy and safety. Adaptive algorithms boost performance, while bioelectric signal integration enables intention recognition. Coupling with virtual or augmented reality further enhances patient engagement.

1 INTRODUCTION

As the joint with the highest load-bearing capacity in the human body, the ankle has a complex physiological structure. Its bony anatomy and degrees of freedom (DOF) are shown in **Figure 1** [1]. The ankle joint is primarily composed of the tibia, fibula, talus, and calcaneus, and has three DOF: dorsiflexion/plantarflexion (DO/PL) in the sagittal plane, adduction/abduction (AD/AB) in the horizontal plane, and inversion/eversion (IN/EV) in the coronal plane.

The ankle is highly susceptible to both acute injuries and chronic disorders. As the primary load-bearing joint of the skeleton, it sustains forces approximately five times body weight during normal walking and up to 13 times body weight during running [2]. Consequently, ankle sprains are among the

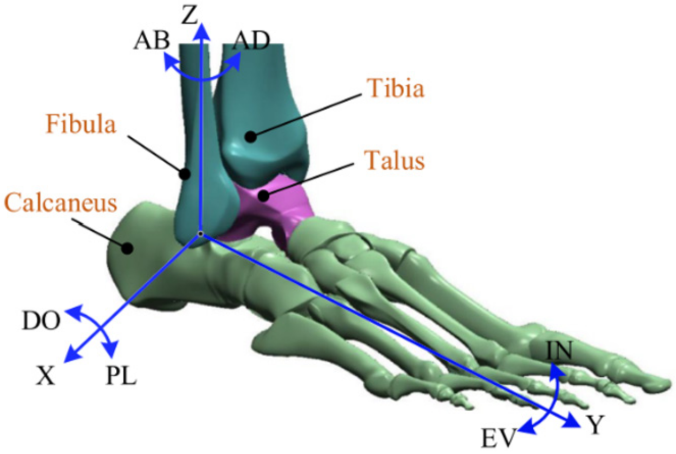

Figure 1. Bony structure and degrees of freedom (DOF) of the ankle joint. This figure is cited from [1]. AD/AB, Adduction/Abduction; IN/EV, Inversion/Eversion; DO/PL, Dorsiflexion/Plantarflexion.

most common sports injuries, accounting for about 7-10% of all cases [3]. Anatomically, the medial malleolus is formed by the distal tibia, whereas the lateral malleolus is formed by the distal fibula. Because the lateral malleolus is positioned lower and the medial deltoid ligament is stronger than the lateral ligament complex, the ankle is more prone to inversion injuries [4].

Notably, up to 50% of patients with acute ankle sprains do not seek formal medical care, leading to recurrent sprains over subsequent months or years. Even with structured rehabilitation, up to 70% experience persistent functional impairment within 6 months, progressing to functional ankle instability [5].

In addition to trauma, chronic neurological conditions—particularly stroke—can severely impair ankle motor function [6]. According to the World Health Organization, the proportion of the global population aged ≥60 years will rise from 12% in 2015 to 22% in 2050, reaching 2.1 billion people [7]. As stroke prevalence increases with age, the incidence of stroke-related ankle dysfunction is expected to rise accordingly.

Ankle injuries, which often result in long-term pain and functional limitations even after the initial recovery, restrict daily activities and diminish quality of life [8]. Patients often face gait instability, balance deficits, and difficulty walking, substantially reducing independence. Therefore, restoring motor function and mobility is a clinical priority.

Rehabilitation training has been shown to improve post-stroke outcomes, prevent muscle atrophy and deep vein thrombosis, and enhance mobility [9, 10]. Early rehabilitation after ankle injury is essential to minimize the adverse effects of prolonged bed rest. Current rehabilitation programs typically include stretching, gait training, constraint-induced movement therapy, and other neuroplasticity-enhancing interventions [11]. However, conventional rehabilitation requires intensive involvement from medical teams and family members, and is limited by constrained healthcare resources, high costs, low efficiency, and inconsistent movement quality [12].

Robot-assisted therapy offers a promising solution to these challenges [13]. It enables more effective, standardized rehabilitation under medical supervision, mitigates workforce shortages, reduces costs, and improves training efficiency. Furthermore, rehabilitation robots can collect detailed kinematic and kinetic data to monitor progress. When combined with virtual reality (VR), such systems can enhance patient engagement and motivation, benefiting both physical and psychological recovery [14-16].

This review summarizes advances in ankle rehabilitation robot design and control strategies based on a comprehensive literature survey. Section 2 discusses mechanical design classifications, Section 3 examines control strategy classifications, and Section 4 presents conclusions and future perspectives.

2 MECHANICAL STRUCTURE DESIGN

The mechanical structure of an ankle rehabilitation robot is a key determinant of its motion performance and therapeutic efficacy. Based on design approach, current systems can be classified as series, parallel, or hybrid structures. Series configurations are lightweight and mechanically simple but have limited capacity to replicate the ankle's complex motions. Parallel configurations offer high precision and large torque output but have a restricted range of motion. Hybrid configurations combine the strengths of both, balancing flexibility and stability, though their structural complexity often leads to classification under either predominantly series or parallel designs.

