IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 18, 2022, accepted April 30, 2022, date of publication May 12, 2022, date of current version May 19, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3174686

Lower-Limb Robotic Assistance Devices for Drop Foot: A Review

NOUR AL-RAHMANI[1,2], DHANYA MENOTH MOHAN[1,2], MOHAMMAD I. AWAD[1,2,3], (Member, IEEE), SABAHAT ASIM WASTI[4], IRFAN HUSSAIN[1,3,5], AND KINDA KHALAF[1,2,3]

[1]Healthcare Engineering Innovation Center, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[2]Department of Biomedical Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[3]Khalifa University Center for Autonomous Robotic Systems (KUCARS), Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[4]Neurological Institute, Cleveland Clinic Abu Dhabi, Abu Dhabi, United Arab Emirates
[5]Department of Mechanical Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates

Corresponding authors: Mohammad I. Awad (mohammad.awad@ku.ac.ae) and Kinda Khalaf (kinda.khalaf@ku.ac.ae)

This work was supported by the Khalifa University of Science and Technology under Award RC2-2018-022 (HEIC).

ABSTRACT Drop foot is a pathological type of gait frequently exhibited by individuals suffering from stroke and other neurological conditions due to the weakness of the ankle dorsiflexor muscles. To avoid common negative compensations, such as foot-slap during the loading response and toe-drag during the swing phase of gait, various drop foot assistive robotic devices and technologies have emerged over the last couple of decades. This review summarizes the design, working principle, and application of robotic devices for drop foot assistance and rehabilitation in the last decade. The research findings describe the design aspects of 72 lower-limb robotic assistance devices for drop foot, including 21 studies that evaluated specific design aspects through experimental trials. All the designs reviewed here demonstrated the capability to successfully improve drop foot impairments in the sagittal plane. Some leveraged advanced functional features to achieve optimal performance without jeopardizing the user's natural range of motion, comfort, balance, or safety. However, there remain certain limitations when combining all these functional features into one robotic device. Overcoming these limitations should add great value to the future of advanced robotic devices for drop foot assistance and rehabilitation.

INDEX TERMS Drop foot syndrome, robotic device, drop foot rehabilitation, lower-limb robotic assistance, gait assistance, motor relearning.

I. INTRODUCTION

Drop-foot, also referred to as foot drop, is a complex gait disorder instigated by total or partial central paralysis of the muscles innervated by the common peroneal nerve, or the anterior tibial muscle and the peroneal group. These muscles play a significant role in producing dorsiflexion of the ankle joint [1]. The etiology of this condition is multi-factorial, which typically includes cerebrovascular accident, amyotrophic lateral sclerosis, traumatic injuries, surgical procedures, prolonged bed rest, pelvic fracture, tibia or fibular head fractures, radical syndrome at L2-L5, neuropathy, myopathy, multiple sclerosis, and cerebral palsy [2], [3]. Drop foot is very common among stroke patients, and reports suggest that approximately 10-20% of stroke survivors suffer from drop foot [4]. This type of pathological gait can be either unilateral or bilateral, where unilateral drop foot is often caused by focal disorders such as radiculopathy, whereas bilateral drop foot is the result of generalized dis- orders including neuropathy [5]. The symptoms of drop foot include difficulty or inability to stand or walk on the heel, loss of balance while standing without support, inability to load the lateral side of the foot, muscle weakness, lower leg muscle atrophy, and contracture [3], [6].

Patients with drop foot often exhibit limited capacity to lift their foot off the ground during the swing phase of gait due to the weakness of the ankle dorsiflexor muscles. This typically leads to a form of compensatory abnormal gait, called steppage gait, which is characterized by dragging of the toe during the swing (i.e., the toe of the affected lower limb makes initial contact, followed by the ridge of the foot, and finally the heel), as well as slapping of the foot at heel

The associate editor coordinating the review of this manuscript and approving it for publication was Aysegul Ucar.

strike (i.e., heel lands uncontrollably on the ground with a slapping noise) [7], [8]. The lack of proper limb advancement and foot clearance places the patients at a higher risk of instability and tripping. To compensate, patients generally lift their lower limb higher than usual, thereby increasing hip and knee flexion, in addition to adopting a circumductive leg swing during the swing phase [1], [9]. This results in greater energy expenditure and causes mobility limitations, thus ad- versely affecting independence and social engagement. The severity of the condition, in correlation with significant walking impairment often dictates the need for medical support and intervention.

Treatment options for drop foot include therapeutic approaches, surgical procedures, and orthotic devices. While physiotherapy remains the gold standard for gait rehabilitation of drop foot, residual deficits can remain or re-emerge in the future due to the multifactorial complexity of the disorder. For example, conventional therapy may not always successfully reinforce repetitive, high-intensity, or task-oriented training and does not typically optimize motor learning and recovery [10].

Functional Electrical Stimulation (FES) has recently emerged as a potential tool for correcting drop foot impairment by applying an electrical current to stimulate the common peroneal nerve over key phases of the gait cycle, where surface or implanted electrodes are employed to deliver the electric pulses. On the other hand, the surface-based systems are limited by complex system setup, as well as skin irritation, discomfort, and pain. Although implanted electrodes alleviate some of these drawbacks, they are invasive and more expensive [11].

Orthotic devices, such as Ankle-Foot Orthoses (AFO) are becoming increasingly common in today's clinical practice for treating patients with drop foot for both assistive, as well as rehabilitative purposes. Depending on the patient's level of functionality, they range from simple passive braces comprised of mechanical elements (springs and/or dampers) which position the foot at a 90° angle, to advanced semiactive and active orthoses equipped with sophisticated onboard electronics to provide flexible positioning of the joint ankle joint with varying impedance levels based on different walking stages [12]. Substantial research effort has been devoted to the design consideration, actuation mechanism, and application of AFOs [13]–[15]. Alam *et al.* extensively reviewed and summarized engineering designs and mechanisms of several articulated ankle-foot orthoses for drop foot application; however, the findings are limited to studies dated up to 2013 [16]. Another more recent review on drop foot robotic devices was conducted in 2019 by Hamedi *et al.*, however, this work mainly focused on the actuation mechanism of active orthoses, characteristics of ideal orthoses, as well as the development of an intelligent system for the rehabilitation of drop foot [17]. Although several review articles have explored the design and mechanism of ankle foot orthoses, there remains a gap in literature regarding a summary of different currently available robotic technologies for treating drop-foot abnormalities. As such, this review is aimed at exploring the design, working principles, and application of the state-of-the-art robotic orthoses/exoskeletons for drop foot assistance and rehabilitation.

The principal objectives of this research effort are to:

1) Review and summarize different robotic orthoses/ exoskeletons which target assistance as well as rehabilitation of drop-foot impairment due to any pathological condition.
2) Understand and summarize the data collection processes, control methods, and actuation mechanisms adopted in these studies.
3) Explore the clinical feasibility of the reviewed robotic systems in effectively assisting/rehabilitating drop-foot impairments.
4) Study the novelty and limitations of the reviewed systems to identify possible areas for researchers to further progress in developing orthoses/exoskeletons which target drop-foot impairments.

This review focuses only on the literature published in the last decade (2011-2021). Based on the research findings, we have divided the studies on robotic orthoses for drop foot treatment into grounded movement assisting robotic devices, and wearable movement assisting robotic devices. Grounded technology includes robot-assisted seated training devices, as well as advanced over-ground gait training devices which involve patient cooperation. Moreover, the literature on movement assisting robotic devices focuses on robotic perceptive systems, control systems, and actuation methods. Studies reporting experimental trials were also included in this review to provide further insight into the impact of robotic assistance on drop foot treatment and clinical implications. Key findings were highlighted, and limitations were discussed.

The remainder of this article is structured as follows: Section 2 provides a brief overview of the current different drop foot treatment procedures. Section 3 highlights the study protocol adopted for this review, illustrating the search strategy and rationale. Section 4 presents the results of the reviewed robotic systems for drop foot rehabilitation. Section 5 discusses the key findings, while section 6 examines the remaining issues and future direction of advanced robotic devices for drop foot. Finally, in section 7, we provide concluding remarks.

II. BACKGROUND

Drop foot treatment using rehabilitation techniques is receiving greater attention nowadays due to the recent accessibility of sophisticated portable devices and technologies, as well as advanced/specialized actuation/control mechanisms. Widely adopted treatment options include Functional Electrical Stimulation (FES) and assistive robotic devices. As previously mentioned, FES delivers an electrical current through electrodes to stimulate the common peroneal nerve to activate the dorsiflexor muscles during the swing phase of gait [18]. This forces the ankle joint to flex past its neutral angle, thus maintaining clearance during swing [18]. Limitations using this technique include reported difficulties in obtaining the optimal intensity level; complications in the positioning of the stimulation electrodes [19]; as well as challenges in stimulating the entire muscle mass, hence reducing the effectiveness of FES [19].

Alternatively, assistive robotic devices have emerged in the last couple of decades as valuable tools for lower limb movement assistance, by either training the deficient limb or offering assistance through a wearable physical interface [20], [21]. The former, so-called grounded training approach aims to assist patients towards regaining normal mobility through repetitive rehabilitative exercises, mainly gait training for patients suffering from drop foot [20]. Lower-limb grounded rehabilitation systems include treadmill gait trainers, foot-plate-based gait trainers, overground gait trainers, stationary gait trainers, and ankle rehabilitation systems [20]. Wearable lower-limb assistive robotic devices, on the other hand, are designed to either compliment, enhance, or substitute the movement of the deficient limb [21]. External information from perceptive systems works in conjunction with the robotic device to transfer the optimal mechanical power at optimal points during the gait cycle. This not only improves the efficiency of the assistance provided to the impaired limb but also improves the robot-human interface safety with the seamless transmission of assistance between the robotic device and the user [21]. Such perceptive sensing systems have been utilized to either measure the limb's range of motion, detect the gait phase, or sense the environment around which the system is used to provide assistance accordingly [22], [23]. Another component that contributes to the efficiency of wearable lower-limb assistive robotic devices is the feedback system. Mimicking human physiology, the feedback system allows the proprioceptive inputs provided by the perceptive systems to be augmented and synchronized with the patient's gait cycle [24]. Finally, the actuation elements embedded within the wearable lower-limb assistive robotic devices provide the user with sufficient mechanical power, hence assisting in the movement of the deficient limb. Typical mechanical components used in assistive lower-limb robotic devices include springs, series elastic actuators, magnetorheological fluids, passive pneumatic elements, frictional clutches, oil dampers, artificial pneumatic muscles, and shape memory alloys [18].

III. METHODS

This study was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [25].

