

Review

Advancements in State-of-the-Art Ankle Rehabilitation Robotic Devices: A Review of Design, Actuation and Control Strategies

Asna Kalsoom ¹, Muhammad Faizan Shah ^{2,*} and Muhammad Umer Farooq ¹

¹ Institute of Mechanical and Manufacturing Engineering, Khwaja Fareed University of Engineering & IT, Rahim Yar Khan 64200, Pakistan; asnakalsoom8@gmail.com (A.K.); umer.farooq@kfueit.edu.pk (M.U.F.)

² Faculty of Science & Technology, University of Canberra, Canberra 2617, Australia

* Correspondence: faizan.shah@canberra.edu.au

Abstract: Neurological disorders like stroke are one of the main causes of motor dysfunction and gait function disabilities in humans. These disorders impact the mobility of patients often leading to weakened and impaired ankle joints which further compromise their balance and walking abilities. Over the span of the last twenty years, there has been a rising interest in designing, developing, and using rehabilitative robots for patients suffering from various ankle joint disabilities. These robotic devices are developed by employing diverse mechanical designs, materials, and control strategies. The aim of this study is to provide a detailed overview of the recent developments in mechanical design, actuation, and control strategies of ankle rehabilitation robots. Experimental evaluation of the discussed ankle robots has also been carried out discussing their results and limitations. This article concludes by highlighting future challenges and opportunities for the advancement of ankle rehabilitation robots, stressing the need for robust and effective devices to better serve patients.

Keywords: ankle rehabilitation robots; ankle exoskeletons; parallel ankle rehabilitation robots; mechanism design; actuator; control technique



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1. Introduction

The human ankle joint, a highly intricate part of the human skeleton, plays a pivotal role in daily life, ensuring stability and balance while enabling movement [1]. It significantly aids in the transmission of forces as the body moves during running and walking [2]. Despite its importance, this joint is one of the most injury-prone areas, facing afflictions like ankle sprains or fractures which hinder the walking capability of the patient [3]. Some other major disorders of the ankle joint include gait function disorders and neurologic impairments like stroke, which compromise the survivor's functional mobility and normal life abilities. Drop foot caused as a result of stroke is one of the major concerns these days regarding ankle joint dysfunctions and is defined as weakness of ankle and toe dorsiflexion [4–6]. Serious injuries like paralysis, hemiparesis, spinal cord injuries, etc., may also lead to ankle joint disabilities.

Ankle joint dysfunctions not only affect the patient's mobility but also damage their central nervous system, which demands stimulation to reorganize and regain motor perception [7]. In order to recover this damage, the need for physiotherapy arises for the patients [8,9]. With the help of physiotherapy, patients can restore their balance, reclaim their range of motion, and strengthen weakened muscles [10,11]. But this treatment requires a lot of work and effort, and therapists can only provide a limited number of

sessions. Moreover, there are no means in a clinical setting to objectively measure a patient's progress in terms of walking dynamics [12–14]. Due to these drawbacks, these conventional ankle rehabilitation techniques must be replaced by modern and advanced rehabilitation methods by utilizing ankle rehabilitation robots. These robots will have the capability to record real-time results and improvements during training while simultaneously being able to adapt and modify according to the difficulty level of the rehabilitation process [15]. These rehabilitation robots provide more objective measures, less workload on therapists and caretakers, as well as personalized sessions, mitigating the drawbacks of physical therapy [16,17].

The devices designed for the purpose of ankle joint rehabilitation are often named ankle joint complexes (AJCs) and are categorized on the basis of their mechanical design as wearable robotic devices and parallel ankle rehabilitation robots [18,19]. As the name suggests, wearable robots can be worn, and they work closely around the joints of the patient. They are also called robotic orthoses or exoskeletons [13,20]. These robots are specifically designed for on-ground walking, utilizing programmable control schemes. Wearable robots are preferred for gait training since they can provide plantarflexion and dorsiflexion, abduction, and adduction, as well as inversion and eversion [21]. Parallel ankle rehabilitation robots (PARRs), also named platform-based ankle robots, operate while the patient is seated and offer multiple degrees of freedom (DOFs) to the patient's ankle joint [19,22]. PARRs are known for their properties like low inertia, high rigidity, greater probability, and compact size [23,24].

Over the past two decades, numerous studies have reviewed ankle rehabilitation robots depending on their type, mechanical design, and performance. Researchers have shown great interest in evaluating different control strategies and actuation methods that have been developed to enhance the efficiency and accuracy of ankle rehabilitation robots [6,9,25]. This study aims to review the types of ankle rehabilitation robots designed in recent years based on their mechanical design and actuation techniques. Specifically, it addresses the following research questions:

RQ1: What are the latest advances in the mechanical design and actuation methods of ankle rehabilitation robots?

RQ2: What traditional and advanced control approaches have been utilized to optimize the performance of ankle rehabilitation robots?

RQ3: What are the features of future-generation ankle rehabilitation robots that emerged in the last decade, and how can they be used for performing active daily life tasks?

2. Materials and Methods

2.1. Methodology

The literature review for this paper has been carried out via the Scopus database, IEEE Xplore, ScienceDirect, and Google Scholar by using keywords like “ankle rehabilitation robots” OR “wearable ankle robots” OR “lower limb rehabilitation using ankle robots” OR “platform-based ankle rehabilitation robots” OR “control of ankle robots”. In Scopus and ScienceDirect, the search was within the title, abstract, and keywords; in IEEE Xplore, the search was performed on the metadata (title, abstract, index terms); and in Google Scholar, a full-text search was performed with a relevance limit of the first 100 results. Inclusion criteria narrowed results to publications from peer-reviewed journal articles only.

As explained in Figure 1, In the initial phase of searching, 2694 papers were found in relevance to the topics being discussed. After the final phase of screening, 175 papers were shortlisted. As the review focuses on journal papers only, conference proceedings and book chapters related to the topic have not been included. The publications reviewed in this article are screened on the basis of the quality of data being presented. Papers containing

substantial information about the mechanical design, actuation, control strategies, and performance of the ankle joint rehabilitation robots have been preferred.

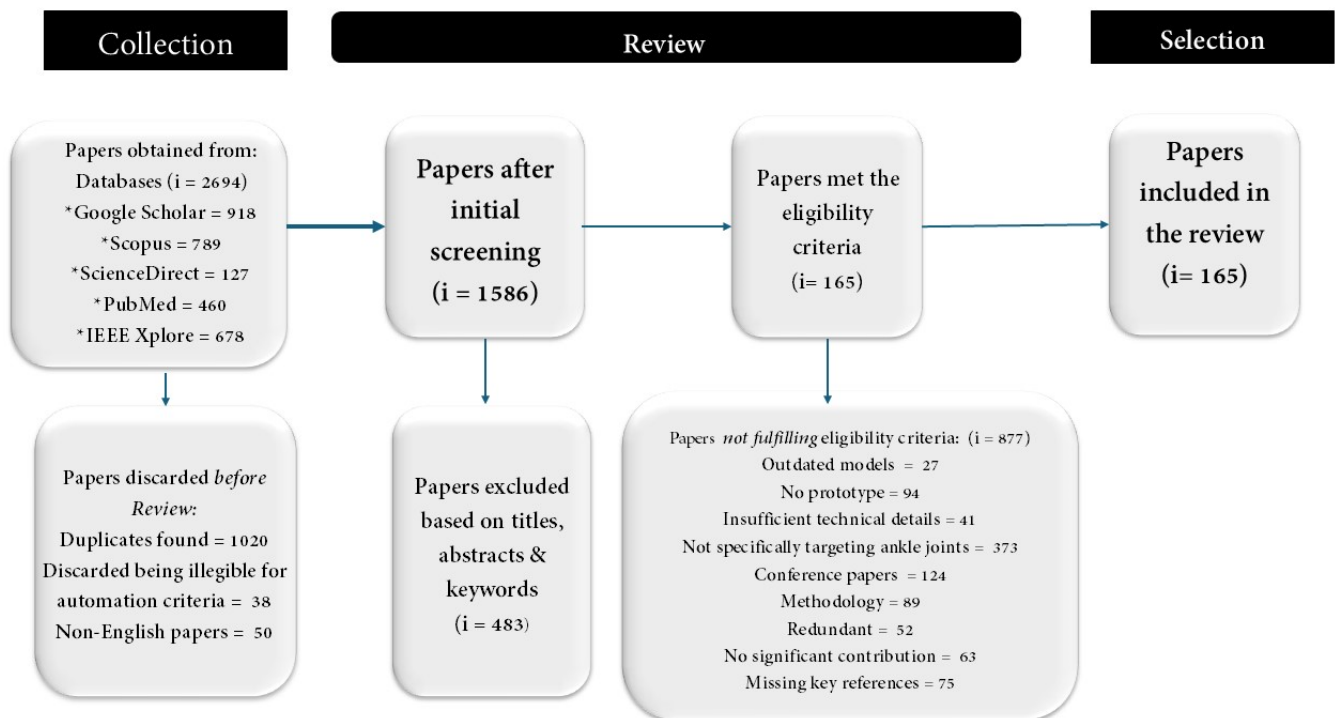


Figure 1. Literature review criteria.

This review paper is structured as follows: Section 2 describes the anatomy of the human ankle complex explaining the structure and range of motion of the human ankle. Since the review paper focuses on different designs and mechanisms used for ankle joint rehabilitation, this section helps in understanding the motion and working of ankle rehabilitation robots in a better way. Moreover, it gives information about the classification of ankle rehabilitation robots on the basis of materials, mechanical design, and type of actuation used in ankle robots. Furthermore, it explains how different ankle rehabilitation robots utilize a diverse variety of controllers to provide precise trajectory training and assistance to patients suffering from ankle joint disabilities. Section 3 elaborates on the results of the experimental evaluation of ankle rehabilitation robots featuring information on different prototypes and clinical studies that have been tried and tested in real environments to prove the efficiency of the robots. A detailed discussion of the merits and demerits of the approaches mentioned in the review article is provided in Section 4.

2.2. Anatomy of the Ankle Joint Complex

This section provides a basic overview of the anatomy of the human ankle joint complex which is essential for designing and understanding the working of ankle joint rehabilitation robots. The anatomic structure of the human ankle is quite complex as it contains four bones, seven muscles, nine tendons, and four ligament groups in such a compact space [6]. The movement of the ankle joint is facilitated by the combination of two articulations: the ankle/tibiotalar joint and the subtalar joint [26]. The tibiotalar joint connects the tibia, fibula, and upper face of the talus, whereas the subtalar joint serves the purpose of joining the lower part of the talus with the upper surface of the calcaneus, as depicted in Figure 2.