The choice of actuation method—such as electric motors or pneumatic muscle actuators (PMAs)—also influences flexibility and energy efficiency. Motor drives are more suitable for late-stage rehabilitation requiring high precision and rapid response, whereas PMAs are preferred in early-stage rehabilitation where safety and compliance are prioritized.

In early rehabilitation, rigid platform-based devices can provide stabilizing support and improve ankle range of motion through passive and active training modes. During gait recovery, flexible wearable robots facilitate real-time, dynamic assistance to restore a normal gait cycle. **Table 1** summarizes the structural characteristics, suitable rehabilitation stages, advantages, and limitations of platform-based versus wearable ankle rehabilitation robots.

2.1 Structural form

2.1.1 Series structure

Lee et al. developed a compact cable-driven series elastic actuator (SEA) capable of lightweight design and high-precision torque output, achieved through gait-phase–synchronized

Table 1. Comparison between platform ankle rehabilitation robot and wearable rehabilitation ankle robot

Ways to use	Platform ankle rehabilitation robot	Wearable ankle rehabilitation robot
Structural features	Rigid structure, often using multi-degrees of freedom parallel mechanism, with certain support force	Flexible and lightweight exoskeleton structure
Drive mode	Mainly motor driven, less pneumatic artificial muscles	Mainly pneumatic artificial muscles, less motor drive
Applicable rehabilitation stage	Suitable for early passive training and mid-term active resistance training, etc.	Suitable for mid- to late-stage gait training and daily activity assistance, etc.
Advantages	Multi-degrees of freedom coupling training capability is strong, output accuracy is high, and load capacity is large	Highly portable, comfortable to wear, supports real-time dynamic gait assistance
Limitation	The system is large and expensive, and is not suitable for home rehabilitation scenarios	Low load capacity, limited freedom, short battery life

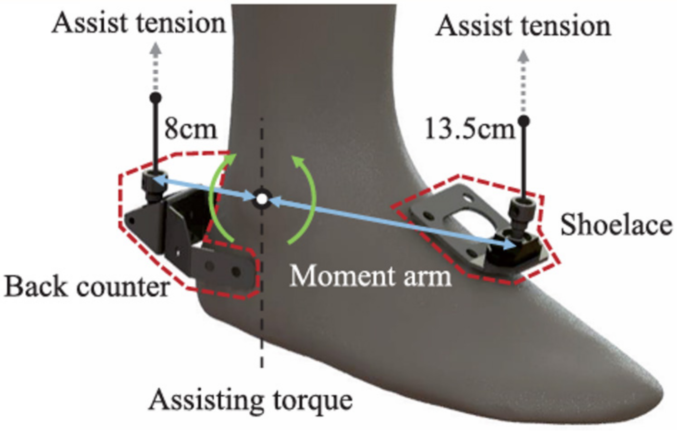

Figure 2. Compact cable driven series flex modules. This figure is cited from [17].

Figure 3. Personalized ankle exoskeleton based on series elastic actuator. This figure is cited from [18]. AFO, Ankle Foot Orthosis.

feedforward friction compensation and nonlinear spring control [17]. This device targets foot drop and propulsion deficits in stroke patients but does not provide full ankle joint DOF (**Figure 2**).

Eraky et al. designed a personalized ankle exoskeleton employing an SEA with cable drive and 3D scanning–based customization, enabling both lightweight construction and high torque output [18]. However, it lacks full ankle DOF coverage and requires individualized parameter adjustments (**Figure 3**).

Choi et al. proposed an SEA driven by a flexible shaft, achieving low inertia and precise torque tracking through nonlinear stiffness linearization and disturbance observer control [19]. Nevertheless, it has limited bandwidth and does not encompass the full DOF of the ankle joint (**Figure 4**).

2.1.2 Parallel structure

Wang et al. designed a novel 2-UPS/RRR parallel ankle rehabilitation robot (PARR) and developed a height-adjustable mobile platform to align with the ankle rotation center of different patients (**Figure 5**) [20]. The 2-UPS/RRR mechanism consists of two UPS active branches and one RRR passive branch, forming a 3 DOF parallel mechanism. Each UPS branch comprises a universal (U) joint, a prismatic (P) joint, and a spherical (S) joint in series, while the RRR branch consists of three revolute (R) joints in series.

Huo et al. developed a full-cycle PARR with large angular range, high torque, and multi-DOF coupled rehabilitation capabilities [21]. The design achieves complete constraint through rigid branches without applying additional force to the ankle, employs a cable drive, and offers three DOF (**Figure 6**).

Xie et al. proposed a 3 DOF dual-ankle rehabilitation robot based on a 3-SPS/RUR parallel mechanism with adjustable inter-ankle distance [22]. The system supports both circular and linear rehabilitation trajectories (**Figure 7**). Here, 3-SPS/RUR denotes a parallel mechanism comprising three SPS active branches and one RU*R passive branch, where the underline indicates a passive kinematic pair.

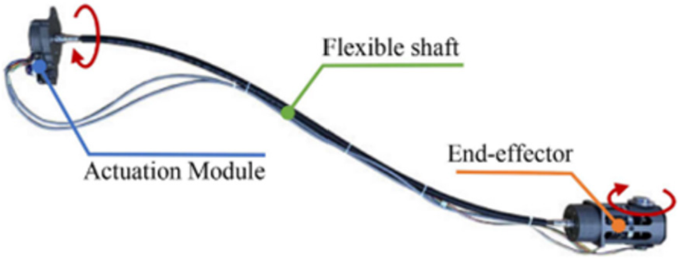

Figure 4. Flexible series elastic actuator. This figure is cited from [19].