A. SEARCH STRATEGY

An extensive systematic literature search was carried out using the electronic databases of Google Scholar, ScienceDirect, JSTOR, and IEEE, which are the core databases for studies on neuroscience and engineering. To identify the articles addressing the engineering design, actuation mechanism, control strategies, and assessment methods of lower limb robotic devices applicable for drop foot treatment, a combination of the following search terms were used: drop foot, foot drop, lower limb, lower-limb, drop foot syndrome, drop foot robotic, foot drop robotic, drop foot orthosis, robotic assistance drop foot. The search was limited to stud- ies published in the last 10 years (2011-2021). The search was performed between 2nd June and 27th September 2021.

B. INCLUSION AND EXCLUSION CRITERIA

This study included original peer-reviewed articles, as well as review papers meeting the following criteria:

1) Articles which investigate the use of robotic orthoses for drop foot treatment (both assistive and rehabilitation robotic devices)
2) Studies which explore the engineering design, actuation mechanism, control strategies, and/or assessment methods of robotic orthoses
3) Studies which report experimental trials of orthotic devices for drop foot application.

Studies addressing drop-foot impairment using surgical procedures and/or electric stimulation therapy were excluded from this review. Studies on surgical robotic devices were outside the scope of this work. Publications in non-English were also excluded. In addition, dissertation papers, works with no institutional access, letters to editor and editorials, opinion pieces, conference summary, short surveys, notes, and preliminary reports were all excluded.

C. STUDY SELECTION AND DATA EXTRACTION

Following the removal of duplicates, each title and abstract were screened against the inclusion/exclusion criteria. The full text of the eligible articles was retrieved and assessed for final inclusion in this study. A PRISMA flow diagram illustrating the process of search and screening of articles is shown in Figure. 1.

Data extraction was performed by the first author and was verified by other authors. Any discrepancies were resolved through discussion among the authors. The extracted data included the author name(s) and year of publication, specification of the robotic system, assistance/rehabilitation strategy, targeted parameters, the feasibility of approach (results), the novelty of the proposed method, and limitations.

Ninety-three studies were included in the final review, of which seventy-two discussed the design aspects and twenty one included the trials and studies on the use of specific devices.

IV. RESEARCH RESULTS

The current literature on robotic orthoses for drop foot treatment could be categorized into two main approaches in terms of rehabilitation and assistance: grounded movement assisting robotic devices, and wearable movement

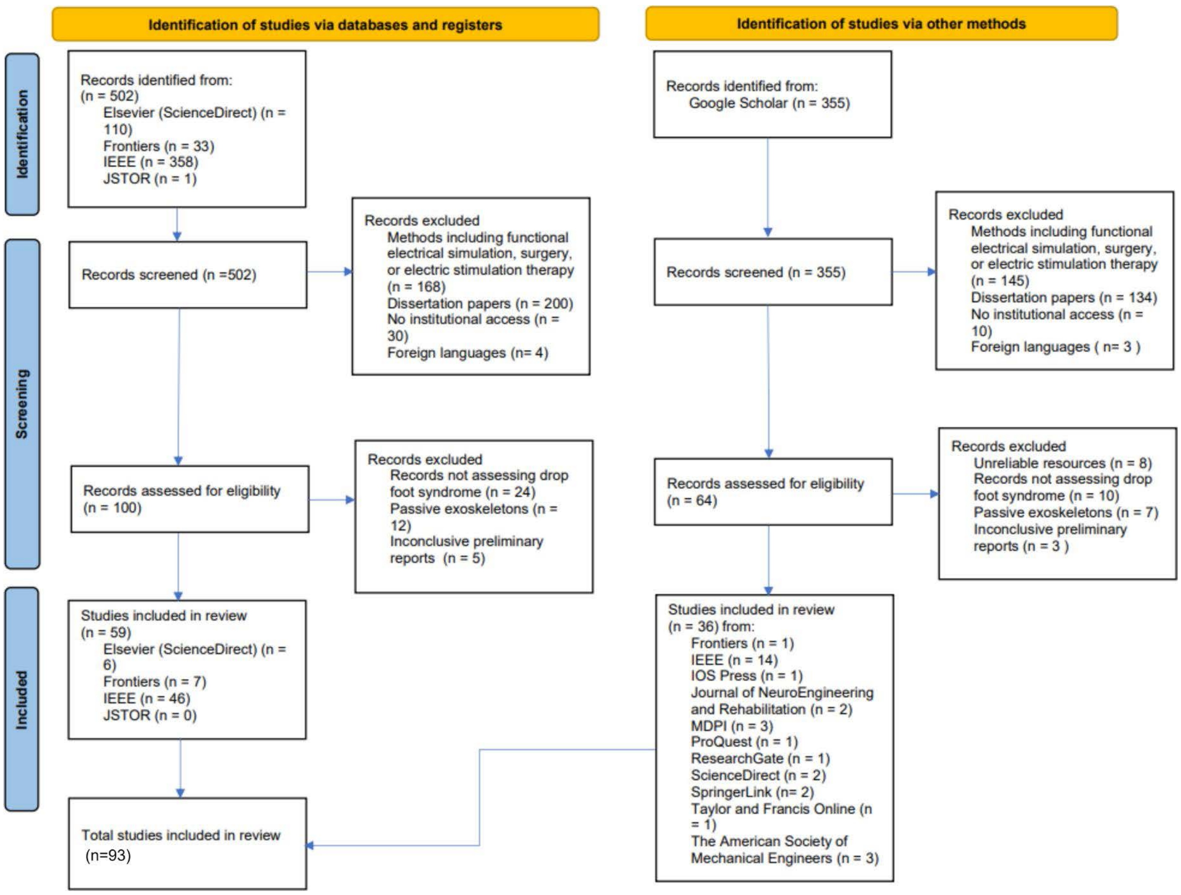

FIGURE 1. Flowchart of the search and screening process.

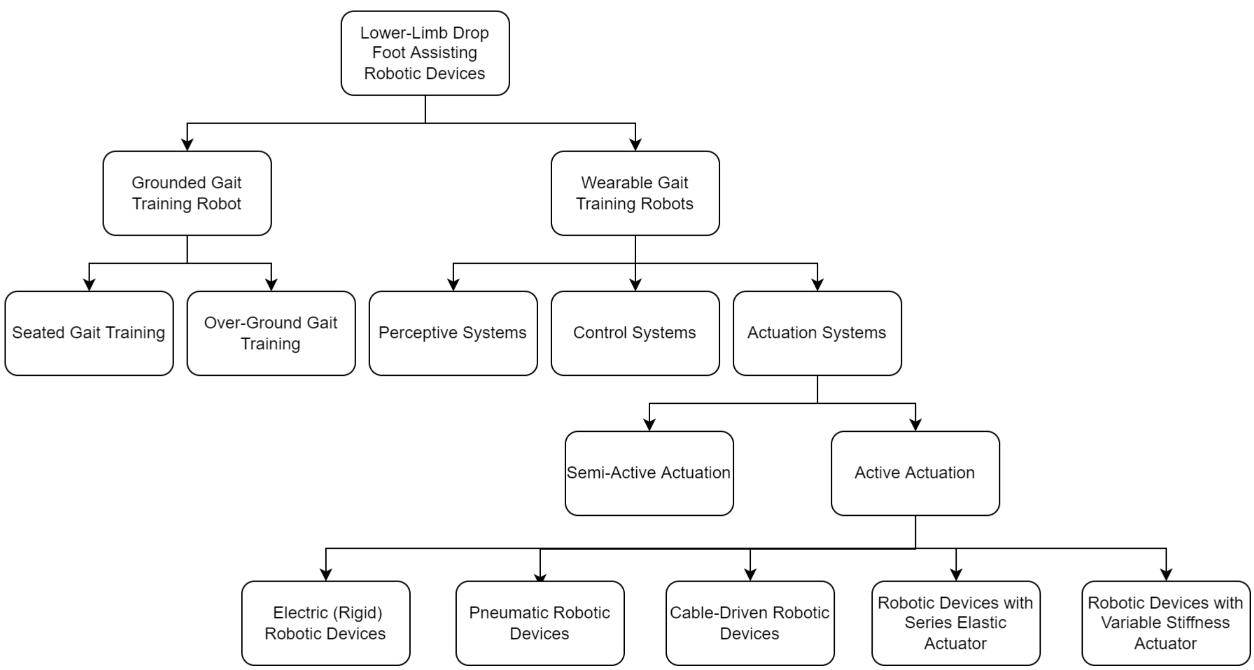

FIGURE 2. Categorization of literature on lower-limb drop foot assisting robotic devices.

assisting robotic devices (see Figure. 2). Grounded technology includes platform robotic seated training devices, as well as advanced over-ground gait training devices which involve patient cooperation.

A. SEATED GAIT TRAINING

Given the weakness and stiffness of the ankle joint in the early stages of rehabilitation, ankle rehabilitation using a parallel platform-based robotic device can ease the user into using a wearable exoskeleton later in the process. For grounded training devices, with which the user's drop foot deficiencies are trained while seated down, eight articles were selected and discussed in the sections below.

Motor relearning of patients with drop foot can be promoted through repetitive skill training which improves neuroplasticity [26]. Given that rehabilitative clinics are not accessible for many patients, Karime *et al.* developed a rehabilitation robotic device that provides rehabilitation training using an interactive wobble board that can be used at home as shown in Figure. 3(A) [27]. With the use of sensors and actuators, the patient interacts with the interface to complete the tasks associated with a 2D golf game. This enables repetitive inversion-eversion motion of the ankle, dorsiflexion plantarflexion of the ankle, and extension-flexion of the toes, leveraging both motor skill training and neuroplasticity. The patient's progress is monitored remotely using a networked system.

Zuo *et al.* developed a wearable ankle rehabilitation parallel robotic system which provides maximum safety protection by a realized aligned rotation of center as shown in Figure. 3 (B). Realizing non-redundant actuation with a simple kinetic configuration and easy operation can help reduce the cost of the robotic device, the complexity of the control system, and the workload on therapists [28]. Although most gait training rehabilitation devices rely on Continuous Passive Motion (CPM) to treat spasticity and/or contracture, it is important to note that the calf muscle cannot typically be fully stretched where the deficits are pronounced. Moreover, passive stretching does not involve active participation of the patients and hence may not result in full functional recovery [29]. To address these issues, Zhou *et al.* developed an active rehabilitation system that uses the Proprioceptive Neuromuscular Facilitation (PNF) technique involving active patient participation. By incorporating PNF, maximum static flexibility is achieved through contracting the opposing muscle to stretch the target muscle as shown in Figure. 3(C) [29]. In comparison to the previous rehabilitation robotic devices which measure the ankle joint's orthogonal axis, a rehabilitation robotic device was developed to detect the anatomical ankle axis towards effective rehabilitation of ankle movement as shown in Figure. 3(D) [30]. The main goal was to produce natural ankle motion to train the pathological ankle joint. In addition to that, the robotic device can collect the user's ankle range of motion, spasticity, and ground reaction forces.