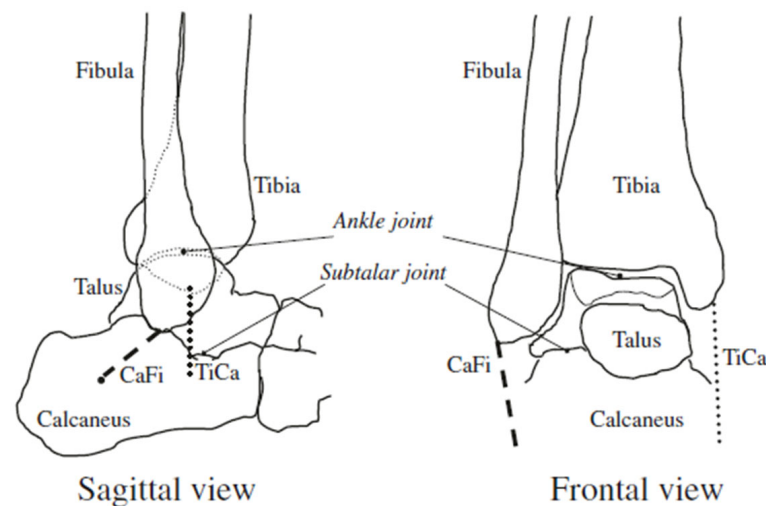


Figure 2. Human ankle joint [27].

Initially, the movement and function of the ankle were explained in terms of its range of motion (ROM). Table 1 explains the ranges of motion associated with each movement and its plane [28]. But with the passage of time, axes and planes have become more crucial for understanding the ankle joint's spatial configuration. Just like the whole human body, the motion of the human foot is categorized into frontal, sagittal, and transverse planes. Using these angles and planes, the motion and rotation of the ankle joint are divided into three types, as mentioned in [29].

Table 1. Range of motion of ankle joint [30].

Axis	Movement	Range of Motion (Degrees)
Transverse	Plantarflexion	37.6–45.8
	Dorsiflexion	20.3–29.8
Anteroposterior	Inversion	14.5–22.0
	Eversion	10.0–17.0
Vertical	Adduction	22.0–36.0
	Abduction	15.4–25.4

- Dorsiflexion/Plantarflexion: Motion in the sagittal plane. Motion of the foot upwards and towards the tibia is dorsiflexion. Motion of the foot downwards and far from the tibia is plantarflexion.
- Abduction/Adduction: Motion of the heel around its axis and parallel to the transverse plane. When the forefoot experiences lateral motion, it is abduction, and when it moves medially, it is called adduction.
- Inversion/Eversion: Motion along the anteroposterior axis and parallel to the frontal plane. Medial movement of the plantar surface is inversion, while lateral movement is eversion.

2.3. Ankle Rehabilitation Robots (ARRs) Classification

Over the years, researchers have implemented several design variations, actuation techniques, and control strategies to achieve desirable DOFs and speedy recovery of patients. These robots have been designed for patients suffering from ankle injuries which lead to serious dysfunctionalities, and they need special assistance to regain their mobility

and functionality. This section describes the improvements in mechanical design and materials as well as actuation methods that have been employed in recent years. These advancements have led to robust, lightweight, and high-performance rehabilitation robots which significantly improved the process of recovery in neurologically disabled patients with various ankle joint disorders.

2.4. Ankle Rehabilitation Robot Design

Depending upon the mechanical design of ankle rehabilitation robots, they are classified into two categories: wearable rehabilitation robots or robotic orthoses and platform-based parallel rehabilitation robots as described by Figure 3. Wearable ankle robots are designed to be directly worn by the user, facilitating gait movements by providing a more natural rehabilitation process. In contrast, parallel/platform ankle robots incorporate a stationary base focusing on exercise-based therapy in a controlled setting. Both categories have distinct advantages depending on the level of mobility and training required [13,14,31].

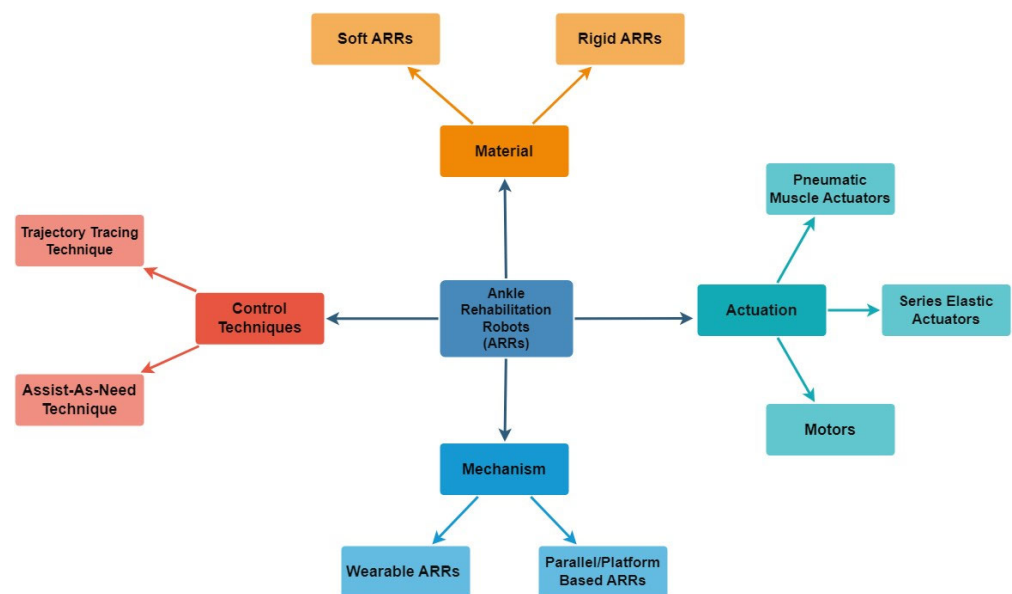


Figure 3. Classification of ankle rehabilitation robots (ARRs).

2.4.1. Mechanical Architecture of Ankle Rehabilitation Robots

The mechanical structure of ankle rehabilitation robots varies significantly according to the design objective and working environment. Platform-type systems commonly use parallel mechanisms (e.g., 2-PSS-(2-PRR-PR)R, 3-RPS) to facilitate multi-DOF actuation and precise control. Wearable robots normally employ serial chains or reduced joint linkages to reproduce natural motion. Slider–crank mechanisms and four-bar linkages are commonly employed for single-DOF rehabilitation with a requirement for compactness. Cable transmissions are gaining popularity, particularly with wearable systems. These employ Bowden cables or tendon-driven structures to transmit actuation from distance-mounted motors to the joints in order to minimize inertia and maximize safety. Though not classically mechanisms, they are an integral part of mechanical transmission and control. Their inclusion enables greater comfort and flexibility for realistic, user-borne use.

2.4.2. Wearable Ankle Rehabilitation Robots

The FDA defines wearable ankle robots as prescribed medical devices, comprising of external powered orthosis which are specially designed for patients with paralysis and mobility disorders (Food and Drug Administration HHS 2015) [32]. The ankle rehabilitation robots offer adjustable features for different body types, simulation of realistic ankle joint

kinematics, and optimization of performance, prioritizing the comfort of patients during therapy [33]. These robots have emerged as an immense help, enabling patients to enhance mobility, regain muscle strength, and recover from dysfunctionalities occurring because of injuries, surgeries, or neurological problems like drop foot and strokes. Figure 4 presents different wearable ankle rehabilitation robots reported in the literature.

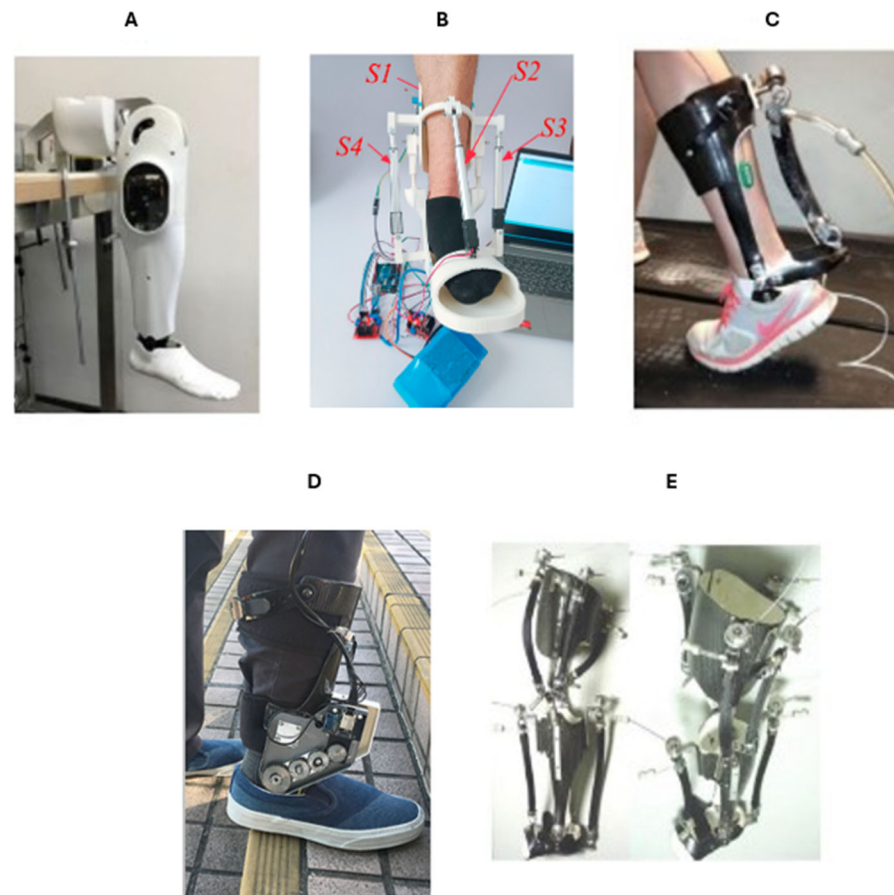


Figure 4. Different WRRs reported in the literature. (A) Ankle–foot simulator [34]; (B) ankle exoskeleton [35]; (C) neuromechanics-based powered ankle exoskeleton [36]; (D) robot-assisted AFO [37]; (E) knee–ankle–foot orthosis (KAFO) [38].