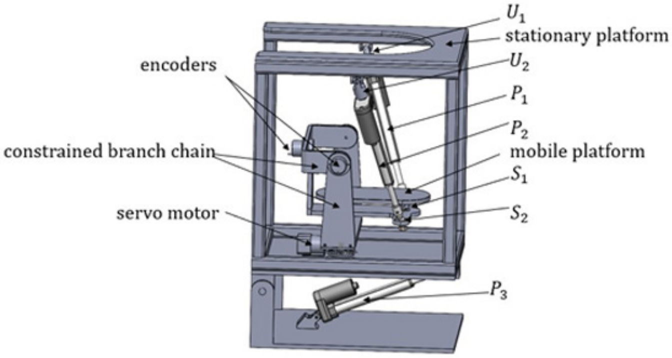

Figure 5. 2-UPS/RRR parallel ankle rehabilitation robot. This figure is cited from [20]. U, Universal; P, Prismatic; S, Spherical; R, Revolute.

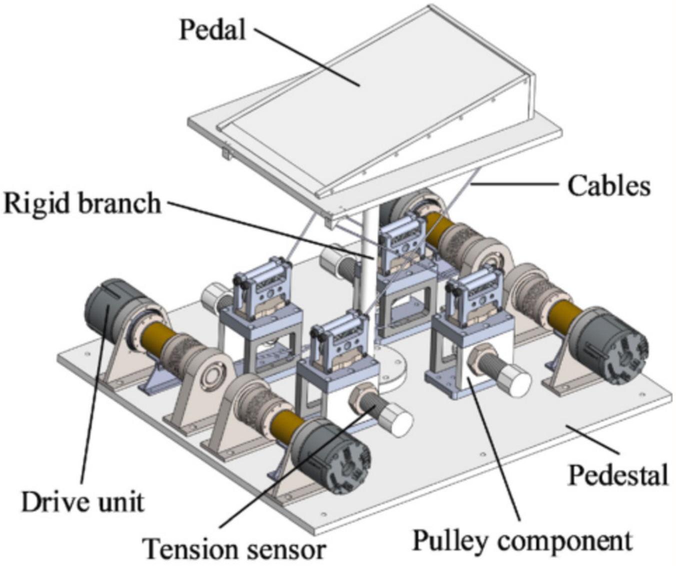

Figure 6. Full-cycle parallel ankle rehabilitation robot. This figure is cited from [21].

2.2 Drive mode

2.2.1 Motor drive

Motors convert electrical energy into mechanical energy via an electromagnetic field, delivering torque or rotational speed. Through mechanical connections such as gears and synchronous belts, the output is linearly related to the input signal, and the electromagnetic response time is extremely short. Consequently, motor control offers high precision and rapid response. However, motors are relatively heavy, have low power density, and often require a reducer. Common types include direct current (DC) motors, servo motors, and stepper motors. DC motors are suited for medium-precision, medium-load control; servo motors are preferred for high-precision, high-power applications; and stepper motors are ideal for low-speed, high-precision tasks.

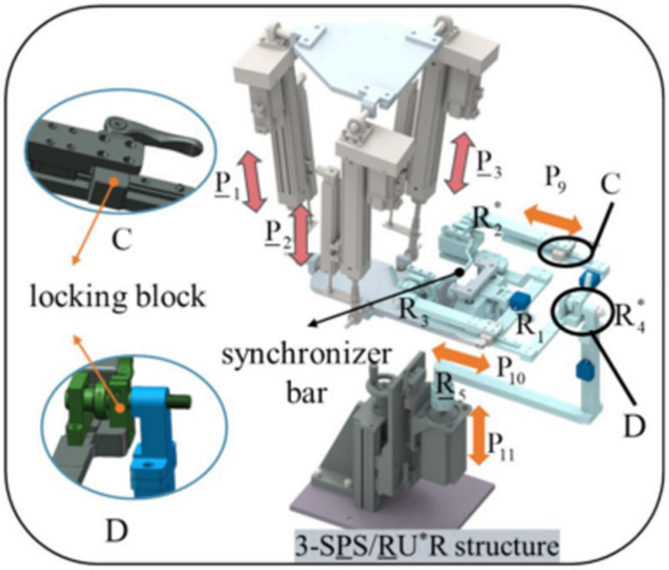

Figure 7. 3-SPS/RU*R parallel ankle rehabilitation robot. This figure is cited from [22].

Wu et al. developed an end-effector ankle rehabilitation robot using magnetic field–oriented control to drive a brushless DC motor, combined with planetary reduction gears of varying ratios to power all ankle motion actuators on a slider (**Figure 8**) [23].

Zeng et al. designed a rope-driven flexible ankle rehabilitation robot inspired by bionic principles [24]. The rope system, directly connected to the mobile platform via a steering pulley, is actuated by a servo motor. By employing a flexible equivalent motion axis and rope-drive mechanism that mimic the physiological ankle structure, this design addresses the human–machine motion mismatch seen in rigid ankle rehabilitation robots, enabling more natural movement compatibility (**Figure 9**).