Instead of collecting data on the impaired limb, MingKai Ankle IV (MKA-IV), an ankle rehabilitation robotic system, uses data collected from the ankle of the sound limb to map out and control the rehabilitative exercises delivered to the impaired ankle as shown in Figure. 3(E) [31]. This mechanism helps users restore their symmetric motor capability for different activities including walking, running, or jumping. The bilateral ankle rehabilitation robot provides mechanical power to the impaired ankle in the three ankle joint rotational planes: the dorsiflexion-plantarflexion sagittal plane, the abduction-adduction frontal plane, and the inversion-eversion transverse plane. Each of the two-foot pedals of the robotic device can collect data and provide assistive exercises to accommodate for hemiplegia on either side.

Robotic devices with two modes of therapy, i.e., passive and active, provide their users with comfortable movement capacity towards reduced muscle atrophy during passive assistance when active assistance is not needed during certain phases of gait [32]. Zhang *et al.* developed a Compliant Ankle Rehabilitation Robot (CARR) that uses a multi-modal control strategy as shown in Figure. 3(F) [33], [34]. The strategy consists of three modes: passive, patient-robot cooperative, and cooperative modes. This robotic device is actuated through bioinspired Festo Fluidic muscles actuated in three rotational degrees of freedom. The position controller and high-level admittance controller work together to collect ankle measurements in real-time and modularly train the robotic device. In another study, Dong *et al.* developed an ankle robotic system that assists with three rehabilitation training modes: patient-passive compliance training, isotonic training, and patient-active training. The training is provided using parallel two-UPS/RRR planar ankle rehabilitation robots with three rotational degrees of freedom as shown in Figure. 3(G) [35]. A summary of the reviewed articles is presented in Table. 1.

B. OVER-GROUND GAIT TRAINING

To improve patients' motor relearning to achieve/improve independent gait, actual over-ground gait training is required instead of seated training [26]. Early designs of grounded movement assisting robotic devices included Body Weight Supported Treadmill Training (BWSTT), with which patients benefit from repetitive, higher intensity, and task oriented therapeutic gait exercises [42]. However, this technique proved to be time-consuming, physically demanding, and in need of multiple therapists [43]. For this reason, robot-assisted stepping training was introduced. This review summarizes seven articles in that area as described below.

As part of successful gait training for hemiplegic patients, the patient's pelvis needs to be suspended and confined of movement within the sagittal plane. A rehabilitation robotic device emulating the lateral pelvic assistance provided by manual physical therapy was developed as shown in Figure. 4(A) [36]. A virtual model control allowed for assistance was specifically customized according to the patient's level of hemiplegia. Similarly, Fong *et al.* developed a robotic device that can apply kinesthetic teaching principles to learn and imitate a therapist's course of treatment. This device was

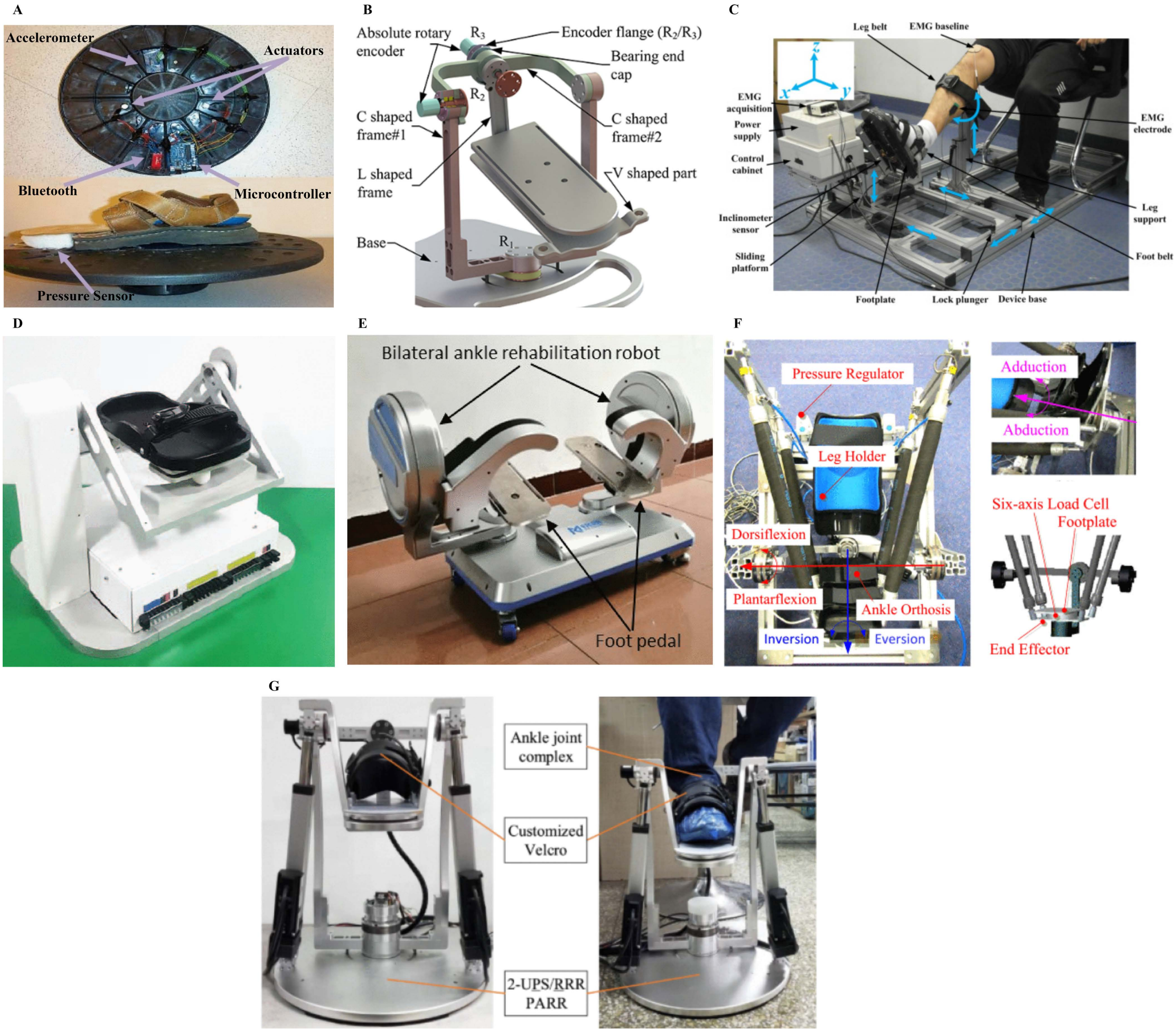

FIGURE 3. Mechanical overview of repetitive seated training robotic devices, (A) Interactive electronic wobble board system [27], (B) Parallel platform-based robotic device [28], (C) A PNF integrated robotic ankle–foot system [29], (D) An AMT [30], (E) MingKai Ankle IV (MKA-IV) rehabilitation robotic device [31], (F) Compliant Ankle Rehabilitation Robot [33], (G) Multi-modal patient compliant ankle rehabilitation system [35].

able to provide toe clearance by lifting the patients' foot during treadmill-based therapy as shown in Figure 3(B) [37].

As drop foot differs in terms of symptoms and severity from one patient to another, compatible rehabilitation was introduced to rehabilitation robotic devices for effective therapy, as well as patient participation. Anklebot is an ankle rehabilitation robotic system developed to train the impaired lower limb by providing assistance precisely timed and compliant to the patient's response as shown in Figure. 4(C) [10], [38], [41]. The assistance provided by the Anklebot is customized to the user's specific degree of impairment [10]. This 2 degrees-of-freedom (DOF) robotic device addresses both foot slap and drop foot, as well as lateral instability. Only actuating 2 of the ankle's 3 DOF permits the use of the robotic device without the precise alignment with the joint axes. The Anklebot estimates the user's passive static stiffness by measuring the angular displacements and applying optimal movement assisting torques in the plantar- dorsiflexion plane and the inversion-eversion plane. Concentric plantar flexion torque is delivered during terminal stance, while concentric dorsiflexion torque is delivered during the swing phase of gait. Additionally, a velocity-dependent resistive torque is applied when the foot lands on the surface to absorb its impact. Similarly, another system was developed that can assess the severity of a patient's foot drop whilst assisting using a locomotor training robotic device [41]. The system can adapt to sub-events and ankle directionality to activate the robotic device for the different phases of gait [41].

TABLE 1. Summary of reviewed articles for seated gait training robotic devices.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Karime et al. 2011 [27]	Interactive ankle training electronic wobble board rehabilitation system	Trains ankle dorsiflexion-plantar flexion and ankle inversion-eversion (2DOF) and toe extension-flexion (1 DOF)	Accessible for at-home use	Difficulty moving ankle in eversion motion due to seated position whilst training
Zuo et al. 2020 [28]	Wearable ankle rehabilitation parallel robotic device	Platform-based ankle training in the sagittal, transverse, and frontal planes (3 DOF)	Realizing non-redundant actuation with a simple kinetic configuration for maximum safety protection	Dimension optimal design needed before prototype construction
Zhou et al. 2015 [29]	PNF integrated robotic ankle-foot training system	Trains ankle dorsiflexion-plantar flexion (1 DOF)	Active participation of the patient	N/A
Cho et al. 2016 [30]	Ankle muscle trainer	Trains ankle dorsiflexion-plantar flexion and inversion-eversion (2 DOF)	Trains ankle muscles using anatomical ankle axes	Differed ankle ROM due to initiation between footplate and user's shoes
Liu et al. 2019 [31]	MingKai Ankle IV (MKA-IV) rehabilitation robotic device	Trains ankle adduction-abduction, dorsiflexion-plantarflexion and inversion-eversion (3 DOF)	Allows patient to exercise affected ankle using motion data collected from the sound side ankle	The motor drivers need a large torque to balance the gravity of the motor and the gearbox
Zhang et al. 2017, 2018 [33], [34]	Compliant ankle rehabilitation robot (CARR)	Trains ankle adduction-abduction, dorsiflexion-plantarflexion and inversion-eversion (3 DOF)	Aligned rotation center, a position controller implemented in joint space and a high-level admittance controller in task space and real-time measurement of patient–robot interaction	N/A
Dong et al. 2021 [35]	Ankle assisting robotic system	Parallel two-UPS/RRR ankle rehabilitation robots with three rotational degrees of freedom (3 DOF)	Assists users with three rehabilitation training modes	Multiaxis patient-active exercise not added and tested