2.4.3. Parallel/Platform-Based Ankle Rehabilitation Robots

Platform-based parallel ankle rehabilitation robots are cutting-edge robots that are designed to facilitate ankle joint recovery by leveraging multiple DOFs. In comparison to wearable ankle robots, platform-based ankle robots have significant advantages like small size, variable resistance, broader range of motion, and less physical burden on the patients. These robots consist of parallel platforms like the Stewart platform with several actuators assembled in such a way that they aim to mimic human ankle dynamics with stability and accuracy [23]. Figure 5 illustrates a collection of various parallel/platform-based ankle rehabilitation robots, which employ different actuation methods, design variations, and control strategies to recreate the human ankle joint motion.

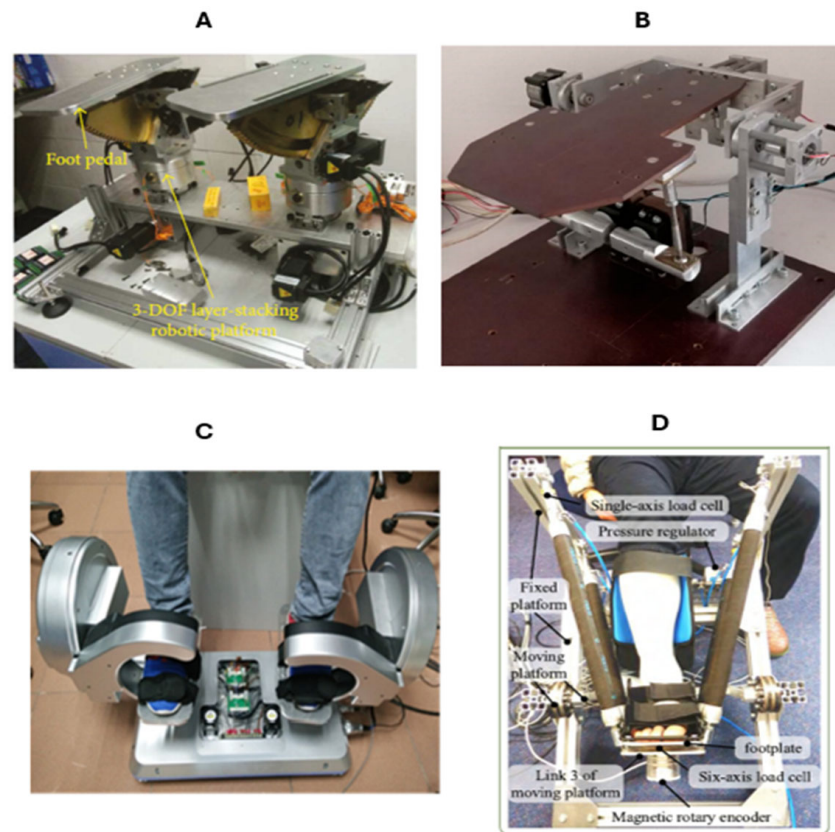


Figure 5. Different PARRs reported in the literature. (A) Ankle rehabilitation platform [39]; (B) ankle robot [40]; (C) novel ankle rehabilitation robot (NARR) [41]; (D) ankle robot [42].

2.5. Manufacturing Material

Ankle rehabilitation robots, when categorized based on materials, fall into two main categories: rigid ankle rehabilitation robots and soft ankle rehabilitation robots. Rigid robots are generally made of hard materials like metals and plastics, etc., for providing better control and stability to patients suffering from ankle joint disorders and gait disabilities. On the other hand, soft robots are usually constructed from soft and flexible materials like silicones, elastomers, etc., to facilitate more natural and adaptive movements. Ankle rehabilitation robots are also classified in the mentioned categories depending on the type of actuators used to power them. Within each category, both wearable and parallel/platform-based ankle rehabilitation robots have been designed to assist the user as per their needs [16,21,43,44].

2.5.1. Rigid Ankle Rehabilitation Robots

Rigid ankle robots use a material that is hard and has good structural integrity and stability. Commonly used materials for such robots are metals, plastics, and firm composites. These robots are known for their robust design which are capable of delivering higher torques, precise motion, and better stability to patients with limited mobility. Wearable ankle robots like AFO, designed by the Massachusetts Institute of Technology (MIT) [13], Lokomat [45], Rewalk [46], Ekso [47], HAL [48], and BEAR-H [49], and exoskeletons developed by North Carolina State University [36] as well as the Chinese University of Hong Kong [37] are prominent examples of rigid ankle robots. Parallel/platform-based ankle rehabilitation robots such as the Rutgers Ankle [31], the Haptic Walker [50], a PLA (polylactic acid)-based platform robot [51], and the ankle robot presented in [52] are made of rigid materials, providing significant stability and durability. These models

proved beneficial in repetitive exercises and muscle strengthening, speeding up the process of rehabilitation.

2.5.2. Soft Ankle Rehabilitation Robots

Soft ankle robots are made of compliant and flexible materials like shape memory alloys or smart materials like nitinol, elastomers, etc., to mimic the human ankle joint motion swiftly offering more flexibility and adaptability. Wearable soft ankle robots such as Exoboot [53], Symbiotron exoskeleton [54], KAFO [38], Soft Exosuits [55], Active Soft Orthotic [56], etc., are designed for rehabilitative purposes. Similarly, devices like Nitinol-based ankle robot [57], Stewart platform-based ankle rehabilitative devices employing shape memory alloys (SMAs) [58], parallel robots proposed in [22], soft parallel robots designed for ankle injuries [59], etc., fall under the category of parallel/platform-based robots. These soft structures provide enhanced adaptability and reduced strain to the patients.

2.6. Actuation Devices

Ankle rehabilitation robots immensely rely on actuation devices for generating precise and flexible movements during training sessions. Through a detailed literature survey, it has been observed that the most common types of actuators used while designing platform-based ankle robots are pneumatic actuators and electric actuators. On the other hand, wearable ankle rehabilitation robots employ a diverse range of actuators like electric actuators, pneumatic actuators, cable-driven actuators, electric actuators, etc., to enhance the quality of the treatment process. This section delves into the various kinds of actuation devices that have been utilized for ankle rehabilitation robots, showcasing their development and evolution over the years.

2.6.1. Pneumatic Air Muscle Actuators

A different category of wearable ankle rehabilitation robots incorporates pneumatic muscle actuators (PMAs) [60]. Inside PMAs, there is a layer of butyl rubber tubing with two terminal connectors, which seals the muscle cylinder [61]. A single-DOF PMA-powered ankle robot was designed at the University of Michigan, which had a considerably low weight and was able to facilitate movement in plantar/dorsiflexion direction. This model used two PMAs for generating the required output since PMAs can provide unidirectional force only [62,63]. To increase the number of DOFs, another prototype inspired by the anatomy of the human foot was suggested [56]. This prototype incorporated four PMAs and several sensors for analyzing gait patterns. A 3-DOF PM-driven ankle robot was developed using five actuators to obtain a full range of forces and motion for a human ankle [64]. In order to reduce the number of actuators, a tripod-based robotic mechanism was proposed by Arizona State University. This robotic mechanism used springs combined with PMA to exert two-dimensional forces [65]. To mimic the function of the ankle joint, especially in the sagittal plane, an ankle robot with a pair of antagonistic PMAs was introduced. When one of the PMAs was inflated to produce linear contractile motion, the other actuator deflated simultaneously and produced linear stretching to achieve the desired motion [66]. A very lightweight one-DOF soft robotic AFO using a flat fabric PMA was proposed for providing plantarflexion motion. The device harmonized with the rhythm of patients by applying periodic pneumatic impulses [67]. The research conducted in [68] suggested the kinematic modeling of an exoskeleton employing PMAs. This modeling utilized anthropometric data for determining several joint angles depending on the nature of movement. A highly durable ankle rehabilitation robot has been designed using pneumatic actuators assembled antagonistically. The device can control air pressure and adjust the brace's stiffness as per the user's needs [69]. A knee–ankle–foot orthosis (KAFO) has been developed recently,

which can provide two ankle movements, i.e., plantarflexion and dorsiflexion. This KAFO is powered by pneumatic actuators for lowering the risk of joint disabilities [70].

A parallel ankle robot consisting of the Stewart platform and pneumatic actuation was developed at Rutgers University [71]. This was a 6 DOF robot with six double-acting pneumatic cylinders, potentiometers, and load cells to generate anatomical motion in all directions. A 4-DOF parallel ankle manipulator incorporating pneumatic actuators was proposed for physical therapy [72]. A study suggested utilizing pneumatic muscle actuators in combination with cables for actuating a 3-DOF parallel ankle robot [19]. An intrinsically compliant parallel ankle robot was designed with antagonistic actuation having four PMAs and impedance control to help patients with neurological impairments [73]. To solve problems related to trajectory tracking and performance under various dynamic conditions, a system with a parallel mechanism and pneumatic actuation has been presented. At Wuhan University, a two-DOF parallel ankle rehabilitation manipulator was designed using three PMAs [74]. An intrinsically compliant parallel ankle rehabilitation (ICPAR) robot has been proposed in the literature, which has a novel design in which the patient places their foot at the bottom platform instead of the top platform. It is a 3-DOF mechanism that is pneumatically actuated to deliver the desired motion. Another study featured a parallel mechanism being actuated by four pneumatic actuators for adaptive trajectory tracking [42]. Reference [75] discusses the detailed analysis of the kinematic design of a 2RIT parallel manipulator employing pneumatic actuation. AirGait, presented in study [76], is a 3-DOF 2-PSS-(2-PRR-PR) R parallel mechanism that is powered by pneumatic artificial muscles. This robot can provide one translational motion along in a vertical direction, one rotational motion, also called dorsiflexion or plantarflexion, and another rotational motion that is inversion or eversion. A platform-based ankle robot powered by PMAs is designed utilizing a slider–crank mechanism to enable muscle movements in patients suffering from different ankle joint disorders [66]. By harnessing the benefits of pneumatic actuation like flexibility, less weight, etc., another study designed a platform-based robot incorporating cables with pneumatic actuators to enable a broader range of motion and higher torques with better stability [64]. The ankle robot mentioned in [77] used pneumatic actuators mainly due to its similarity with human muscles for training and treating people suffering from stroke. The Compliant Ankle Rehabilitation Robot (CARR) utilized four PMAs, facilitating 3 DOFs and ensuring safe interaction between the user and the robot [78].