Do et al. proposed a 1 DOF ankle rehabilitation system in which a stepper motor directly drives the pedals to perform dorsiflexion/plantarflexion [25]. This low-cost system aims to provide an economical and adaptable ankle rehabilitation solution for resource-limited settings (**Figure 10**).

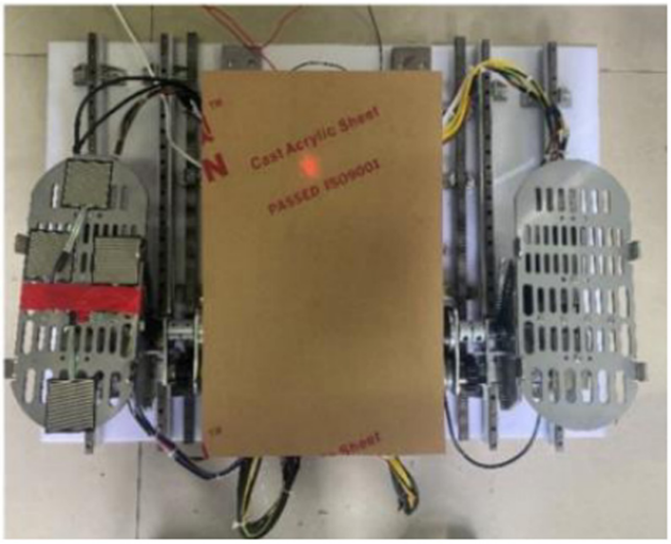

Figure 8. Brushless direct current motor ankle rehabilitation robot. This figure is cited from [23].

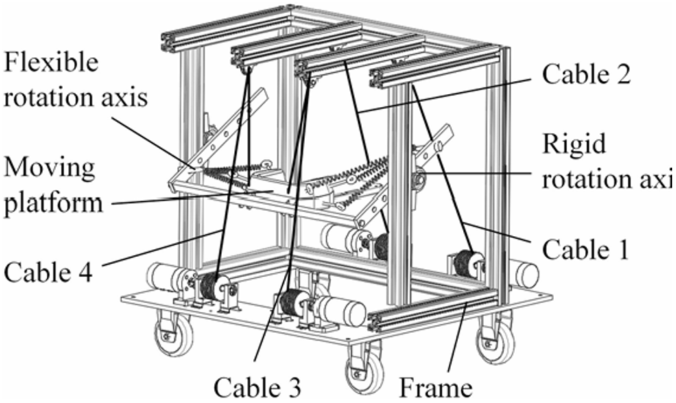

Figure 9. Servo motor ankle rehabilitation robot. This figure is cited from [24].

2.2.2 PMA

PMAs offer muscle-like compliance, making them well-suited for rehabilitation robots requiring flexibility and human-like motion, particularly in early rehabilitation stages or for compliant control. PMAs operate by using compressed air to contract a rubber or fabric tube, generating tension through material deformation. However, elastic hysteresis, creep, and the pressure transmission delay caused by air compression/expansion reduce control accuracy.

Lu et al. developed a flexible multi-DOF ankle rehabilitation robot using five PMAs, with tension transmitted to the moving platform via a flexible cable–pulley system [26]. A redundant drive configuration ensures forced closure and high platform stability (**Figure 11**).

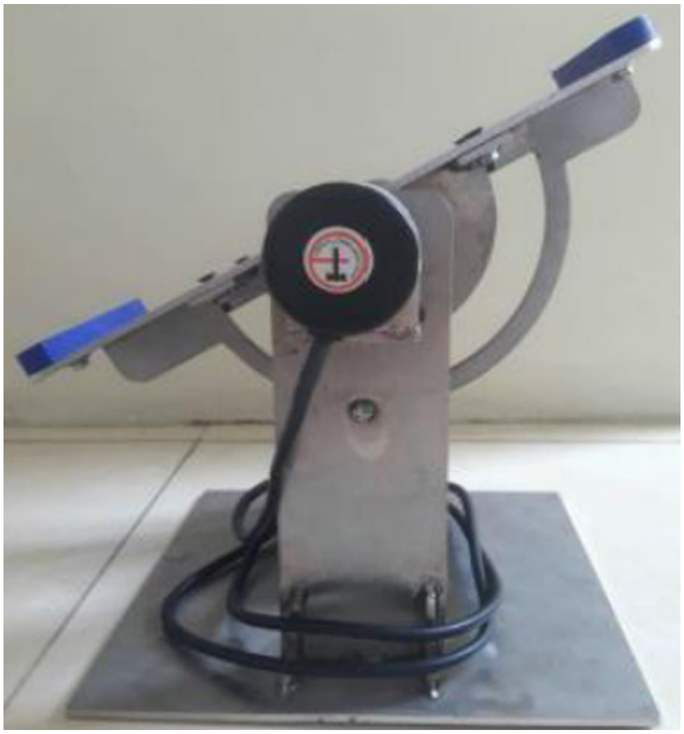

Figure 10. Stepper motor ankle rehabilitation robot. This figure is cited from [25].