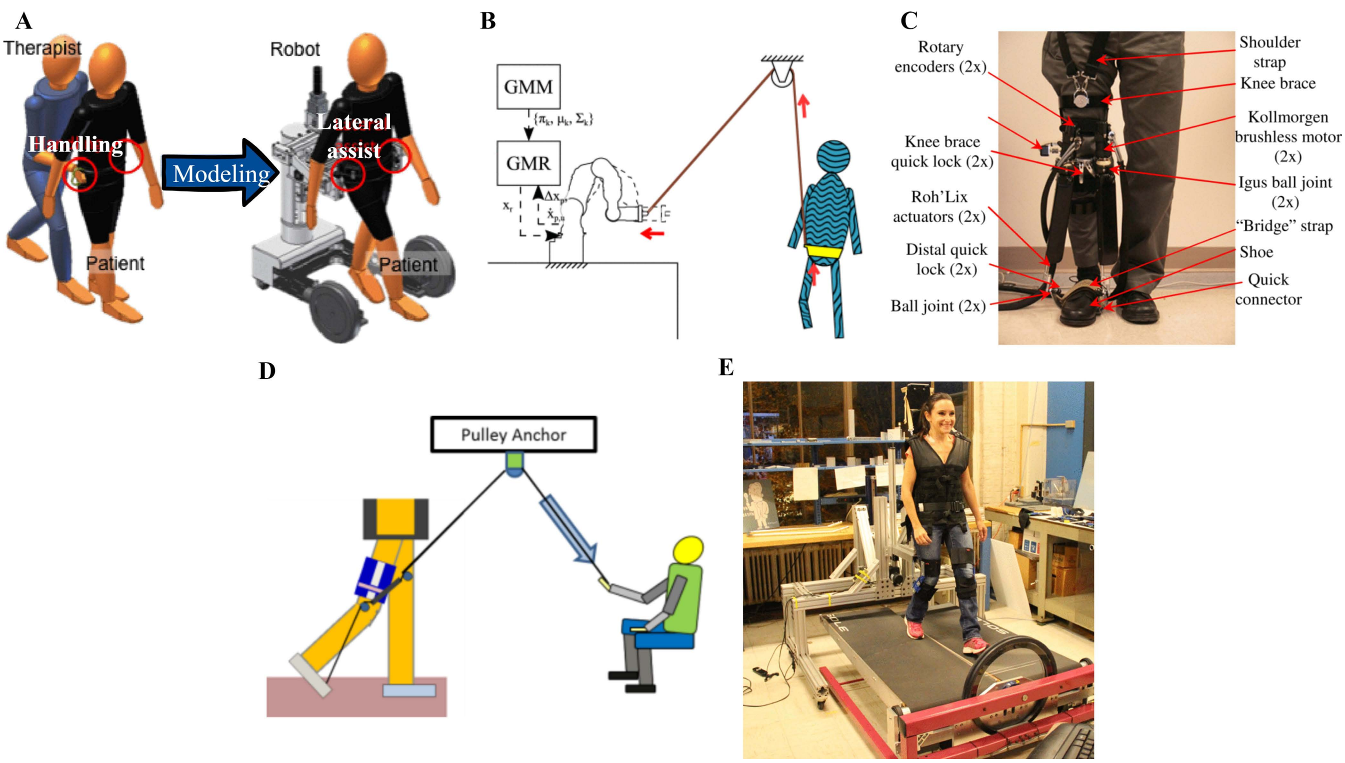

FIGURE 4. Mechanical overview of over-ground gait training robotic devices, (A) Robotic device with Therapist assistance mimicking pelvic assistance [36], (B) Toe-clearance assisting treadmill-based system [37], (C) Patient compliant Anklebot [38], (D) Minimally-required-assistance gait training device [39], (E) MIT-Skywalker split down treadmill training [40].

The adaptive feature of the developed device allows for increased safety and autonomy by adapting to the variability of gait with each step during the gait cycle. In this study, the phases of gait are detected through a bilateral micro-switch insole. This modular system can determine gait impairments in the stance and swing phase of gait, actuate the robotic device at the events of deficit detection, adapt to step-to-step variability, and modulate the robotic devices' actuation in real-time.

Different from the assist-as-needed training paradigm previously developed, Liu *et al.* developed a training device that uses a minimally-required-assistance strategy to rehabilitate patients as shown in Figure. 4(D) [39]. This method defines the assistance needed to assist movement deficiencies, and then defines the areas in need of minimal assistance through defining the specifics of stepping tasks. For example, the identified movement specifics for step movement in this study include hip flexion during the period between the end of the stance phase to the swing phase and ankle dorsiflexion during the period between the end of the stance phase and the first half of the swing phase. This system allows for the patient's active engagement in training activities, the benefit of motor learning, the reduction of sensory disturbances, and the reduction of obstructed gait.

Based on the sub-movements, oscillations, and mechanical impedances of a sound limb, the MIT-skywalker, a gait rehabilitation device, was developed. This device trains the impaired limb to accommodate a spectrum of gait impairments as shown in Figure. 4(E) [40]. This was possible through developing three training modes: discrete, rhythmic, and balance training modes. The MIT-Skywalker's treadmill track is split down the sagittal plane; it recognizes when the impaired limb is proceeding from toe-off and initiating into the swing phase of gait, where the treadmill training track drops at the side of the impaired foot and allows for toe clearance. The rhythmic training mode tracks the user's heel position on the track and drops the track during the swing phase to provide toe clearance for the user, with which the gait speed and asymmetry are controlled and trained. The discrete training mode displays a target on the track for the user's foot to land onto and hence train the impaired foot. For the balance training mode, the user is trained by introducing gait perturbations in the frontal and sagittal plane for the user to overcome. A summary of the reviewed articles is presented in Table. 2.

C. WEARABLE GAIT TRAINING ROBOTS

Unlike grounded movement assisting robotic devices, which deal with improving ankle performance, wearable movement assisting robotic devices work on improving gait [29]. Given the wearability feature, these systems are able to provide assistance and rehabilitation during activities of daily living.

The literature on wearable robotic devices was found to mainly focus on robotic perceptive systems, control systems, and actuation methods for assistance/rehabilitation of drop foot impairments. Those are detailed in the following subsections.

1) PERCEPTIVE SYSTEMS

Perceptive sensing systems are essential components of an assisting robotic device as they can measure the limb's range of motion, detect the phase of gait, and/or detect the environment around which the robotic device is used, hence providing assistance accordingly. The sensing system typically works with the rest of the robotic device to transfer the optimal mechanical power at optimal points of the gait cycle which improves the robot-human interface safety and the efficiency of the provided assistance [21]. According to research findings, the main type of sensors currently used in drop foot assisting robotics is in the form of insole sensors which measure the user's phase of gait, IMU sensors which capture the kinematics/kinetics of the user, Electroencephalogram (EEG) and Electromyography (EMG) sensors which can estimate the user's intention of motion, optical strain sensors which measure strain and position of bio-inspired tendons, or a combination of the aforementioned sensors. Eight articles were identified and discussed in the sections below.

Kim *et al.* developed the COWALK-M, a lightweight knee assisting robot, which assists gait for patients with impaired knees, as shown in Figure. 5(A) [22]. The COWALK-M perceptive system consists of insole sensors used to detect the user's phase of gait in real-time, while encoders placed at the knee and ankle joints estimate the user's gait speed and ground inclination. In another study, to facilitate stair walking for chronic stroke patients, joint motion, as well as real-time phase of gait, were detected and used in the work of Yeung *et al.* [44]. Specifically, Yeung *et al.* designed an ankle robot that enables three movement conditions in real-time: level walk- ing, stair ascending, and stair descending. The conditions are detected using Inertial Measurement Unit (IMU) sensors embedded in the shank which measure the leg tilting angle and leg angular velocity as well as force-sensitive resistors that measure the user's phase of gait through foot loading patterns as shown in Figure. 5(B) [26], [44]. Similarly, Meng *et al.* designed a gait feedback system for the treatment of drop foot using IMUs, as shown in Figure. 5(C) [24]. This system applies a two-layer model with which both gait phase and ankle angle are simultaneously measured.

Incorporating the user's intention of motion allows for active patient participation during rehabilitation. Addressing this through perceptive systems involves using the user's bioelectric signals that can be utilized to trigger motion support. To further understand and incorporate the neurophysiological mechanisms into assistive robotic devices interacting with the user, He *et al.* used the previously developed robotic device NASA's (National Aeronautics and Space Administration) Xl, along with EEG and EMG interfaces, to estimate the lower-limb movement as shown in Figure. 5(E) [46].

In soft robotic devices, perceptive systems are designed to measure strain and position through optical-fiber technology. Casas *et al.* developed the T-Flex orthosis using a lightweight optical strain sensor which is easily fabricated and installed onto tendons [48]. The optical strain sensor implementation could help identify the user's intention of motion without affecting the tendon's mechanical properties.

TABLE 2. Summary of reviewed articles for over-ground gait training robotic devices.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Watanabe et al. 2013 [36]	Robotic control system for pelvic assistance	Control of lateral pelvis motion during robotic device gait training	Enhances self-dominated gait, adapts to asymmetric gait, and adapts to individual differences	Gait fluctuations not accommodated due to constant estimated parameters in the model
Fong et al. 2019 [37]	Therapist assistance mimicking robotic device	Treadmill-based therapy with therapist mimicking assistance	Kinesthetic teaching principles to imitate a therapist's course of treatment	Left foot late peak phase shift and reduced maximum toe clearances
Roy et al. 2013 [10]	Impedance-controlled Anklebot	Control of ankle dorsiflexion-plantar flexion (1 DOF)	Precise timing and estimate of the level of robotic assistance to key functional deficits of hemiparetic gait	N/A
Roy et al. 2017 [38]	Anklebot ankle robot	Trains ankle dorsiflexion-plantar flexion and inversion-eversion (2 DOF)	Backdriveable with low intrinsic mechanical impedance	Inaccurate data due to postural adjustments, in-shoe slippage-movement, movements not being truly passive, elicitation of stretch reflex, or effects of gravity
Roy et al. 2018 [41]	Ankle robot-assisted locomotor training	Trains ankle dorsiflexion-plantar flexion and inversion-eversion (2 DOF)	Estimation of the human ankle torque contribution during dynamic patient-robot interaction by measuring the device peak torques that meet desired design criteria across gait cycles	N/A
Liu et al. 2018 [39]	Gait training assistive device	Assists hip flexion (1 DOF) and ankle dorsiflexion (1 DOF)	Minimally-required-assistance principle to induce motor learning of consequential movement errors when only necessary movements are assisted	N/A
Susko et al. 2016 [40]	MIT-Skywalker treadmill gait training device	Treadmill training for gait impairments: Provides toe-clearance during gait	Trains according to the working model of movement primitives based on submovements, oscillations, and mechanical impedances with three distinct training modes	N/A