2.6.2. Electric Actuators

Ankle rehabilitation robots powered by motor actuators have been utilized over the years to improve the quality of life for patients suffering from ankle joint disabilities [35]. For treating drop foot, a 3-DOF ankle robot named AnkleBot was designed by researchers at MIT. It was actuated by brushless DC motors and provided motion while sitting as well as walking [79]. A wearable exoskeleton has been designed for in-bed rehabilitation of stroke patients actuated by an electric motor for facilitating plantarflexion–dorsiflexion [80]. Another exoskeleton was developed using servo motors and Arduino Uno to improve flexibility in patients facing calf muscle problems [81]. An ankle robot with a lightweight motor was proposed to decrease the power requirement of the model, achieve high-power assistance, and reduce the overall weight of the device [82]. A research study utilized brushless motors to drive magnetorheological clutches for generating motion in the plantarflexion direction. This robot was designed to facilitate the patient for different motions like walking, landing, and jumping [83]. In order to overcome the limitations of voluntary control, a study proposed an ankle robot with non-back-drivable motors assembled with harmonic drives for actuating joints in the sagittal plane [84]. Some of the models utilized motors in junction with other systems like cables to derive the robot and provide smooth

movement while walking [85]. Exowalk used rear motors to help patients move and rotate easily [86]. Active AFO, proposed in [87], incorporated servo motors in its prototype to aid motions like dorsiflexion and plantarflexion. These signals of the servo motors were captured by electromyography. The feedback mechanism-based exoskeleton was designed for flexion and extension, and it was powered by two servo motors to enable the required motion [88]. Featuring a switchable actuation configuration, the mobile ankle exoskeleton can operate between single and double motors depending on the nature of the task being performed. For lightweight tasks, a single motor is selected, but for heavy-duty tasks, the robot opts for double motors [89]. A prototype proposed for angular-assisted motion consisted of linear actuators, servo motors, and other electrical components to assist patients with gait dysfunctionalities [35].

In parallel/platform-based ankle rehabilitation robots, electrical actuation is employed, commonly including different types of motors, electrical linear actuators, etc., or diverse actuation mechanisms that are assembled with these electrical actuators for powering the platform-based ankle rehabilitation robots. A parallel mechanism named ARBOT was designed using brushed DC motors along with components to generate plantar/dorsiflexion and inversion/eversion motions [14]. A 3-RUS/RRR parallel robot capable of 3 DOFs of motion was developed in China using electric motors and gear assembly [30]. A low-cost 3-PRS parallel ankle manipulator containing three active legs was proposed in [90]. These legs were actuated by servo DC motors individually. Reference [24] presents a single-DOF parallel robot incorporating one motor to trace human ankle trajectories. A 6-DOF parallel ankle robot actuated by linear electric actuators demonstrated promising results for motions like marching, stair climbing, and hip exercises [91]. A modified version of the robotic ankle rehabilitation system (RARS) for poststroke rehabilitation was designed and tested using DC motor actuation [92]. Another research paper presented a 2-DOF redundantly actuated ankle robot consisting of a fixed bottom plate, movable top plate, three legs, and a strut leg. These three legs were actuated by DC electrical actuators [93]. For the purpose of easily treating and training patients suffering from ankle disorders at home, clinics, hotels, etc., a 3-RRS spherical parallel robot was introduced in [94]. The design of this model included a motor for actuating the system. At the Universitat Politècnica de València, researchers designed a 3-PRS mechanism-based parallel ankle rehabilitation robot which was powered with the help of brushless servomotors [90]. The paper suggested a novel design of a parallel robot for hemiplegic patients suffering from stroke. The design consists of a complex assembly of different gears and a brushless DC motor to perform three different ankle exercises [39]. The upper platform of the Stewart platform-based robot discussed in [95] moves and aims to trace the desired trajectory. This movement of the upper platform is facilitated by a DC motor. The Vi-RABT rehabilitation device was designed to perform two most crucial ankle motions, i.e., dorsiflexion or plantarflexion and inversion or eversion. The mechanical model of this device consisted of several components including high power DC gear motors [95]. For treating athletic injuries, a unique rehabilitation device was proposed, which was a combination of both serial and parallel mechanisms. The key feature of the device was a rotating platform that was being actuated by stepper motors [96]. To replace the need for a professional physiotherapist while enabling the patients to train themselves on their own depending on their needs, researchers from China came up with a novel ankle rehabilitation robot (NARR). The mechanical model of this device consisted of a detective device as well as a training device. The actuators used in this device were a DC brushless motor and the IBL3605A intelligent servo driver [41]. For patients suffering from drop foot and talipes valgus, a 2-UPS/RRR parallel robot has been developed with advantages like compact size, higher interaction compatibility with patients, and a wider workspace. The ankle robot introduced in the study [97] also used

DC motor actuators to run the system smoothly. To treat patients with stroke and cerebral palsy, a novel design was suggested by authors in [52] with quite a simple structure and non-redundant actuation as key features. The actuation in this paper was also carried out using stepper motors and linear actuators. The extensive use of electric actuators in parallel and platform-based robots stems from their better torque, precise control, and back drivability. A 3-DOF 2-UPS/RRR parallel mechanism was developed being powered by two servo linear actuators and one servomotor for attaining rapid recovery [98]. Reference presented a novel 2- (CRS + PU) and R-type parallel ankle robot with adjustable features depending on the user's need. It can perform all three desired ankle motions due to its unique mechanical design consisting of a hybrid platform, DC servo motor, push rod motor, and different limbs [99].

2.6.3. Series Elastic Actuators (SEAs)

To assist individuals suffering from medical conditions, especially drop foot, the researchers from Massachusetts Institute of Technology (MIT) designed robotic ankle-foot orthosis (AFO) using series elastic actuators (SEAs) [13,100]. SEA consists of a brushless DC motor combined with a spring in a series combination and has various advantages like lower impedance and higher precision control [100]. AFO not only enabled the patient to move in the sagittal plane but also reduced the chances of foot drag and foot slap. A similar active ankle-foot orthosis (AAFO) was also developed at Yonsei University serving the same purpose as AFO [101]. These devices mentioned had considerable weight, and to cater to this issue, a SEA-actuated portable device was designed which improved walking efficiency and gait kinematics [65]. Another portable ankle robot was proposed with an innovative actuation system consisting of SEA with two springs (both linear and torsion). The SEA promotes safe interaction for patients suffering from gait disabilities [102]. Furthermore, the author introduced modifications like better force control, compliance, and improvement of spring assembly in the previously presented robot. These modifications broadened the scope of the ankle robot [103]. AssistOn-Ankle featured Bowden cable-based SEA, which facilitated high-fidelity force and impedance control [104]. A study put forward a unique SEA design incorporating a double-tendon sheath transmission mechanism and a torsion spring. This novel design demonstrated promising results and proved its effectiveness for patients [105]. In 2021, a new SEA-based training simulator was proposed for the treatment of another medical condition called ankle clonus. It is a 2-DOF mechanism and provides dorsiflexion/plantarflexion and inversion/eversion movements enabling smooth patient-robot interaction [34].

2.6.4. Other Emerging Actuation Devices

While most ankle robots consist of the above-mentioned types of actuators, some have incorporated different actuators which have also proven beneficial like an electro-hydraulic ankle-foot orthosis (EHO) designed at Laval University [106,107]. This is a high-power and low-weight model consisting of all three pneumatic, hydraulic, and electric systems. A two-DOF ankle foot robot featured a Bowden cable-based actuation system and impedance controller to counter the challenges of high energy requirements and gait asymmetries for affected patients [108]. In 2018, a study suggested a VS-Ankle Exo design robot that incorporated compliant actuators with the capabilities to mimic the mechanism of the human ankle [109]. A robotic sock utilizing elastomeric actuators was proposed to replicate the plantarflexion-dorsiflexion of the ankle joint [110]. An ankle robot with a magnetorheological actuation system was introduced having several benefits like less consumption of power, high torque, and fast response [111]. This model utilized the concept of skin surface electromyography for sensing human movement intentions. BioComEx designed

by researchers employed variable stiffness actuator (VSA) and magneto-rheological brakes for tracking the trajectory and ensuring safe interaction [112]. Tendon-driven actuators were incorporated into the studies due to their advantages like improved alignment, fast connectivity, and walking stability [113]. In recent research, twisted and coiled polymer actuators have been used for pediatric ankle rehabilitation as they offer mobility, comfort for children, less injury risks, and high adaptability [114].

2.7. Control Techniques

Control techniques and strategies are crucial in the field of ankle rehabilitation robots as the success of these robots is greatly dependent on them. So far various control schemes have been implemented in the literature for both wearable and parallel/platform-based ankle rehabilitation robots. The main purpose of these techniques is to provide better assistance to the user as well as guide the user's ankle robot on the predefined trajectories accurately. Broadly the control schemes have been categorized as: trajectory-tracking control techniques and assist-as-needed (ANN) control methods. The details of both kinds of controllers have been provided below.

2.7.1. Trajectory-Tracking Control Methods

Trajectory-tracking control-based ankle robots are designed in such a way that they trace predefined reference trajectories that have been sourced through healthy people under specific conditions. The patient's ankle and foot will move around these reference trajectories during the rehabilitation phase. At Arizona State University, an exoskeleton was developed on the basis of a trajectory-tracking control scheme. The desired motion was fed to the controller, and the performance of the robot was determined by its tracking capability [115]. A bio-inspired AFO was proposed employing a linear time-invariant control law for the same purpose of tracking a predefined goal [56]. The prototypes discussed in [116,117] all implemented the above-mentioned trajectory-tracking technique. For the treatment of ankle sprains, a wearable ankle robot was presented in the literature that incorporated a fuzzy logic controller and fuzzy-based disturbance observer, which primarily focused on tracking the trajectories and approaches used by therapists commonly [118]. An advanced-level adaptive sliding mode controller was used in designing a wearable ankle robot for children suffering from gait disabilities. This second-order sliding mode controller works in combination with a higher-order sliding mode differentiator to reduce the tracking error by controlling the motion of the exoskeleton accurately [119]. An exoskeleton with the ability to track reference trajectories online was introduced in [120]. This model used an adaptive control law based on cost functions that leveraged the use of both interaction force and trajectory modification. At the University of Pham Van Dong, an exoskeleton was designed using a PD controller and Arduino UNO to perform the task of tracking the trajectories of the human ankle. The robot demonstrated promising results when the tracking performance was checked by comparing the input and output angular positions of the robot [121]. The exoskeleton presented in [122] traced the trajectory when a human foot pedals a bicycle. The schematic diagrams shared in the mentioned paper depicted a controller, but its specifications were not provided.