Shamkhani et al. designed a wearable flexible ankle rehabilitation robot powered by six PMAs positioned around the foot (front, back, left, and right) [27]. Inflation and deflation of each PMA are manually controlled to provide assistance in all ankle joint directions (**Figure 12**).

Banyarani et al. proposed a soft wearable robot incorporating pleated fabric PMAs for walking assistance [28]. Their work covered mechanical modeling, manufacturing, exoskeleton system integration, biomechanical analysis, and experimental validation, demonstrating that pleated fabric PMAs offer lightweight, flexible support for individuals with disabilities or muscle weakness, reducing muscle fatigue during walking (**Figure 13**).

2.3 Ways to use

2.3.1 Platform ankle rehabilitation robot

Early ankle rehabilitation robots typically featured only 1-2 DOF and limited functionality. Since Girone et al. at Rutgers State University introduced the “Rutgers Ankle”—a 6 DOF PARR driven by pneumatic actuators based on a Stewart platform—the field has advanced significantly (**Figure 14**) [29]. The Stewart platform, widely used in flight simulators, precision positioning systems, robotics, and medical rehabilitation, comprises two parallel rigid platforms: a fixed lower platform and a movable upper platform with 6 DOF. The platforms are

Figure 11. A flexible multi- degrees of freedom ankle rehabilitation robot. This figure is cited from [26].

Figure 12. A wearable flexible ankle rehabilitation robot. This figure is cited from [27].

connected by six independently adjustable retractable links, actuated pneumatically, hydraulically, or electrically, enabling translational and rotational motion of the upper platform in space.

Budaklı et al. developed a rehabilitation robot capable of simultaneous ankle and knee therapy by incorporating a seventh linear actuator and a specially designed mechanical structure, thereby expanding the traditional Stewart platform's workspace to accommodate knee rehabilitation (**Figure 15**) [30].

Wang et al. proposed a 6 DOF PARR employing flexible ball joints [31]. This design uses motor actuation, replaces conventional spherical joints with flexible hinge technology to eliminate clearance errors, and integrates Stewart platform architecture with compliant mechanism technology to form a novel hybrid structure (**Figure 16**).

Beyond Stewart-platform-based 6 DOF PARRs, other platform-type designs with varying actuator configurations and linkage arrangements are also applied. For instance, Zou et al. designed a 3-RRS PARR capable of performing both single-ankle and compound-ankle rehabilitation training [32].

2.3.2 Wearable ankle rehabilitation robot

Xia et al. developed a wearable rope-driven ankle exoskeleton capable of providing DO/PL assistance [33]. The system employs an iterative adaptive threshold algorithm combined with a peak detection algorithm to identify gait patterns in real time, enhancing detection accuracy. A hierarchical adaptive force–position hybrid control strategy is implemented to dynamically adjust control modes and optimize assistance. Preliminary tests on three healthy subjects demonstrated that the device effectively reduced metabolic cost during walking (**Figure 17**).

Wang et al. proposed a wearable ankle exoskeleton with a self-locking protection system based on plantar pressure feedback [34]. Real-time plantar pressure sensing is used to monitor gait state, distinguish normal walking from accidental falls, and improve fall detection accuracy through support vector machine–based data processing. The design integrates passive self-locking with active control strategies to provide dynamic ankle protection (**Figure 18**).

3 CONTROL STRATEGY DESIGN

Ankle rehabilitation robots employ various control methods, each of which can influence the patient's rehabilitation experience. Control strategies can be classified according to factors such as control objectives, interaction modes, and feedback signal types. For clarity, these strategies can be divided into two core categories: motion control and human–robot interaction control, corresponding to low-level and high-level control, respectively.

Low-level control focuses on the basic motion functions of ankle rehabilitation robots, including position control, speed control, and trajectory tracking. High-level control emphasizes interactive functions, with the most fundamental form being physical-layer interaction—such as force or resistance control. Building on this foundation, control can extend to intention-level interaction, where movement intention is recognized via bioelectrical signals such as electromyography (EMG) or electroencephalography (EEG), and to cognitive interaction, which