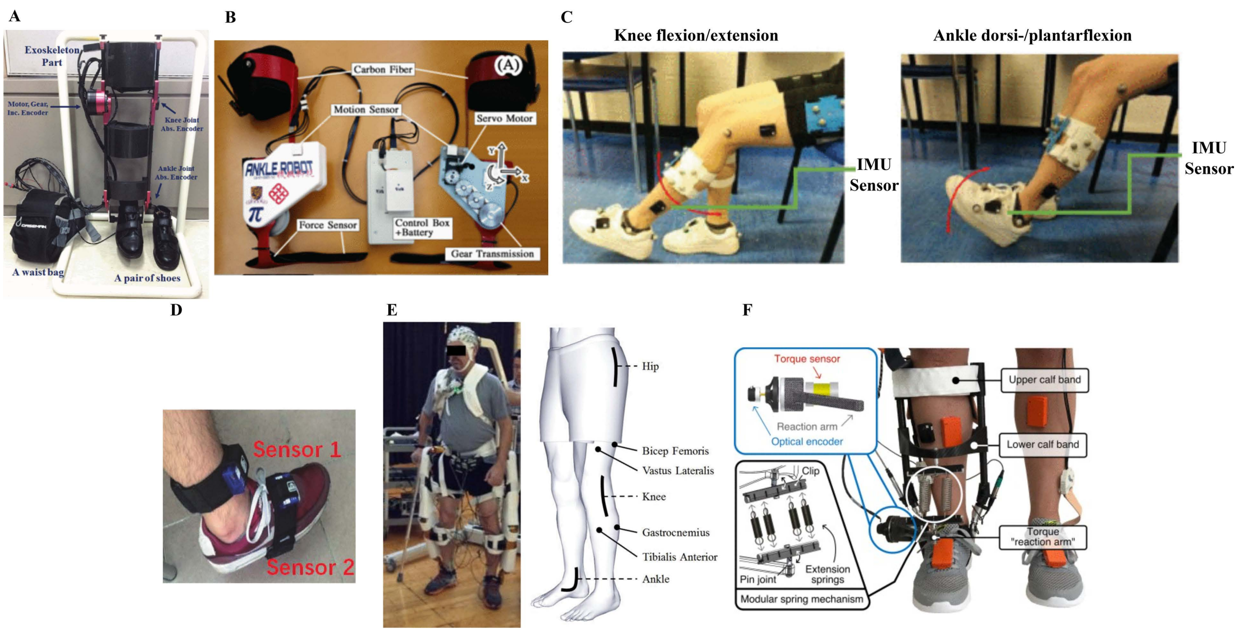

FIGURE 5. Sensor placement of robotic devices with advanced perceptive systems, (A) Absolute encoder sensor placement of Compliant Ankle rehabilitation Robot [22], (B) Motion and force sensor placement of Ankle Robot [44], (C) IMU placement for gait feedback on drop foot [24], (D) WB sensor placement on Ankle joint intelligent rehabilitation robot [45], (E) EEG and EMG interface placement of NASA's powered robotic lower-limb exoskeleton X1 [46], (F) Different sensor components placed on iAFO [47].

Combining different perceptive system approaches, Bolus *et al.* proposed an instrumented Ankle-Foot Orthosis (iAFO) with sensing capabilities capable of measuring ankle joint kinematics and kinetics, EMG, and orthosis interface pressure, to guide the instrumentation as shown in Figure. 5(F) [47]. Similarly, Wang *et al.* designed a detection

TABLE 3. Summary of reviewed articles for robotic devices with advanced perceptive systems.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Kim et al. 2015 [22]	Compliant ankle rehabilitation robot (CARR)	Knee motion assistance in the sagittal plane (1 DOF)	Detects gait phases in real-time, FSM is implemented for quiet standing and forward walking, and ground slope and gait speed is estimated	As gait speed increases, gait phase asymmetry increases.
Yeung et al. 2017, 2018 [44], [26]	Ankle Robot	Assists dorsiflexion and plantar flexion of ankle joint (1 DOF)	The walking conditions are detected using IMU sensors embedded in the shank that measure the leg tilting angle and leg angular velocity	N/A
Meng et a. 2019 [24]	Sensory feedback system	Assists dorsiflexion of the ankle joint (1 DOF)	An inertial sensor system that detects gait phase and measures joint kinematics	N/A
Wang et al. 2019 [45]	Ankle joint intelligent rehabilitation robot	Drop foot deficit rehabilitation (sagittal plane/ 1 DOF)	Using electrical signals to detect gait. Synchronization of plantar pressure and ankle angle	N/A
He et al. 2014 [46]	NASA's powered robotic lower-limb exoskeleton X1	Assists knee flexion-extension (1 DOF) and hip flexion-extension (1 DOF) for each leg	Powered exoskeleton used with EEG and EMG interfaces	Low decoding accuracies in EMG and EEG activities because of electrode interference.
Casas et al. 2019 [48]	T-Flex orthosis optical strain sensor	Assists ankle dorsiflexion and plantar flexion (1 DOF)	Identify the user's intention of motion without affecting the tendon's mechanical properties. Easily fabricated and installed onto the tendons	The sensor could be detached from the tendon leading to inaccuracies in several dynamic cycles
Bolus et al. 2017 [47]	An instrumented ankle-foot orthosis (iAFO)	Selectively modifying orthotic ankle joint stiffness for drop foot impairment	Measure the ankle joint kinematics and kinetics, EMG, and orthosis interface pressures. Provides the following three walking conditions in real-time: level walking, stair ascending, and stair descending	Needs spring-like elements that can provide orthotic resistance in both directions simultaneously and can be adjusted continuously

platform that uses an electrical signal detection scheme to detect the motion of the ankle joint as shown in Figure. 5(D) [45]. More specifically, two WB sensors (LPMS-B) measure the ankle's joint angle, while four insole sensors measure the plantar pressure. The WB sensor is a small, wearable, and precise sensor which consists of a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer. The placement of two WB sensors, along with four insole sensors allow for exploring the relationship between the spatial posture of the ankle joint and the change in plantar pressure during gait. A summary of the reviewed articles is presented in Table. 3.

2) CONTROL SYSTEMS

Using the data retrieved from the sensing systems, a control system is employed for utilizing the data to trigger the actuator with the optimal assistance at the optimal time [49]. Interaction control in wearable robotic devices allows for human-exoskeleton proper joint alignment, which is critical considering that joint misalignment introduces unwanted interaction forces driving the user to compensate with increased metabolic cost [49]. Nineteen articles relevant to control systems were identified and discussed in the sections below. These are categorized into model-based, physical parameters-based, and user-adaptive control adapted from [50]. Furthermore, the articles relevant to user-adaptive control are further classified into the following subsections: active disturbance rejection-based, assist-as-needed-based, and deep neural network-based control systems. This classification is based on the differences established between the different approaches as demonstrated in Table. 5.

a: MODEL-BASED CONTROL

Model-based control comprises systems that use models based on either the dynamics of the structure or muscle models. Dynamic models are typically derived from mathematical models, system identification, or artificial intelligence [50].

Recent technological advancement allowed for the introduction of intelligent control systems biomimetic to biological control. Duvinage *et al.* developed an algorithm called the Programmable Central Pattern Generator (PCPG) which emulates the physiological rhythmic movements in gait, as shown in Figure. 6(A) [49]. This control system can assist drop foot during the swing phase whilst allowing for movement during the stance phase to be undisturbed by transitioning between modes according to the gait phases.

Fuzzy logic systems can emulate human decision-making without any mathematical modeling involved. Kanthi *et al.* developed a control design based on a fuzzy controller to implement symmetrical gait for patients suffering from drop foot as shown in Figure. 6(B) [51], [52]. Similarly, Adiputra *et al.* developed a passive control AFO that uses a magnetorheological brake actuator controlled through fuzzy logic control [60]. Combining both neural controllers and fuzzy logic systems, a neural-fuzzy controller was developed by Kocchar *et al.* [61]. The neural network can estimate rule bases for the fuzzy logic, hence allowing it to receive linguistic information using numerical data. This enables the

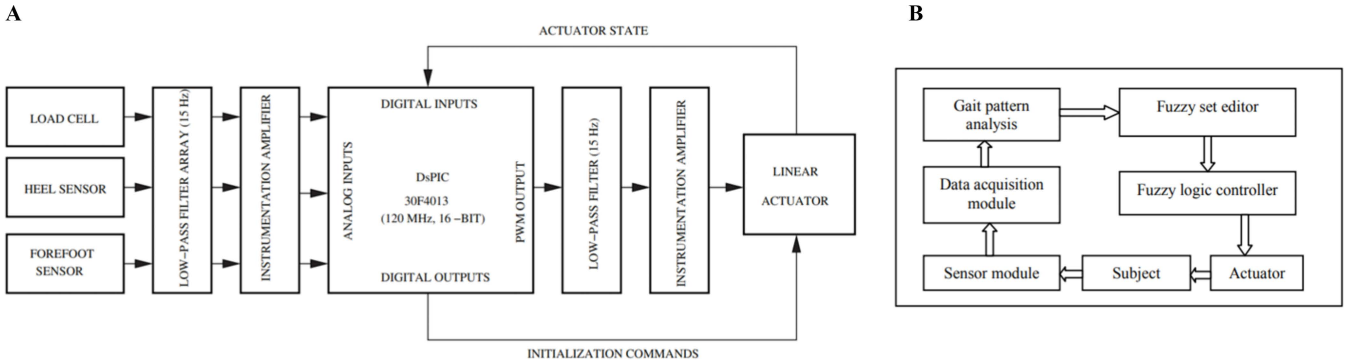

FIGURE 6. Block diagrams of robotic devices with model-based control systems, (A) Programmable Central Pattern Generator (PCPG) microcontroller architecture [49], (B) Fuzzy logic-based control [51] [52].