Trajectory-tracking control is also common in parallel/platform-based ankle rehabilitation robots. The Rutgers Ankle mechanism implemented a trajectory-tracking technique [31]. A parallel ankle robot employing PMAs and a fuzzy logic controller was designed to trace reference trajectories selected by the authors while countering the errors caused by the non-linear and time-variable behavior of PMA [118]. To solve the problems related to the issues mentioned related to PMA, another parallel robot CARR was proposed [74,123]. This robot used an iterative feedback tuning law to solve trajectory-

tracking errors. A 2-DOF parallel robot was developed in Wuhan, China, which consisted of a trajectory-tracking controller [74]. Another single DOF parallel ankle robot was designed to trace predefined paths of the human ankle using an adaptive proxy-based sliding mode controller [124]. Researchers at Karadeniz Technical University also built a parallel ankle robot depending on the trajectory-tracking technique [74]. A PD controller actuated by a motor was proposed to solve errors related to trajectory tracking [39]. The parallel mechanism-based robot mentioned used a feedforward controller to replicate the trajectories of human ankle joints [76]. To facilitate smooth tracking of a predefined ankle joint trajectory, a 2-DOF internal model controller was embedded in the parallel robot to achieve the desired goal [97]. A research paper focused on achieving better tracking performance, and for that purpose, it proposed three different strategies for a 3-PRS parallel robot. These control techniques were a conventional PID controller, a PID controller using genetic algorithms, and an adaptive fuzzy PID controller [125].

2.7.2. Assist-As-Needed (AAN) Control Methods

Although trajectory-tracking control methods have proved quite beneficial for patients suffering from ankle joint injuries or disabilities, they only track the reference trajectories without considering the level of disability of the patients. To overcome this drawback, another type of control strategy is suggested, i.e., assist-as-needed (AAN) control, which facilitates patients to be trained as per their requirements. In the literature, both wearable and parallel ankle robots have employed AAN control techniques to enhance their performance.

When the AAN control scheme was introduced with MIT's robotic AFO for patients suffering from drop foot, a reduction in foot slap and improvement in performance was observed [13]. The integration of the AAN control scheme with AnkleBot subsequently improved the results of the system [126–128]. A robot named PediAnkleBot was designed for children affected by cerebral palsy. This robot employed an impedance control scheme to enhance motor function in the affected children [79]. AFO designed by researchers at the University of Michigan underwent an examination incorporating the EMG control technique [129]. The examination included both walking over ground and on a treadmill, and the results from both cases suggested that anatomical structure must be considered while designing control strategies for ankle rehabilitation robots. Ghent University's AFO [130], a bio-inspired AFO [56], and AssistOn-Ankle [104] employed impedance control schemes and delivered satisfying results when tested with healthy subjects during real experimentation. MIT's AFO utilized an adaptive impedance controller, for real-time learning from patients and adapting the changes accordingly [131]. A fuzzy logic-based controller was implemented for an ankle exoskeleton in [132]. A controller leveraging an electromagnetic (EMG) feedback mechanism was proposed for the robotic exoskeleton. It also proposed a Hill-type neuromusculoskeletal model (HNM) in combination with a linear proportional model (LPM) to check the adaptability of the robot with changes [133]. A study focused on using a proportional joint moment control theory for a wearable ankle robot [134]. In SNU, the ankle orthosis model was embedded with a real-time gait phase detecting algorithm where pressure sensors measured the gait cycles, and depending on these observed gait cycles, an assistive force for the patients was produced [39]. Usage of a similar approach was observed in [135,136]. A robot named SAFE presented in [137] used a combination of an AAN control strategy and feedback control mechanism to detect and mitigate undesired moments developed during training. AAN-based control approaches have been developed in [21] for a robot manufactured at the Chinese University of Hong Kong. The soft Exo suit being studied in [138] also implemented admittance control, which is also an AAN control method. For the purpose of both muscle strengthening and assistive training, the AAN control scheme was used for an in-bed rehabilitation exoskeleton.

Depending on the patient's performance, it adjusted the resistive and assistive forces simultaneously to enhance the patient's mobility [80]. The robotic ankle exoskeleton discussed in [132] used an experience-based fuzzy logic controller featuring a muscle–tendon complex model. The robot's performance enhanced as the feedback mechanism collected different results from different users with diverse body types and disorders. A study presented an EMG-based admittance control (EACS) and an EMG-based open loop control scheme (ECOS) for the ankle exoskeleton. When compared to the results, EACS displayed more promising results [139]. Another study explored and assessed the biomechanical impacts of an adaptive impedance control strategy, which significantly enables flexibility in both gait trajectories and interaction-based stiffness, aiming toward a fully assistive robotic technology [140]. To predict human ankle behavior and assist users in training when suffering from neurological disorders, a deep learning model was developed along with an AAN control scheme [141]. An AAN controller worked in conjunction with neural networks to boost the overall performance of the system. A rigorous Lyapunov-based analysis proved that the implementation of AAN control achieved the desired task [142].

Impedance control law was implemented for parallel mechanisms like ARBOT to observe their performance while training. The robot also employed a compliant controller which further improved the training results [17,143]. In the literature, a cascaded position control utilizing the basics of impedance control was reported for a 4-DOF parallel ankle manipulator [72]. A parallel ankle robot powered by PMA discussed in [73] employed an impedance controller for assistive training purposes. A 2-DOF fuzzy logic-based controller has been integrated for a parallel ankle robot which uses the cuckoo searching algorithm with the ability to adapt resistive/assistive forces according to the user's needs [93]. ICPAR named parallel ankle robot used an adaptive impedance controller for the first time as reported in [144]. Several studies in the literature have mentioned the use of AAN-type control schemes for parallel manipulator CARR [42,145,146]. Recently, a data-driven adaptive iterative learning controller (DDAILC) has been incorporated into a CARR, investigating its training control properties for a repetitive range of motion [78]. The robot being studied in the article [147] used an adaptive control strategy to adapt according to the trajectory changes when the patients performed different rehabilitation exercises. A study proposed different platform-based ankle robot solutions for the problems faced during the rehabilitation process of ankle injuries. These models employed adaptive AAN control schemes to deliver the desired output [40]. A parallel mechanism actuated by motors used three different admittance control strategies for assistive physical therapy. The controller used time shifting and a proportional approach to determine its outputs [98]. A gait telerehabilitation robot has been designed to incorporate two new control strategies: therapist modulation mode and self-modulation mode. The first control strategy did not use any kind of on-line modulation while the second mentioned technique provided real-time modulation, increasing patients' control and involvement in the treatment [148].

2.7.3. Adaptive and Intelligent Control Techniques

Recent developments in machine learning (ML) and artificial intelligence (AI) have started to transform the design and control of ankle rehabilitation robots. Classical control strategies, although successful in trajectory tracking and force control, tend to be non-adaptive to patient-specific requirements or rehabilitation progress. Controllers based on ML provide a hopeful solution by facilitating real-time adaptation, pattern identification, and predictive decision-making. These intelligent control algorithms can learn from sensor data, anticipate patient intention or motor capability, and adapt control parameters in response [149]. Promising among them are reinforcement learning (RL), fuzzy logic systems, convolutional and recurrent neural networks, and multi-model hybrid decision-

making architectures integrating multiple AI models and clinical judgment. Qian et al. [150] established a new progressive learning-based assist-as-needed (AAN) control method designed to enhance participation in ankle rehabilitation training. Their method applies a fuzzy logic system to design a global performance measure through the integration of kinematic and dynamic metrics such as motion error, interaction torque, and participation ratio. This measure is then included in a cost function to optimize tracking error and robot stiffness. Compared to conventional fixed-assistance schemes, their control algorithm gradually reduces assistance with improving patient performance. Clinical trials conducted with healthy subjects demonstrated that the controller shown here not only encouraged active engagement but also increasingly adjusted robot stiffness in a subject-specific manner. Compared to minimal assist-as-needed (MAAN) strategies, the new strategy yielded greater active torque production and consistent engagement throughout multiple sessions, with a high potential for individualized and adaptive rehabilitation. In another innovation application of machine learning, Zhang et al. [151] suggested a VR-aided rehabilitation decision-making framework based on a convolutional gated recurrent neural network (CNN-GRU). Their approach integrates wearable motion sensors, virtual environments, and a hybrid deep learning framework for monitoring patient performance and recommending stage-specific training sessions. CNN separates space information from movement signals, while the GRU takes advantage of temporal relationships for classifying periods of rehabilitation perfectly according to the Brunnstrom scale. In an effort to deal with unbalanced data, authors used data augmentation, and the hyperparameters were tuned using a whale optimization algorithm (WOA). High accuracy of classification reaching 99.16% was achieved using their method, while high agreement (greater than 0.9 in correlation coefficient) with clinical testing was also revealed. This approach recognizes the potential of AI to enable real-time decision-making in virtual training environments as a scalable solution for personalized rehabilitation strategies.

In addition, Zhang et al. [152] created an adaptive sliding mode controller that utilized a radial basis function neural network (RBFNN) to enhance motion control in lower-limb rehabilitation. The approach demonstrated enhanced disturbance rejection and low tracking error, which verified the use of machine learning models in real-time joint control. These studies indicate the growing significance of smart controllers in providing tailored and efficient rehabilitation outcomes, especially when traditional control approaches lack flexibility and user input. Among the more sophisticated control methods utilized in rehabilitation robots, model predictive control (MPC) has been considered a promising method for delivering compliant and safe human–robot interaction.

3. Results

Experimental Setup Evaluation and Clinical Outcomes

The development of ankle rehabilitation devices is a complex and delicate process but testing them in a real environment is of equal importance as well to ensure the safety and well-being of patients. The majority of robotic devices are tested on healthy individuals with no history of neurological disorders. This helps the researchers to evaluate and optimize the mechanical design and control system of the device precisely. Following this initial testing phase, the devices undergo tests and trials for neurologically impaired patients. This phase decides the effectiveness of the developed system in real-life scenarios. This section outlines an evaluation of the experimental setups previously discussed in the above sections focusing on the devices developed in the last decade.