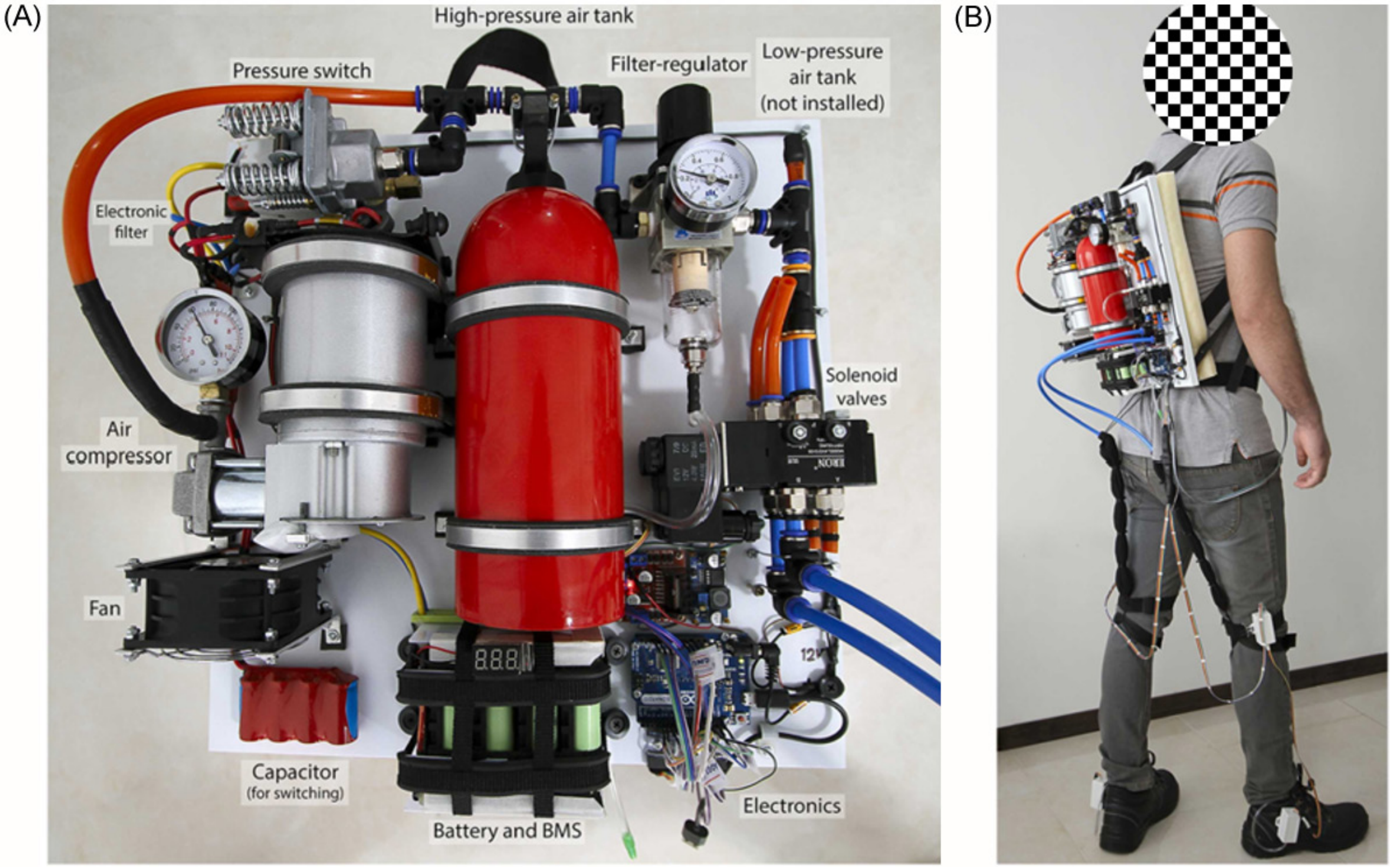

Figure 13. Wearable soft wearable robot. (A) Air supply backpack; (B) Wearing Diagram. This figure is cited from [28]. BMS, Battery Management System.

Figure 14. Rutgers Ankle. This figure is cited from [29].

uses multimodal control through VR or augmented reality (AR).

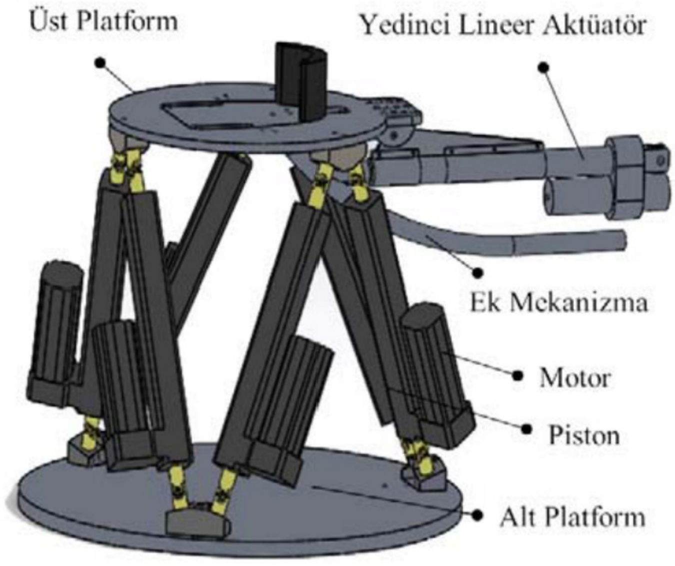

Figure 15. Ankle and knee rehabilitation robot based on Stewart. This figure is cited from [30].

Table 2 summarizes the design objectives, advantages, and limitations of different control methods—including position/speed control, trajectory tracking, force/impedance control,

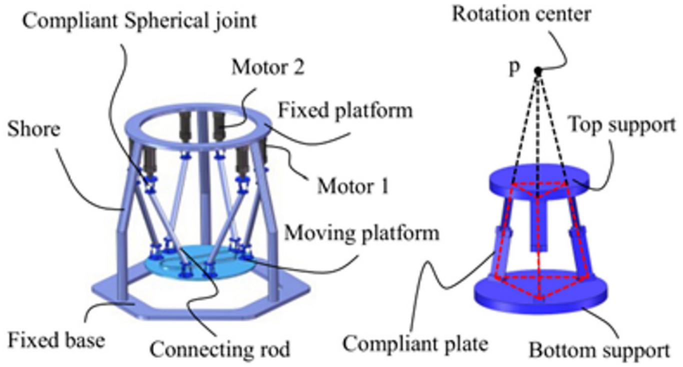

Figure 16. 6 DOF PARR based on flexible ball joints. This figure is cited from [31].