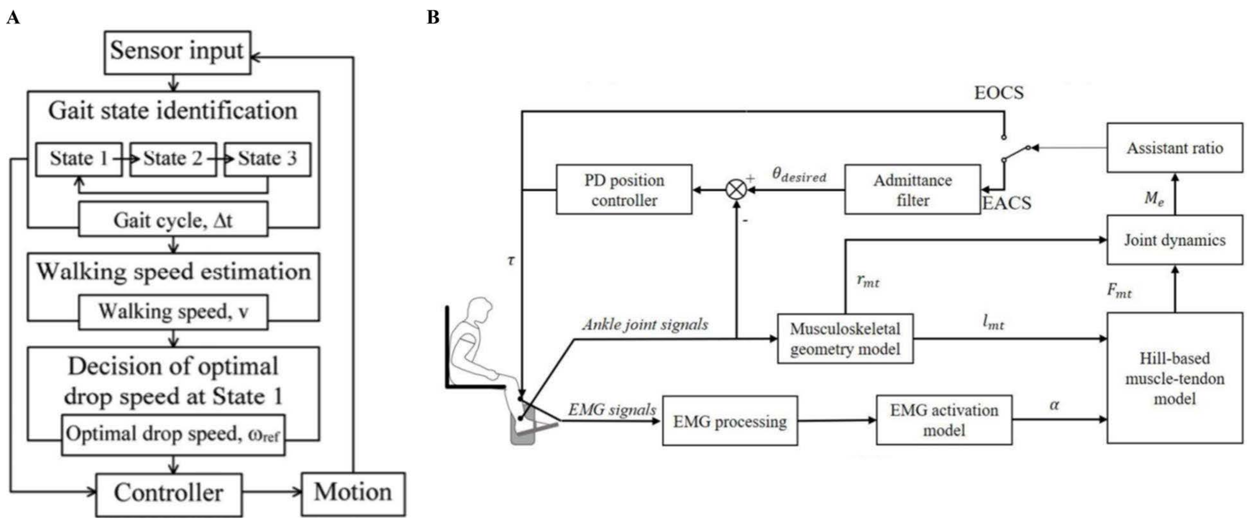

FIGURE 7. Block diagrams of robotic devices with physical parameters-based Control Systems, (A) Automatic adjustable control for i-AFO [53], (B) EACS and EOCS systems [54].

Adaptive Neuro-Fuzzy Inference System (ANFIS) to effectively input gait parameters, such as angular velocity and foot positioning, and return them to the AFO with optimal actuation.

Lack of real-time assisting robotic devices, which do not rely on the identification of user/robotic device parameters, drove Arnez-Paniagua *et al.* to develop a model reference adaptive control system to assists foot-drop patients which do not require previous estimation of the foot-robotic system's parameters [62]. The ankle reference trajectory was extracted from healthy subjects in a clinical setting and utilized as the predefined desired trajectory of the AAFO.

In later works of Yeung et al, over-ground and stair training were facilitated through switching between two modes: active assistance when augmenting motor function and passive support when providing toe-clearance during the swing phase of gait [63]. The control algorithm operated according to the detected gait and walking condition using a Finite-State Machine (FSM).

b: PHYSICAL PARAMETERS-BASED CONTROL

Physical parameters-based control strategy estimates the user's intention of motion through physiological signals captured from the human body to provide optimal assistance [50].

Kikuchi *et al.* developed an intelligent controllable Ankle-Foot Orthosis (i-AFOs), in which the controller utilizes initial foot contact to control the speed of the drop foot as shown in Figure. 7(A) [53]. The system measures the kinematic information of the impaired limb and uses inverse-dynamics to estimate the muscle activation of the anterior tibial muscle. The ankle torque is then controlled via a compact magnetorheological fluid brake to provide the user with sufficient toe-clearance during the swing phase of gait.

Although several control systems were developed to measure the user's intention of movement, ensuring movement stability, alongside an EMG-based control method, was still lacking. To bridge this gap, Zhuang *et al.* developed an EMG-based Admittance Control Scheme (EACS) to drive

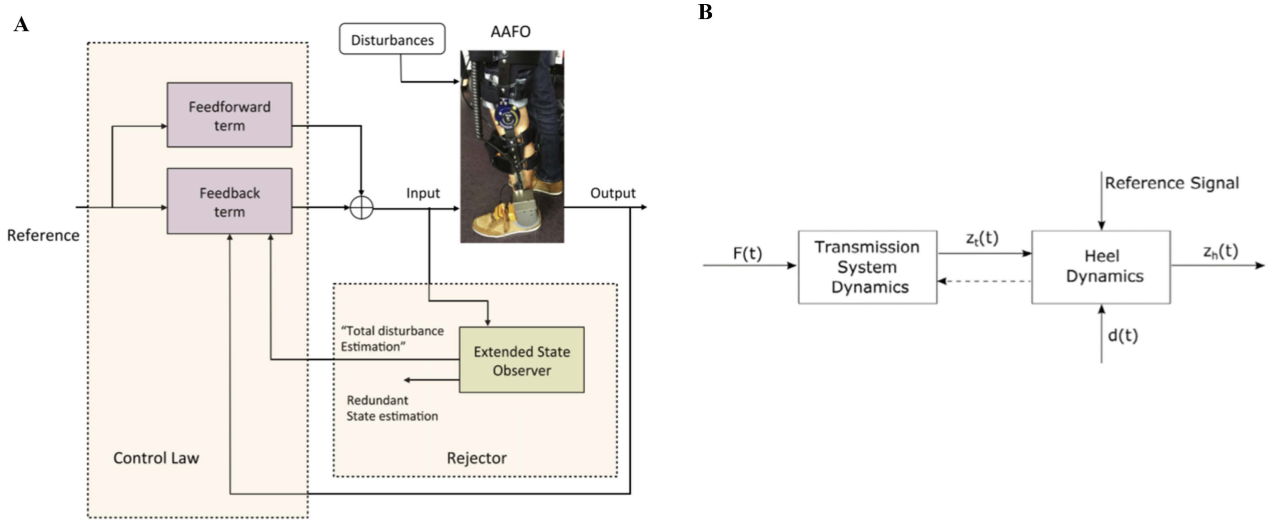

FIGURE 8. Block diagrams of robotic devices with active disturbance rejection control systems, (A) ESO and control law based on CLF approach [55], (B) Representation of model used during the application of backstepping technique [56].

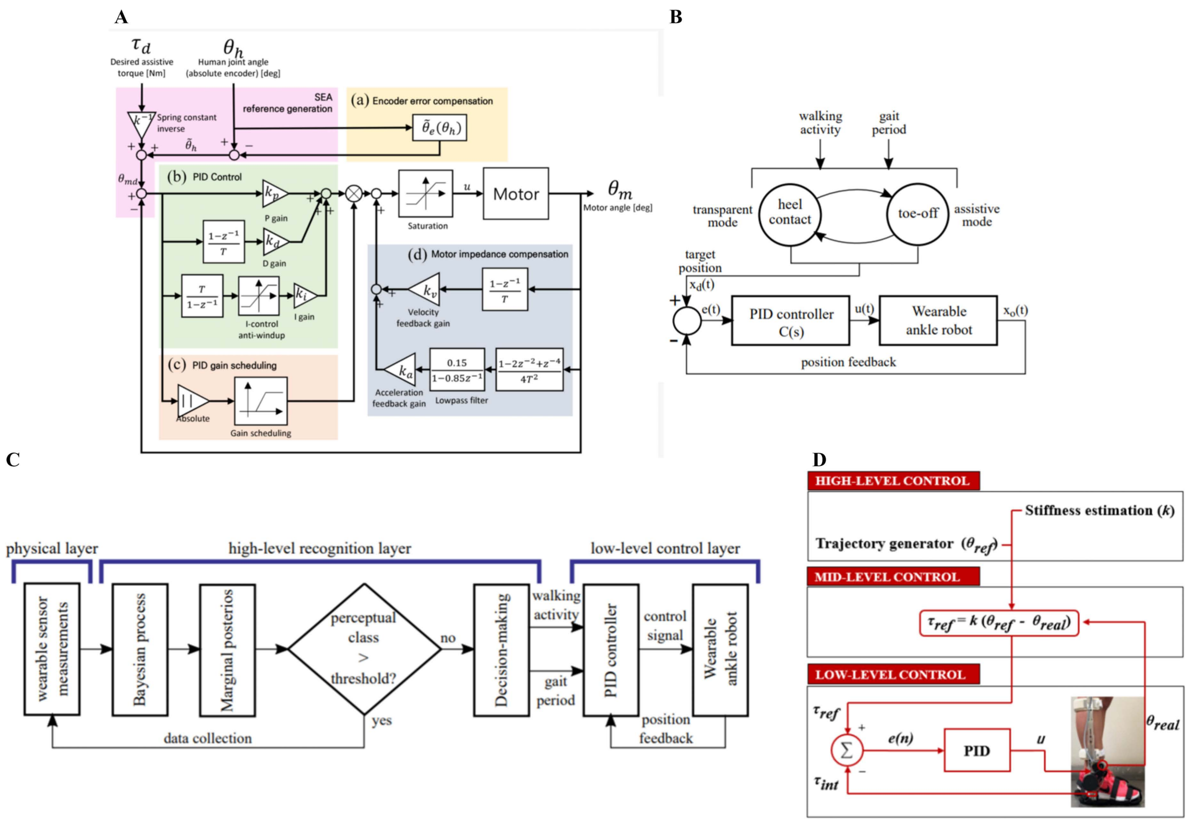

FIGURE 9. Block diagrams of robotic devices with Assist-As-Needed control systems, (A) Torque control of transparent actuation system [57], (B) Low-level controller [58], (C) Multilayer architecture implemented in the wearable ankle robot for data collection, recognition and control processes. [58], (D) Adaptive impedance control strategy [59].

an ankle rehabilitation robot as shown in Figure. 7 (B) [54]. Movement stability was guaranteed with this control scheme due to the system's effective Human-Robot cooperation using an EMG-Driven Musculoskeletal Model (EDMM), an admittance filter, and an inner Proportional-Derivative (PD) controller.

c: USER-ADAPTIVE CONTROL

The implementation of user-adaptive control strategies allows for adaptive tuning of a robotic device according to patients' recovery conditions. Active disturbance rejection control, assist-as-needed control, and deep neural network control systems mutually allow for the robot's adaptive assistance, as well as improved Human-Robot interaction [64].

d: ACTIVE DISTURBANCE REJECTION CONTROL

Trajectory tracking control is only effective if the system knows the precise reference trajectory and interaction forces. This is difficult with active patient participation, where unknown disturbances are typically unavoidable. To overcome this drawback, several studies implemented a so-called adaptive backstepping controller.

Adaptive backstepping control with Extended State Observer (ESO) was applied in the work of Guerrero Castellanos *et al.*, where it was able to detect and counteract unknown disturbances through entering the output of the ESO into the feedback loop, as shown in Figure. 8(A) [55]. In another study, Kirtas *et al.* developed a backstepping control algorithm that reduces the effects of unknown disturbances of the force input provided to the AFO system. Implemented with a real-time operating system, the algorithm controls the AFO to reduce any perturbations within the gait cycle as shown in Figure. 8(B) [56].

Based on the patient's progress during the rehabilitation period, Santos *et al.* developed a dynamic rehabilitation robotic device, which provides the user with adaptable assistance based on adaptive impedance control [65]. This is accomplished by using a generalized moment-based disturbance observer, as well as a Kalman filter algorithm, to compensate for torque disturbance and effectively estimate the torque and impedance parameters of the patient in real- time during gait. The patient's torque is estimated based on the stiffness and damping parameters of the knee and ankle joint during swing, with which the impedance is then optimized and delivered to the actuator's controller.

e: ASSIST-AS-NEEDED CONTROL

Within the rehabilitation process, adapting assistance to only include the deficient muscular force is important to avoid constraining natural human motion and encourage patients to apply maximal voluntary efforts. Towards this, Choi *et al.* developed Angel Legs, a powered exoskeleton with a transparent actuation system, where only the needed assistive force is delivered as shown in Figure. 9(A) [57]. The user can hence choose to apply the desired assistive torque through a user interface system.