In the category of wearable ankle exoskeletons, a bio-inspired AFO developed in 2014 was evaluated for one healthy participant and the robot performed satisfactorily when the participant ran on the treadmill indicating a successful experiment [56]. The

PediAnklebot designed by the authors [79] underwent experimental testing for three children suffering from a neurological disorder named cerebral palsy. The results obtained during this trial were affirmative and a notable improvement was observed in the children's implicit and explicit motor function. This setup had some really interesting features like video games, which made the training process more interactive and enjoyable for children. The exoskeleton designed at Sun Yat-Sen University employed an AAN control strategy and was tested for a sample group of eight healthy members including both men and women. The robot demonstrated smooth tracking motion and delivered positive results for treating neurologically affected individuals [133]. The ankle exoskeleton named SAFE was tested with the implementation of an AAN control scheme for 12 healthy individuals who were all males. The results of the trial indicated a reduction in torque which is produced usually due to the interaction of robots and test subjects [137]. The robotic sock was tested for a single test subject and the results concluded that this wearable ankle device can facilitate dorsiflexion or plantarflexion motion of the ankle joint by providing the required torque [110]. The working capability of the Samsung robot was tested with a healthy individual. The robot met the expectations of the researchers by providing enough peak torque and mechanical power as required by the test subject [135]. The AssistOn-Ankle device presented in [104] was used by five volunteers. The volunteers registered positive feedback on the device as it was capable enough to carry out the movement in the desired direction. A SEA-based ankle-foot simulator designed with two levels of controllers was assessed by 17 expert clinicians. The testing was performed on the basis of control features of the robot and the testing continued for two days. At the end of the trial, the clinicians approved the simulator and suggested that it be used for training purposes [34]. An offline assistive optimization setup was developed for ankle rehabilitation and tested for six poststroke patients. It incorporated an admittance control strategy and offline biomechanical data for the generation of positive and negative augmentation torque [138]. At the University of Pham Van Dong, a PD controller Arduino UNO was proposed and developed in the university's workshop. The output of this robot was verified by testing it on human subjects. On comparison of input and output angular positions, it was concluded that the discrepancy was very minute, and the experimental setup can be employed for real applications [121]. An adaptive impedance controller-based ankle robot with the integration of neural networks was tested for five healthy subjects with no prior neurological disorders. The results demonstrated that the model successfully improved the robot's control performance and increased the prediction capability of the device [142].

To provide an orderly overview of reported experimental validations, Tables 2 and 3 present a comparative overview of wearable and platform-type ankle rehab robots, respectively. Both tables provide the key design features, type of actuators utilized, control methods adopted, as well as the nature of experimental studies (in terms of the type and number of subjects). Table 2 focuses on wearable systems utilized in clinical applications and research studies, and Table 3 focuses on platform-based robots assessed primarily for multi-DOF. These previews are intended to promote comparison and highlight existing flaws in clinical proof and application diversity.

Table 2. Overview of different wearable ankle rehabilitation robots.

Reference	Name	DOFs *	Actuator	Control Technique	Experimental Evaluation
[56]	Bio-Inspired AFO *	2	PMA *	Linear Time-Invariant	Healthy Participants
[79]	PediAnklebot	3	Motor	Impedance Control	CP Patients *

Table 2. Cont.

Reference	Name	DOFs *	Actuator	Control Technique	Experimental Evaluation
[133]	Sun Yat-Sen University Robot	1	Motor	EMG-based ANN Control *	Healthy Participants
[137]	SAFE *	1	SEA *	ANN Control	Healthy Participants
[135]	Samsung Robot	2	Motor	Assistance Force Control	Healthy Participant
[104]	AssistOn-Ankle	2	SEA	Force/Impedance	Healthy Participant
[34]	Ankle-Foot Simulator	1	SEA	Cascaded + Impedance	Clinicians
[138]	Soft Exosuit	1	Motor	Force/Admittance Control	Stroke Patients
[121]	Ankle Robot	1	Linear	PD Control *	Not mentioned
[131]	AnkleBot	2	Motor	Impedance Control	Stroke Patients
[134]	Ankle Exoskeleton	2	Motor	Proportional Joint-Moment	CP&PD Patients *
[36]	Ankle Exoskeleton	1	PMA	EMG Control	Stroke Patients
[153]	Ankle Exoskeleton	1	PMA	EMG Control Finite state Control	Healthy Participant
[80]	In-bed Rehabilitation Robot	1	Motor	Force Control	Stroke Patients

* DOF, degrees of freedom; AFO, ankle foot orthosis; SEA, series elastic actuator; PMA, pneumatic muscle actuator; PD, proportional derivative; ANN, assist-as-needed; EMG, electromyography; CP, cerebral palsy; PD, Parkinson's Disease.

Table 3. Overview of different parallel/platform-based ankle rehabilitation robots.

Reference	Name	DOFs	Actuator	Control Technique	Experimental Evaluation	Number of Participants
[73]	PARR *	3	PMA *	Position Control + 3 Impedance Control	Healthy Participants	10
[93]	Ankle Robot	2	Motor	Fuzzy Logic Control	Not specified	-
[74]	ARR *	2	PM *	ABS-SMC *	Healthy Participants	05
[41]	NARR *	3	Motor	PID/Position Control *	Healthy Participants	01
[98]	2-UPS/RRR ARR *	3	Motor	Admittance Control	Healthy Participants	05
[148]	PARR	6	Hydraulic	FGTM + TTM + SSM *	Healthy Participants	01

Table 3. Cont.

Reference	Name	DOFs	Actuator	Control Technique	Experimental Evaluation	Number of Participants
[118]	PARR	2	PMA	Adaptive Fuzzy Logic Control	Healthy Participants	01
[123]	PARR	3	PMA	IFT Control *	Healthy Participants	04
[95]	ARR	2	Linear	PID + RC-PID *	Not specified	-
[42]	CARR *	3	PMA	Admittance Control	Stroke Patients	01
[131]	ICPAR *	3	PMA	Adaptive Impedance Control	Stroke Patients	04

* DOF, degrees of freedom; PMA, pneumatic muscle actuator; PARR, parallel/platform-based ankle rehabilitation robot; ABS-SMC, adaptive backstepping sliding mode control; FGTM, fixed-gait trajectory mode; TTM, therapist modulation mode; SMM, self-modulation mode; IFT, iterative feedback tuning; RC, repetitive control; -, number of patients has not been provided.

An impedance controller was implemented for a parallel ankle robot by researchers [73]. The working ability of the robot was validated by testing it on 10 healthy participants. The designed device delivered promising results and motivated the participants to engage more actively, which proved its compliance and success. A 2-DOF redundantly actuated ankle robot was developed using an adaptive fuzzy logic controller. The experimental results of this device showed that employing this control technique improved the performance of the robot and reduced 50% of the steady-state tracking error when compared with conventional PID controllers [93]. A PARR named ankle robot was tested for 15 neurologically intact individuals. Another parallel robot CARR was put under experimental examination to determine its performance in practical applications. It was tested for one subject and delivered promising results [42].

Despite rapid advancements in the field of ankle rehabilitation, only a few robotic devices have undergone clinical trials. To determine the effectiveness of ankle robots in physical seating and physiotherapy sessions, clinical validation of these robots must be carried out. The results of this validation will not only highlight the performance of the robots but will also help researchers identify the loopholes and weaknesses of the designs. Some ankle rehabilitation devices like AnkleBot [131], Exoskeleton Ankle Robot [154], ReWalk [46], Rutgers' ankle robot [31], and ARBOT [14] have been validated in several clinical setups. These robots demonstrated promising results and positive outcomes from users. But still, the number of clinical tests is very small, and this is due to many factors like the cost and complexity of the ankle robots, limitations, and constraints of scalability. Designing and developing ankle robots involve considerable financial and logistical obstacles which cause difficulties for researchers to go beyond the research phase. Moreover, platform ankle robots have bulky designs and larger sizes, which makes it more difficult to provide them commercially for clinical setups and facilities. Hence, it can be deduced that the sizes of platform-based robots should be standardized so that their manufacturing and delivery to clinical facilities can be increased. Increasing the reach of ankle rehabilitation robots will expedite the recovery process, enhance mobility in patients, and improve their quality of life [155–157].

4. Discussion

This review article presents a detailed literature survey that includes different kinds of ankle rehabilitation robots that have been developed until now primarily focusing on the developments that took place in the last decade. This study pointed out that

significant advancements have been made in the mechanical designs, actuation, and control technologies of both wearable and parallel ankle rehabilitation robots. The goal of the ongoing research is to develop robust, durable, and human-friendly ankle rehabilitation robots that can replicate the movements of the human ankle joint precisely. It is evident from the current study that with the passage of time new techniques and approaches have been adopted by the researchers to improve the performance of the ankle robots in order to facilitate a large group of people suffering from neurological disorders and gait disabilities. Without a doubt, ankle robots hold great potential in rehabilitation and training processes, and there are still some challenges that hinder the performance of the robots.

4.1. Robot Design of Ankle Rehabilitation Robot

One of the major concerns while designing an ankle robot is ensuring the precise alignment of the robot with the human body. This alignment is crucial for robots to function accurately as it has a huge impact on the final performance of the robot. In case of misalignment, serious issues like injury, discomfort, or improper load distribution may occur. Within the framework of rehabilitation robotics, robot alignment with the human body implies a precise correspondence between the mechanical joints, axes, and points of rotation of the robot and the corresponding anatomical joints of the patient (e.g., the center of the ankle joint). Proper alignment ensures that the robot can replicate and support human natural movement without causing discomfort, shear forces, or inappropriate loading. Misalignment can result in decreased efficacy of therapy, user discomfort, or even risk of injury. Ankle rehabilitation devices such as initial versions of AFO [13,100], Rutgers Ankle [31], and ARBOT [14] faced some serious alignment issues causing discomfort for the users. Several cases in the literature have been reported where the initial design of the robot was correct, but due to misalignment in practical applications, the performance of the robot deteriorated. One such case is reported in [40], where the patient faced some displacement issues due to misalignment at the center of the ankle joint. It has been noted that in case the central point of the ankle robot and end effector do not coincide with the ankle joint's center of rotation, some serious alignment issues may occur. Researchers have made great improvements in solving these problems by designing modern devices like AssistOn-Ankle [104], AnkleBot [91], Bio-Inspired Soft Wearable Robotic [56], CARR [89], and ICPAR [131]. These devices have significantly reduced the errors and inaccuracies arising from misalignments. Addressing issues related to misalignment is very important because it will not only improve the performance of the robot during the experiments, but it will subsequently decrease the mechanical stress on the human body, reducing the chance of wear and tear as well as increasing the lifespan of the robot.