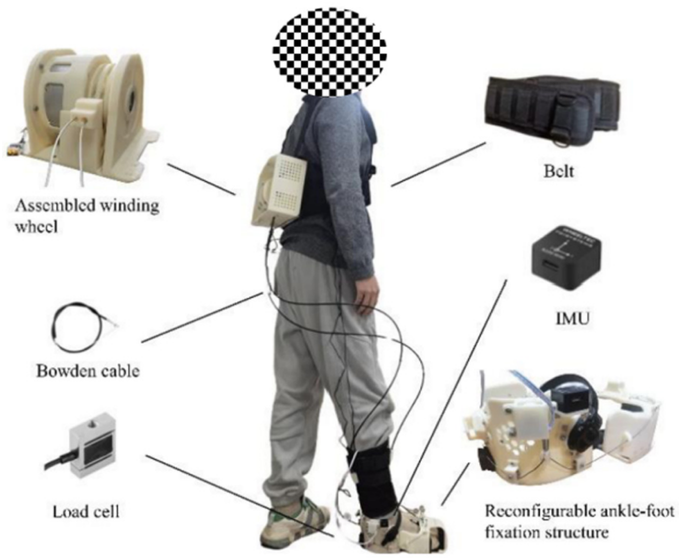

Figure 17. Wearable rope-driven ankle exoskeleton system. This figure is cited from [33]. IMU, Inertial Measurement Unit.

intention recognition, and cognitive interaction—according to their control strategy.

3.1 Motor function control

3.1.1 Position and speed control

Azizi et al. developed a DC motor position control system using a classical proportional–integral–derivative (PID) controller to regulate motor position and speed in ankle rehabilitation robots, enabling precise angle adjustment during training [35]. Lee et al. proposed a 2-DOF ankle exoskeleton employing PID neural network control, in which neural networks adaptively optimize PID parameters, providing high-precision and robust performance [36]. Li et al. introduced an isokinetic muscle training strategy based on adaptive gain and cascade PID control [37]. In this approach, when patients actively exert force, the robot maintains constant-speed motion while applying variable resistance, enhancing muscle training across different joint angles.

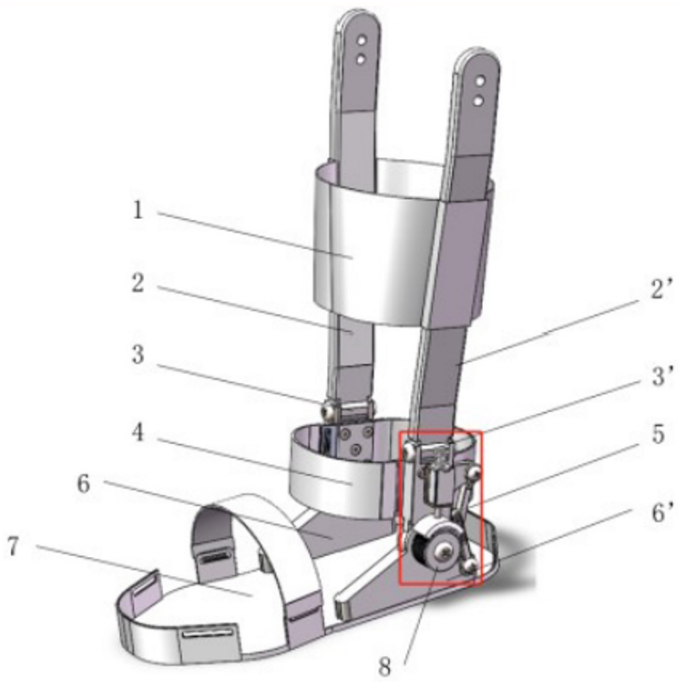

Figure 18. Wearable ankle exoskeleton self-locking protection system based on plantar pressure feedback. This figure is cited from [34]. 1, Fixing strap; 2, Leg support; 3, Joint bearing; 4, Leg support; 5, Achilles tendon connecting rod; 6, Support frame; 7, Base plate; 8, Self-locking device.

3.1.2 Trajectory control

Zhang et al. presented an adaptive trajectory tracking strategy for PARR systems with joint-space force distribution, combining cascade control with a motion-intention–guided algorithm to ensure accurate path following [38]. Liu et al. designed a multi-mode ankle rehabilitation robot for IN/EV training, normal gait training, and stepping training [39]. Dedicated trajectory plans for each mode enable complete motion execution and emergency stops at any position. Wang et al. developed a multistage hemiplegic lower-limb exoskeleton [40]. Gait data were collected via motion capture, calibrated with a backpropagation neural network, and fitted using Fourier functions to generate a high-precision trajectory model, achieving accurate multi-joint (hip, knee, ankle) tracking.