Another study used a Proportional-Integral-Derivative (PID) controller to determine whether the ankle robot operated in an assistive or transparent mode as shown in Figure. 9(B) [58]. The assistive mode provides the user with a force emulating dorsiflexion at the toe-off stage of gait, while the transparent mode allows the natural motion of the limb without any assistance at heel strike. The mechanism of the assistive device adopts the protocol, where upon data collection by the IMU sensors, and gait detection using a probabilistic process (Bayesian method), the wearable ankle robot is controlled using a PID controller as shown in Figure. 9(C) [58]. Similarly, Lopes *et al.* presented a rehabilitation robotic device that adapts to the user's progress and need of assistance whilst using the robotic device [59]. An adaptive impedance control system modulates the Human-Robotic device interaction through real-time swapping between two types of assistances: passive and active assistance. During passive assistance, no assistance is imposed onto the user, while active assistance allows the robotic device to deliver the required assistance for effective gait training as shown in Figure. 9(D) [59].

f: DEEP NEURAL NETWORK CONTROL

To provide the optimal assistance specifically personalized to the needs of each patient, establishing the proper reference for the ankle joint torques is important. Moreira *et al.* developed a system that estimates healthy user-oriented reference ankle joint torques based on an Artificial Intelligence (AI) algorithm [32]. The estimation of the joint torques of the healthy limb occurred offline through collecting the user's ankle joint kinematics, gait speed, body height, and body mass. The Multilayer Perceptron (MLP) and the Long-Short Term Memory (LSTM) neural networks were validated and compared for modeling the nonlinear relationships of data from gait motion. Between the two tested regression models, the LSTM neural network proved to generate the ankle joint torque more accurately [32].

To accommodate different levels of severity of gait impairment, Huang *et al.* presented a control strategy that adapts the controller of both limbs of different patients by modeling it as a Leader-Follower Multi-Agent System (LFMAS) [66]. The leader constitutes the sound limb, while the lower limb ex- tremity of the exoskeleton act as the follower. Subsequently, the LF-MAS and a reinforcement learning framework work together to adapt to different patients. More specifically, a Policy Iteration Adaptive Dynamic Programming (PI-ADP) is used in the reinforcement learning framework as the conformable controller of the exoskeleton [66]. In continuation of this work, Peng *et al.* developed a Data-Driven Reinforcement Learning (DDRL) control strategy which adapts to different unpredictable gait disturbances and degrees of impairment severity [67]. An LFMAS framework was used to model the Human-Robot interaction between the two diseased limbs and the patient's sound limb, after which, an optimal control problem was derived from the walking assistance control problem. To model the optimal assistance controller, a Policy Iteration (PI) algorithm was employed. In order to allow adaptation to different wearers, an Actor Critic Neural Network (AC/NN) was used, where optimal actuation was accomplished through learning the optimal control strategy based on the PI algorithm.

To minimize any mechanical variability restricting the optimal delivery of assistance, Lee *et al.* implemented a PID neural network controller (PIDNN) as shown in Figure. 10(A) [68]. This approach implements an artificial neural network to update the weight of the gain value of a PID controller through back-propagation, as shown in Figure. 10(B).

A summary of the reviewed articles is presented in Table. 4, while a summary of the advantages and disadvantages of the different categories outlining the control systems is given in Table. 5.

3) ACTUATION SYSTEMS

Actuation systems designed to provide sufficient gait assistance can be classified into two main categories: passive and active. Active systems are preferred over passive systems due to their capability to adapt to changing walking conditions [72]. Bridging the two systems, semi-active systems combine the passive energy storage element with an additional powered component [73]. Active and passive systems can be differentiated according to their role in the output of assistive energy. Passive systems expend, redirect, and store- restore energy, while active systems add to the output energy. Semi-active systems, on the other hand, tend to use powered components, such as motors, to support the passive interface [74]. The following published research findings on actuation systems of robotic devices were categorized according to the type of actuation. These are mainly classified as semiactive and active actuation. The literature on active actuated robotics included different mechanisms discussed in the following section.

a: SEMI-ACTIVE ACTUATION

Semi-active robotic devices typically provide assistance through a brake-type controllable mechanism. This entails the AFO dynamically braking at heel strike to loading response in order to prevent foot slap; exerting no assistance during push-off to prevent hindering plantar-flexion force; then assisting dorsiflexion during swing to provide toe clearance [76]. Three relevant identified articles are discussed below.

Previously designed magnetorheological robotic devices inherently added impedance to the ankle joint throughout the gait cycle, which hindered the push-off force of the ankle joint. Moreover, toe-clearance was not provided in these designs, as they did not consider fully active assistive mechanisms. To bridge these gaps, Zhang *et al.* developed an instrumented AFO, in which torque is provided through an electromagnetic clutch, a spring, and a motor, as shown in Figure. 11(A) [73]. At the beginning of the stance phase, the clutch is disengaged, while the spring is compressed storing energy. Energy is released at the end of the stance phase, where the clutch is engaged, the motor is enabled, and hence the torque is provided by both the spring and the motor [73]. Similarly, Ohba *et al.* developed the SmartAFO, a semi-active AFO, which uses an elastic link controlled with a magnetorheological fluid and an electromagnetic coil as shown in Figure. 11(B) [75]. Energy is stored and released through a compression spring which delivers a resistive torque during heel-strike to adverse foot slap and provides dorsiflexion torque during the swing phase. With this mechanism, the ankle motion during push-off is left unaffected. In continuation of this study, Hassan *et al.* improved the magnetorheological brake AFO with regards to its braking and force retention, as shown in Figure. 11(C) [76]. The modified SmartAFO employs an elastic link mechanism that consists of magnetorheological brakes and a spring. The spring aids in dorsiflexion by storing energy during the stance phase and releasing it at the beginning of the swing phase [76]. A summary of the reviewed articles is presented in Table. 6.

b: ACTIVE ACTUATION OF ELECTRIC (RIGID) ROBOTIC DEVICES

Actuated articulated robotic devices use powered actuators to directly assist the impaired limb and hence overcome the limited mobility constraint imposed by passive assistive devices. Three articles were identified as relevant to this class of devices and are discussed below.

To make active assistive robotic devices attainable for individuals who cannot afford the existing expensive robotic devices on the market, Shah *et al.* developed a low-cost gait assisting robotic device which compensates for lower extremity weakness using a dual four-bar linkage system coupled to a motor, as shown in Figure. 12(A) [77]. The robotic device is actuated at the hip and the knee joints, while a leaf spring AFO compensates for the drop foot [77]. Aboamer *et al.* presented an electromechanical wearable orthosis that facilitates foot drop using a low-cost stepper motor and controller as shown in Figure. 12(B) [78]. The robotic device, consisting of an Arduino microcontroller, bipolar stepper motor, and current driver circuit, proved to be able to drive the foot upwards and downwards. Comparably, Font-Llagunes *et al.* developed a modular robotic exoskeleton with two robotic orthoses assisting the knee and the ankle joints as shown in Figure. 12(C) [79]. The knee joint consists of a motor harmonic drive actuation system to control flexion-extension, while the ankle joint is passively actuated through plastic support to prevent drop foot during gait [79]. A summary of the reviewed articles is presented in Table. 7.

c: ACTIVE ACTUATION OF PNEUMATIC ROBOTIC DEVICES

Conventional rigid AFOs constrict the natural motion of the ankle joint, which can be uncomfortable and may alter the biomechanics of gait in the long run. Electric robotic AFOs utilize motors to provide the user with sufficient dorsiflexion force during the swing phase of gait. On the other hand, the heavy-weight motorized active actuators can interfere with and negatively affect the user's gait. Pneumatically actuated assisting robotic devices were introduced as they can provide active assistance while remaining soft and flexible. Pneumatic robotic devices can provide users with gait assistance while remaining inexpensive, lightweight, and ergonomic. Eleven relevant articles were identified as discussed below.

Shorter *et al.* developed a Portable Powered AFO (PPAFO) which provides both plantarflexion and dorsiflexion assistance using a rotational pneumatic actuator, as shown in Figure. 13(A) [80]. Similarly, Ulkir *et al.* developed a pneumatic AFO which assists the ankle via a pneumatic

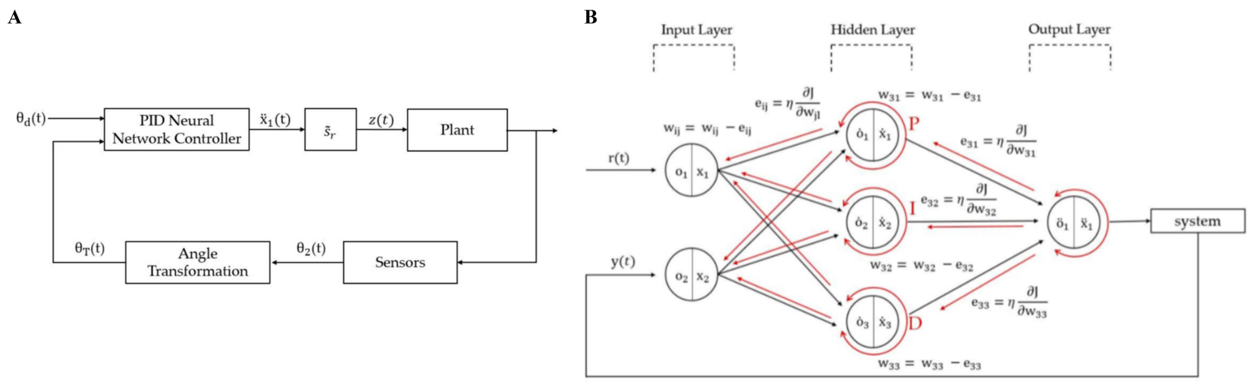

FIGURE 10. Block diagrams of robotic devices with deep neural network control systems, (A) Ankle exoskeleton controller system [68], (B) PID neural network (PIDNN) controller back-propagation system [68].