Ankle rehabilitation robots are primarily designed for facilitating joint motion and should replicate all joint movements, but the majority of ankle robots are unable to do so as they provide limited DOFs. While conducting a literature review for this study, it was observed that most of the wearable ankle robots were designed to carry out dorsiflexion and plantarflexion. Very few designs performed inversion and eversion, which are equally important movements of the human ankle joint [3]. Except for a few devices like [79,104,128,131,134,135], almost all other wearable ankle devices provide single DOF motion only. This can be noticed in Table 2, which summarizes different wearable ankle robots. But this is not the case in platform/parallel configuration-based ankle robots. As shown in Table 3, the majority of rehabilitation devices provide motion in 3 DOFs, even though the device mentioned in [148] was able to achieve 6 DOFs. More DOFs allow robots to mimic human behavior and motion naturally; hence, it is necessary for future designs of ankle rehabilitation robots to be able to provide multiple DOFs to perform efficiently.

Another key factor that is directly related to the success of any robot is its simple and robust mechanical design. Ankle robots must be designed in such a way that they are easy to use for patients without requiring much external help. But it has been reported in the literature that rehabilitation robots are difficult to operate by laypeople and cannot be used domestically. Hence, the ankle rehabilitation robots intended to be designed for both clinical practices and domestic use should be lightweight, robust, and easy to utilize.

4.2. Actuation Methods

The performance of both wearable and parallel ankle robots greatly depends on the type of actuators used in them [17,118]. Initially, the majority of ankle rehabilitation devices incorporated electromagnetic actuation to generate the desired motion [17,118]. Electromagnetic actuation is commonly used for its benefits like smooth motion delivery, quick response, and low maintenance, which made it favorable for researchers to incorporate them in early designs of ankle robots. Despite the benefits of electromagnetic actuators, they have some major drawbacks like high stiffness, bulky structure, continuous power consumption, and overheating, which influence the training results of ankle rehabilitation robots. To resolve this issue, SEA and PMAs were introduced in the literature [36,104]. The use of these actuators offered greater flexibility, higher mechanical safety, and better adaptation to human behavior as compared to electromagnetic actuators.

As reported in this review paper, mostly wearable robots [34,101,102,104,105] have utilized SEA-based actuation in their design since they have been proven helpful in terms of less energy consumption and better shock absorption. Another benefit of SEAs includes a precise force regulation ability which can provide assistance or resistance during the training process. Due to their elastic nature, they can store and release energy when needed during repetitive rehabilitation processes. This kind of actuation has provided considerable safety to patients as compared with electromagnetic actuation because they have minimized the risk of excessive force exertion on the user's joints. But these actuators too have some drawbacks, which include stiffness issues and energy loss. Stiffness issues may arise due to the elastic component of the actuators, which can lead to less effective rehabilitation when a patient requires higher resistive forces. Energy loss may be due to several factors like material friction, hysteresis, etc., which again deteriorate the robot's efficiency.

Another type of actuation that was commonly observed among both wearable ankle robots and platform/parallel mechanism-based ankle rehabilitation robots is PMAs. PMAs have lightweight and human muscle-like properties that benefit the patient by being comfortable and compliant. They work on the principles of contraction and extraction when air pressure is applied. They have a versatile trait of mimicking the natural behavior of human ankle joints while providing smooth and controlled motion. As listed in Tables 2 and 3, PMAs can facilitate multi-DOF motion in the case of both wearable and platform-based ankle robots due to their high power-to-weight ratio. Although PMAs have shown promising potential for ankle rehabilitation robots, these actuators require constant maintenance because they might develop air leaks over time.

There is no doubt that SEAs and PMAs have enhanced the performance, safety, and efficiency of ankle robotic devices by providing compliant, smooth, and controlled motion and biomechanical properties, and recent studies and research have still indicated favorable results from the use of electric and electromagnetic actuators like DC motors, servo motors, linear actuators, etc. [23,35,75,82,84,85,87–89]. It is mainly due to many factors such as needing any kinds of external sources like PMAs, having a slower time response, and having unpredictable force outputs of SEAs and PMAs in some severe cases, which hinder performance. Moreover, they can be easily integrated with other sensors for real-time feedback control. Hence, it is proved that each and every type has its pros and cons, and

their use depends upon the goals needed to be achieved by ankle rehabilitation robots. The drawbacks of each actuator can be catered to by implementing hybrid actuators combining the benefits of both electric motors and SEAs or PMAs [106,107].

4.3. Control Techniques

The working capabilities of ankle rehabilitation robots have been assessed by the type of control incorporated in them. The ankle robot controllers primarily fall into two categories: trajectory-tracking controllers and assist-as-needed (AAN) controllers [16–18]. Trajectory-tracking controllers enable precise control over predefined paths and trajectories focusing on targeted therapies while AAN controllers aid as per patients' needs and adapt according to the desired situation. These broad categories of controllers involve further different types of control techniques to perform the desired tasks as intended by ankle rehabilitation robots.

4.3.1. Trajectory Tracking Controllers

Position tracking or trajectory tracking controllers employed the linear time-invariant control law for bio-inspired AFO in [56]. This type of controller is easy to implement and demonstrates consistent performance but cannot counter the non-linearities that might occur during the training process. In some cases, like [39,121,125], a PID controller was utilized for following the predetermined path by the ankle robots. The advantage of using a simple PID controller is that it provides good control performance in diverse situations, but manually tuning the gains may be time-consuming and not very ideal in time-variable cases like those faced during rehabilitative procedures. However, implementing adaptive laws with PID controllers has shown beneficial results in the non-linear behavior of ankle robots. But this implementation increases the complexity of the system. The use of sliding mode controllers has been noticed in the literature for trajectory tracking due to their robustness for tackling the device's uncertainties. To achieve a balance between robustness and the robot's performance, an internal model controller (IMC) was utilized in [97]. IMC no doubt filters the noise and disturbances of the system well, but it greatly depends on the internal modeling of the system. If the modeling of the ankle robot is not close to reality, the controller may fail to deliver the desired output.

4.3.2. Force and Impedance Controllers

Force controllers used for [80,104] provide high-precision control based on the forces mainly exerted by actuators making them beneficial for robotic rehabilitative devices. These controllers have the ability to provide resistance during stretching exercises which helps in increasing the strength of patients. This type of controller may compromise the robot's performance depending on the kind of actuation used in the robot. When using these controllers in ankle rehabilitation devices, careful selection of actuators is needed, because if the actuators are too rigid, the robot will become unstable, and if they are too soft, the controller will not perform as required. Force controllers have also been used in combination with impedance controllers to enhance the efficiency of ankle robots. While the impedance control scheme offers an effective balance between position and force, it requires patient-initiated motion, making its adjustment a bit tricky. Moreover, high impedance can overburden the stiff joints of patients, leaving them with limited mobility, and lower impedance may lead to uncontrolled movements.

Another type of control technique, i.e., EMG-based control [36,129,133,139,153], has been employed in ankle rehabilitation robots, which is superior to previously mentioned controllers. EMG-based controllers work by translating muscle movement to control signals, facilitating a natural approach in ankle robotic devices. These controllers are known for providing personalized treatment as they adapt according to every patient's muscle activity.

Despite the benefits of this revolutionary control scheme, it may lose its effectiveness when dealing with patients suffering from severe muscle atrophy and paralysis, because in such cases, muscles become very weak or paralyzed, which makes it difficult to generate EMG signals.

Modern ankle rehabilitation robots are now designed more towards addressing real-time human–robot interaction problems, namely the unpredictability of patient response, safety concerns, and fatigue indicators. Adaptive control mechanisms such as impedance/admittance control and reinforcement learning-type controllers allow the robot to modify its behavior adaptively based on sensor feedback such as torque, joint angle, and EMG signals. For instance, by monitoring deviations in trajectory or increased resistance from the patient, the system can automatically reduce levels of support or switch to a passive mode. Fatigue detection is usually implemented through EMG signal trends or performance measures such as torque output reduction and movement velocity reduction. Safety is guaranteed by compliance-based designs (e.g., soft actuators or series elastic actuators), force monitoring of interaction, and internal torque and speed limiters. Such technologies ensure that therapy will be both effective and safe, even under the occurrence of fluctuations in strength, attention, or engagement of the patient during a session.

The integration of wearable sensors and AI-driven control methods is transforming ankle rehabilitation into a more personalized and adaptive treatment process. Inertial measurement units (IMUs), electromyography (EMG) sensors, and smart insoles can provide real-time feedback on joint angles, muscle activation levels, gait symmetry, and ground reaction forces. These data streams can be processed by machine learning algorithms such as neural networks, decision trees, or reinforcement learning agents to recognize patient intent, quantify fatigue, and adapt assistance levels as needed. EMG signals, for example, can be used to provide movement support only in response to voluntary effort in order to encourage active participation. Smart insoles can track load distribution and feedback to balancing control algorithms. Furthermore, IoT-based rehabilitation platforms can embed these wearable sensors within cloud-based systems to support remote monitoring, longitudinal follow-up, and therapist assessment. Such highly networked architecture supports in-home rehabilitation, increases accessibility, and allows clinicians to make adjustments in real time based on quantitative patient information in order to deliver improved overall rehabilitation results.

4.3.3. Assist-as-Needed and Adaptive Controllers

Unlike the above-mentioned ankle robots, which depend on specific parameters for operating, adaptive controllers offer distinct advantages by automatically adjusting to changing system dynamics or patient needs. In this review paper, AAN-based ankle devices mainly incorporated adaptive control laws. Adaptive controllers have the ability to change the system according to changes in the patient's state. By utilizing the knowledge of the robot under different circumstances, such controllers learn to behave well by automatically tailoring the robot's parameters both efficiently and safely. Among the adaptive control strategies, adaptive fuzzy logic controllers have been utilized the most in ankle rehabilitation devices. These controllers work on Mamdani's fuzzy logic concept for interpreting the input data and making decisions based on the fed information maintaining a smooth interaction between the training device and user. This dynamic adjustment capability of adaptive controllers enhances the overall efficiency and effectiveness of the robotic device by delivering an adequate level of support as needed by the user.