3.2 Human-robot interaction control

3.2.1 Force/torque control

Qian et al. proposed an iterative impedance learning method with a dual-loop structure: the outer loop adapts impedance parameters, while the inner loop executes torque control [41]. This allows patient-specific impedance adaptation through

Table 2. Summary and comparison of control strategies

Control strategy	Subcategories	Design purpose	Advantages	Limitation
Motion Control	Position/speed control	Achieve precise angle or speed adjustment	The algorithm is simple and reliable	Fixed parameters are difficult to adapt to individual differences or changes in rehabilitation progress
	Trajectory tracking control	Plan and track complex rehabilitation trajectories	Preset Trajectory, high stability	High computational complexity, relying on predefined trajectories or training data
Human-robot interaction control	Force/Impedance Control	Achieving safe human-machine interaction	The algorithm is simple and reliable	Sensitive to sensor accuracy and feedback delay
	Intention recognition control	Identifying patients' active movement intentions through bioelectric signals	Improving patient engagement and promoting neuroplasticity	Individual differences are large, and the signal is easily affected by interference
	Cognitive Interactive Control	Combine virtual scenes to enhance the fun of training	Enhance immersion, improve training fun and active participation	High hardware cost and complex algorithm development

repeated tasks, improving interaction quality. Liu et al. developed a redundant pneumatic muscle–cable-driven ankle robot with a hierarchical force–position control scheme [42]. Using the Karush–Kuhn–Tucker theorem and iterative optimization, force distribution is solved as a constrained problem, ensuring all actuators remain in tension for safety and controllability while combining precise trajectory tracking with safe force regulation. Li et al. introduced a dynamic admittance control strategy using a variable-operator fuzzy neural network to adjust virtual damping in real time, reducing muscle fatigue and extending training sessions according to patient needs [43].

3.2.2 Intention recognition control

Shi et al. presented an EEG-driven collaborative control model, extracting EEG deep features via convolutional neural networks and classifying them with a support vector machine to achieve high-precision intention recognition and active control, enhancing patient engagement [44]. Zhou et al. developed an sEMG-based ankle motion prediction model to estimate torque generation during movement, improving adaptability and control accuracy across individual differences [45].

3.2.3 Cognitive interaction control

Covaciu et al. designed a VR-based intelligent ankle rehabilitation system with an apple-catching game [46]. Motion data from accelerometers, gyroscopes, and EMG sensors are processed using a k-nearest neighbors algorithm to adapt task difficulty and control strategies, reducing therapist workload while enhancing engagement. Zhang et al. proposed a VR-assisted decision model based on a convolutional gated recurrent neural network, optimized via the whale optimization algorithm [47]. Immersive environments such as space walking and mountain climbing allow patients to control virtual characters through ankle movements for tasks like path following and obstacle avoidance. Vaida et al. developed an AR-integrated lower-limb rehabilitation system combining the LegUp parallel robot with HoloLens 2 [48]. Serious-game modules ("football mode" and "color mode") target motor coordination, strength, and cognitive training, offering multi-plane hip, knee, and ankle rehabilitation with real-time feedback.

4 CONCLUSION AND OUTLOOK

This review summarizes recent progress in the mechanical design and control strategies of ankle rehabilitation robots, highlighting notable advances while identifying persistent limitations. Series structures, though lightweight and suited for simple motion training, have limited dynamic performance, whereas parallel structures provide high precision and multi-DOF capability but require complex control, making them more appropriate for advanced rehabilitation and currently the most widely adopted. In actuation, motor drives offer high precision and strong rigidity for heavy-load applications but are less flexible, heavier, and less portable, while pneumatic muscles enable compliant control and passive stretching in early rehabilitation but suffer from nonlinear air pressure characteristics, inflation/deflation delays, and limited high-frequency responsiveness. Platform-based systems deliver stable support and accurate multi-DOF motion for early-stage passive training but are bulky and unsuitable for home use, whereas wearable devices, despite their portability, have lower load capacity and DOF, rely on batteries or pneumatic systems, and are better suited for mid- to late-stage gait recovery. Motion control strategies based on traditional robotics provide reliable and easy-to-implement algorithms for passive rehabilitation but are limited to basic movement execution, often failing to adapt to patient-specific needs or detect active intentions, which may reduce engagement. Human–robot interaction control, incorporating biological signals or VR/AR, enables more active participation, with intention recognition emerging as a key research focus; however, signal noise, individual variability, and real-time constraints remain technical challenges, and VR/AR integration, while improving engagement, increases system complexity and cost. Looking forward, the development of ankle rehabilitation robots is expected to move toward greater flexibility, intelligence, and accessibility by combining lightweight designs with flexible materials to enhance comfort, integrating multimodal biosignals such as EMG, EEG, plantar pressure, and inertial measurements into efficient AI-based control for improved intention recognition, and enriching VR/AR interaction through eye tracking, tactile feedback, and biomechanical sensing to create more immersive and realistic training. At the clinical level, adopting modular designs and scalable manufacturing will help reduce costs, enabling broader access to high-quality rehabilitation for patients in need.

DECLARATIONS

Author contributions

Jiajia Zha: Conceptualization, Methodology (Discussion), and Writing original draft preparation. Qingyun Meng: Conceptualization, Supervision, Project administration, and Writing reviewing and revising. Hongtao Shen and Mingxia Wei: Critical review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript and ensure the integrity of the work.

Funding

This research received no external funding.

Data availability

All data analyzed during this study are included in this published article. No new data were created or analyzed.

Ethics approval and consent to participate

Not applicable. This is a literature review article that does not involve any new studies with human participants or animals.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

Not applicable.

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