Until now, different control techniques have been used by ankle rehabilitation robots, which have delivered varying levels of effectiveness in patients with ankle joint disorders. Further advancements in these technologies will lead to more personalized treatment and a

user-friendly environment, and artificial intelligence and machine learning-based adaptive control algorithms must be implemented. Additionally, the use of multimodal sensors should be encouraged, which will combine information from various sensors and develop a comprehensive understanding of the patient's condition and their required treatments. Future control strategies must be more user-centric, meaning they should not only ensure accurate and safe movement based on mechanical and kinematic requirements but also promote psychological engagement and motivation. This can be achieved by incorporating real-time feedback, gamified interfaces, adaptive challenge levels, or virtual environments to sustain patient interest and adherence throughout the rehabilitation process. Incorporating algorithms that can provide assistance depending on the exertion and fatigue levels of the patients would be a huge contribution to the field of ankle rehabilitation robots.

The selection of control strategies for ankle rehabilitation robots is often guided not only by the desired therapeutic benefits but also by computational and real-time implementation constraints, which differ significantly across platform-based and wearable exoskeleton devices. Platform-based robots, with fixed structures and access to offboard computation, are better suited for computationally expensive algorithms such as nonlinear MPC or reinforcement learning-based controllers requiring real-time trajectory optimization and dynamic system identification. Wearable exoskeletons are limited by onboard processing capabilities, weight, and power consumption. Therefore, these systems can employ low-complexity adaptive controllers, pre-trained ML models, or fuzzy logic control with minimal computation load to allow for quick response while maintaining safety or wearability. Some of the devices leverage distributed frameworks or edge-computing protocols to balance responsiveness and control quality in real time. This must be closely balanced in order to preserve the effectiveness and wearability of the device while it is being used in useful practice as part of real-life rehabilitation regimens.

4.4. Experimental Setup and Clinical Testing

The experimental evaluation of ankle rehabilitation robots is the most crucial stage of designing and implementing robotic technology. This phase will decide how the robot will perform in real conditions. The performance of the robot is tested when it is used by neurologically impaired subjects in order to determine whether the designed ankle robot can provide the desired motion and assistance or not. But after conducting this review, this has been observed that the majority of the ankle rehabilitation robots have been tested using healthy subjects. Tables 2 and 3 reported in this review article support this claim. Hence, to make use of common and successful ankle robots among neurologically impaired patients, it is necessary that they should be tried and tested on the targeted group of patients during experimental evaluations. Moreover, it has been noticed that when ankle robots were tested for neurologically impaired subjects, the test groups usually included stroke patients only. Very few studies, like Refs [79,134], included patients belonging to a different group of neurological disorders. So, it is highly recommended that ankle robots should be designed keeping a diverse range of ankle joint dysfunctionalities in view.

Another issue that has been observed while conducting research surveys for this article is that almost all the research projects and devices have been designed on the prototype level, which is not directly aligned with clinical setups. Prototypes like AFO [13], Lokomat [45], Rewalk [46], and Rutgers Ankle [31], etc., have been incorporated in clinical practices, but they have somehow become outdated due to some of their major drawbacks such as heavy weights, limited ranges of motion, high maintenance, and less efficient control algorithms. Modern advancements in ankle rehabilitation robots have overcome these challenges as they use lightweight materials [54,58,59], improved actuation facilities [36,104,123], and

adaptive control techniques [42,124,131,145] to provide more comfortable and personalized therapy for patients suffering from ankle disorders.

Despite positive results being obtained in early clinical trials, several important issues remain to be resolved before ankle rehabilitation robots can be taken from the research prototype to the clinical prototype stage. Compliance by the patient is one of the major barriers, and this can be influenced by pain, fear of robotic assistance, and perceived complexity of the device. Most of these systems are still not user-friendly enough to be operated even by patients and therapists with extensive training. Moreover, usability and portability are essential to support home-based rehabilitation, but wearable systems sacrifice usability for accuracy or power. Another important gap is the lack of long-term clinical outcome evidence; most of the evidence refers to short-term increases in muscle strength or joint mobility, but the long-term impact on quality of life and functional independence remains under-researched. Personalization to individual patient needs, the equipment cost, and integration within existing clinical routines are other challenges to widespread application that must be overcome. The resolution of these problems will require multidisciplinary collaboration between clinicians, engineers, therapists, and patients.

4.5. Energy Efficiency

Energy efficiency is critical when designing wearable ankle exoskeletons, particularly for handheld or battery-operated devices during home-based rehabilitation or daily-life rehabilitation [158]. Classic electric motors exhibit high precision and control but come in bulky designs with high power demand, possibly diminishing battery lifetime and contributing significant thermal load. Pneumatic actuators display high torque, but low weight usually accompanied by requirements of air compressors from an external source, losing portability and energy efficiency. Cable-driven systems have the possibility of offering improved energy distribution and lighter actuation at the joint, but will tend to have mechanical complexity and friction losses. New technologies such as twisted-string actuators and dielectric elastomer actuators offer the possibility of lightweight and energy-efficient designs but are currently limited by precision and robustness in control. Soft actuators, like artificial muscles, have intrinsic compliance and low power needs but are in their infancy when applied at the ankle. In each case, the challenge is to balance torque output, response time, weight, and power consumption; a trade-off that continues to drive innovation in actuator design for wearable rehabilitation systems.

4.6. Future Challenges and Recommendations

The future challenges regarding ankle rehabilitation robots are described below.

- Not every patient suffering from ankle joint disorders or neurological diseases has quick and easy access to clinical therapy and experts. In future, ankle rehabilitation robots must be designed keeping in view all kinds of people and their resources. The design and operation of the robot must be simple enough to be used easily by patients in the comfort of their homes. The concept of home rehabilitation using ankle robots is gaining steam due to the potential it offers to improve access and reduce expenses. Worth mentioning, however, is the fact that such devices must be designed with non-professional use in mind, featuring safety features such as compliant actuators, force and position limits, user interfaces, and emergency stops. Remote clinician monitoring and adaptive control systems can further help individualize therapy while ensuring safety. Clinically, home usage is permissible only if the devices are clinically proven, have undergone appropriate regulatory approvals, and are accompanied by explicit guidelines for usage. Without such controls, inappropriate usage, injury, or ineffective

therapy can occur. Thus, while promising, home usage needs to be implemented cautiously and within an appropriately monitored environment.

- One of the major challenges faced with ankle orthosis and rehabilitation platforms is their size and weight. It is necessary to design devices with reduced weight and size employing smart materials and nanotechnologies.
- Implementation of artificial intelligence and intelligent control systems to enhance the performance of AAN-based ankle rehabilitation robots.
- In order to regulate the use of ankle rehabilitation devices more commonly, it is recommended that a set of general guidelines should be issued. This will promote the user's confidence and control resulting in positive impacts on their health.
- Creating opportunities for engineers, clinicians, and researchers to work together in a team in order to design and develop ankle rehabilitative devices that have the potential to cater to real-world needs and demands.

For ease of frequent benchmarking and improved comparability of future studies of ankle rehabilitation robots, a standard set of measures of performance is required for evaluation. Some of the most common measures used include tracking accuracy (e.g., root mean square error of joint angle trajectories), interaction torque (for evaluation of transparency and safety), and electromyographic (EMG) response for evaluating muscle activity and patient participation. In addition, energy usage and control effort can be a means of gaining insight into the performance of actuators and the system. Subjective measures such as patient-reported outcome measures (PROMs), comfort, and usability scores can complement quantitative data to determine the user experience. For clinical relevance, gait symmetry, range of motion (ROM) improvement, and completion time of ADL-like tasks also count. Developing a multi-dimensional test framework combining biomechanical, energetic, and user-oriented measures would provide more comprehensive insight into robotic system behavior and enable better-informed comparisons across studies. Confronting the issues and adopting the recommendations will strengthen the integration of ankle rehabilitation devices, leading to improved results and better healthcare.

The review identifies several key features characterizing future-generation devices:

- Multi-DOF capabilities: Advanced robots increasingly support dorsiflexion/plantarflexion, inversion/eversion, and internal/external rotation, essential for natural and adaptable gait patterns.
- Wearability and portability: Lightweight, modular exoskeletons are replacing bulky setups, making these robots viable for use during daily walking or in home-based rehabilitation.
- User-adaptive control: Integration of EMG signals, force sensors, or learning-based control allows real-time customization of assistance based on patient effort or intention.
- Functional task training: Rather than repetitive motion alone, modern systems focus on training users through goal-oriented tasks, e.g., walking on uneven terrain or climbing stairs.
- Remote monitoring and telerehabilitation: With the increasing use of wireless sensors and cloud platforms, therapists can remotely assess progress and adjust therapy protocols.
- Engagement and motivation features: Gamification, biofeedback, and virtual environments are being used to keep users motivated and improve adherence.

These features enable the transition of robotic therapy from supervised clinical environments to everyday life. Future robots will not only assist in recovery but will also support users during active daily living tasks (ADLs) such as walking in public spaces, navigating stairs, or recovering balance after perturbation. This shift aligns with the growing focus on community reintegration and long-term self-management of mobility impairments.

5. Conclusions

In recent years, remarkable progress has been made in the field of ankle rehabilitation with a focus on enhancing the design of both wearable and parallel/platform-based ankle robots. This progress, driven by improvements in actuation methods, materials used for manufacturing ankle robots, and control techniques has enabled the development of more robust and efficient ankle rehabilitation robots over the passage of time. This review covers these cutting-edge robotic devices, focusing on their actuation technologies, control strategies, and experimental evaluations explored and implemented in the last decade. Despite the recent advancements, further optimization of the ankle robots is needed in order to make these devices more adaptable and efficient so they can understand and interpret the condition of the patients in a better way. Moreover, the aim of the researchers should be the design of more autonomous ankle rehabilitation devices that will decrease the load on therapists as well as provide personalized treatments as per patients' needs. As reported in this study, the number of clinical trials and validations of designed ankle robots is very low, so it suggests the need for more rigorous and comprehensive clinical experimentation of the proposed devices in order to determine their therapeutic potential and safety.

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