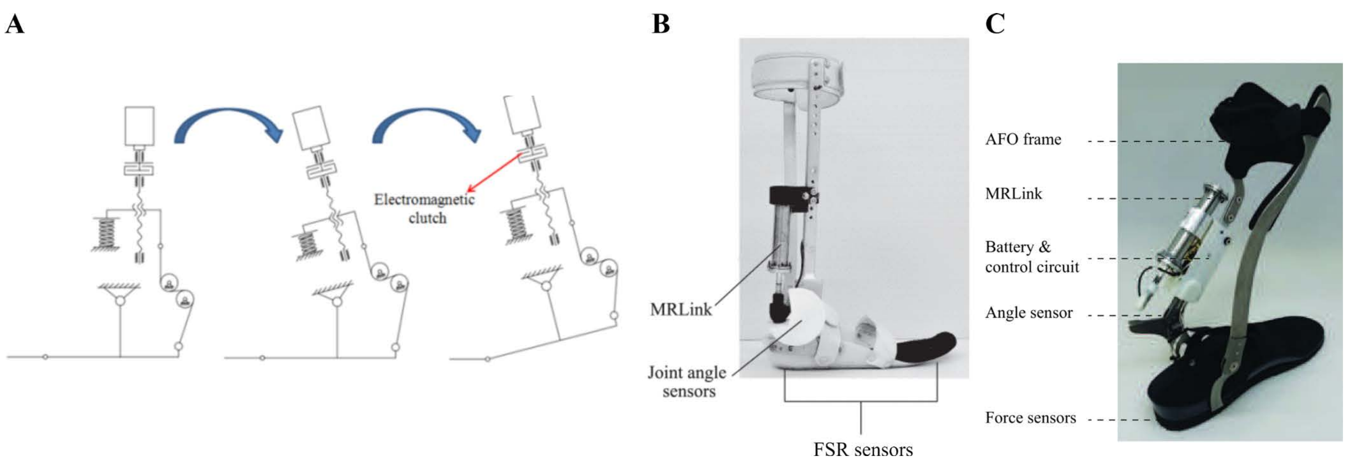

FIGURE 11. Mechanical overview of semi-active robotic devices, (A) Instrumented AFO actuated by electromagnetic clutch, a spring, and a motor [73], (B) SmartAFO actuated by an elastic link mechanism consisting of magnetorheological fluid and electromagnetic coil [75], (C) Improved SmartAFO consisting of magnetorheological brakes and a spring [76].

artificial muscle with a pneumatic rotary actuator to effectively assist any weakness in the ankle joint as shown in Figure. 13(B) [81], [89]. Pneumatic artificial muscles provide plantarflexion assistance, while pneumatic rotary actuators provide dorsiflexion assistance.

Hong *et al.* developed a lightweight AFO which provides a high dorsiflexion force during the swing phase and supports the heel rocker during the loading response phase using a McKibben-type artificial muscle aligned in series with a tension spring as shown in Figure. 13(C) [82]. The tension spring is employed to resolve the problem with artificial muscle support requiring a long time constant. Similarly, a fully portable pneumatic AFO was developed by Kim *et al.*, where the wearable connected air compressor effectively powers the AFO to provide a dorsiflexion torque as shown in Figure. 13(D) [83]. Further optimizing the aforementioned study, a wearable pneumatic AFO was developed with an improved flow rate for periodic assistance using a compact custom compressor worn around the user's trunk as shown in Figure. 13(E) [84].

Salmeron *et al.* developed a compact and portable soft robotic AFO (SR-AFO) composed of compliant fabrics which uses pneumatic actuation as shown in Figure. 13(F) [85]. The soft exosuit contains two components: an electrical component that supplies the power; and a fluid component that drives the airflow to the origami. This allows for natural and unrestricted movement along with possible proper joint alignment of the exosuit. The origami actuator can assist both ankle dorsiflexion and plantar flexion by expanding and contracting. In another study, a soft robotic ankle orthosis was developed to aid in the push-off force needed before initiating the swing phase of gait as shown in Figure. 13(G) [86], [90]. The soft robotic device, which is placed at the posterior end of the foot such that its contraction pulls the foot, proved to increase the plantarflexion angle while maintaining the natural ankle range of motion.

Murphy *et al.* aimed to develop a pneumatic robotic device capable of providing assistance with the 4 functional motions at the ankle joint, including dorsiflexion-plantarflexion and inversion-eversion. They introduced a pneumatic artificial

TABLE 4. Summary of reviewed articles for robotic devices with advanced control systems.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Duvinage et al. 2011 [49]	A foot lifter orthosis	Assists ankle dorsiflexion (1 DOF)	PCPG algorithm generates adequate rhythmic gait patterns both for constant speeds and acceleration phases	Low-speed phase recovery in the soft phase
Kanthi et al. 2013, 2018 [51], [52]	Ankle foot orthosis	Assists ankle dorsiflexion and plantar flexion (1 DOF)	A self-adaptive fuzzy controller that controls the symmetry in gait and provides real-time corrective actuation	N/A
Adiputra et al. 2018 [60]	Passive control AFO that uses an MRbrake actuator	Controls foot slap (1 DOF)	Experimentally designed FLC membership functions	Needs reduction of the standard error of the control reference estimation. MR brake torque was insufficient in maintaining the lock ankle position for a longer period
Kochhar et al. 2016 [61]	Ankle foot orthosis	Assist ankle dorsiflexion and plantar flexion (1 DOF)	A fuzzy inference system that can take linguistic information using numerical data (input/output pairs) to achieve better performance	Error in the rule base as well as rule and parameter sharing problem
Arnez-Paniagua et al. 2017 [62]	Ankle-foot-orthosis	Assists ankle dorsiflexion (1 DOF)	A model reference adaptive control that does not require any prior estimation of the system's parameters.	The initial position of the ankle joint in the swing sub-phase differs in every step affecting the adaptive performance
Yeung et al.2021 [63]	Over-ground training	Assist ankle dorsiflexion and plantar flexion (1 DOF)	Switching between two modes (active assistance and passive)	N/A
Kikuchi et al. 2013 [53]	Intelligently controllable ankle-footorthoses (i-AFOs)	Controls foot slap (1 DOF)	Control of the drop speed of foot using the initial contact	N/A
Zhuang et al. 2021 [54]	Rehabilitation robotic device	Assists ankle dorsiflexion (1 DOF)	An EMG-based admittance control scheme (EACS)	N/A
Guerreo-Castellanos et al. 2018 [55]	Extended State Observer (ESO) controlled AFO	Corrects ankle dorsiflexion and plantar flexion deficits (1 DOF)	Rejects disturbances via ESO and rejector-controller-plant using the notion of ISS	N/A
Kirtas et al. 2021 [56]	Ankle foot orthosis	Assists ankle joint along the sagittal plane (1 DOF)	An adaptive backstepping control algorithm	Increasing walking speed tracking error increases because of the speed limitations of the DC motor
Santos et al. 2016 [65]	Hips-knee-ankle exoskeleton	Coordinates the level of robot assistance in the sagittal plane of the hip (1 DOF), knee (1 DOF), and ankle joints (1 DOF)	Estimation and tuning of torque and impedance parameters during the gait using the generalized momenta-based disturbance observer	N/A
Choi et al.2021 [57]	Angel Legs	Hip joint flexion-extension assistance (1 DOF) and knee joint flexion-extension assistance (1 DOF)	Transparent actuation system	Use of assistance structures like walking aids and crutches hinders motor learning
Martinez-Hernandez et al. 2019 [58]	Assistive rehabilitation robotic device	Assists ankle dorsiflexion (1 DOF)	Controlled the mode selected (assistive or transparent), using a proportional-integral-derivative (PID) controller	N/A
Lopes et al.2020 [59]	Ankle foot orthosis	Regulates ankle joint interaction stiffness	Interaction-based assist-as-needed impedance control strategy that adapts the robotic device assistance by changing the Human-Robot interaction stiffness	Some users felt the system "stiffer" and had to perform more effort to maintain the same walking pattern
Moreira et al. 2020 [32]	Robot-based gait assistance	Estimates healthy user-oriented reference ankle joint torque trajectories for control strategy	Generates healthy reference ankle joint torques using AI algorithms to model nonlinear relationships of the walking motion	LSTM estimation is only valid if walking on a flat surface and at a specific range of walking speeds, user heights, user weights.
Huang et al. 2018 [66]	Lower limb exoskeletons (LLE)	Learning-based walking assistance control strategy joint assistance of affected limb based on unaffected limb	Controlled with a Leader-Follower Multi-Agent System (LF-MAS) and a Policy Iteration Adaptive Dynamic Programming (PI-ADP) reinforcement learning algorithm w to adapt the controller of both lower limbs with different patients	N/A
Peng et al.2020 [67]	Lower limb exoskeletons (LLE)	Learning-based walking assistance control strategy joint assistance of affected limb based on unaffected limb	Data-Driven Reinforcement Learning (DDRL) control strategy to adapt different hemiplegic patients and unpredictable disturbances	N/A
Lee et al. 2021 [68]	Bidirectional tendon-driven ankle exoskeleton	Ankle joint dorsiflexion and plantar flexion assistance (1 DOF)	Adaptive control with PIDNN	Dependent on designed parameters. A significant increase in learning rate created an unstable system with increased errors

TABLE 5. Summary of reviewed articles for robotic devices with advanced control systems.

Control System Classification	Advantages	Disadvantages
Model-based control [49], [51], [62], [63], [69], [70]	· Reproduces different rhythmic gait patterns · PCPG adjusts between different speeds with smooth transitions · Provides symmetrical gait with real-time corrective actuation · Avoids reliance on prior estimation of Human-Robot parameters · Incorporate multi-modal assistance	· Lacks precise system dynamics · Does not adapt to disturbances or external perturbations · Fixed impedance/admittance models do not allow personalized assistance
Physical parameters-based control [50], [54], [71]	· EMG-based controller estimate human motion intentions and improve Human-Robot synchronization · Able to detect the variation trend of the tracking performance · Adapts to different users' EMG signals and users with muscle deficits	· EMG-based signals requires minimum residual muscular activities which are lacking for some patients with acute stroke symptoms · EMG signals are random and nonlinear causing instability overtime in an open-loop control scheme
Active disturbance rejection control [55], [70]	· ADRC estimates and cancels total disturbance (unknown system dynamics and external disturbances) · Adapts to uncertainties (i.e. environmental interaction forces and human–robot interaction forces)	· Difficulty in tuning ADRC's parameters
Assist-as-needed control [58], [59]	· Provides compliant assistance, patient-robot cooperation, and active rehabilitation · Modulates interaction stiffness · Incorporates multi-modal assistance	· Needs an accurate user-oriented reference joint trajectory to provide adequate assistance and therapy sessions
Deep neural network control [32], [66]–[68]	· Provides personalized robotic gait · Support according to each subject's needs · Enhances rehabilitation with proper determination of reference ankle joint torques by providing the most suitable assistance level oriented to the needs of each user. · Able to provide interaction communications between the two lower limbs exoskeletons · A reinforcement learning method (i.e. AC/NN) achieves better control performance · Minimizes uncertainty	· Validity of LSTM estimation is still limited on flat surfaces and specific user parameters · High dependency on designed parameters · High learning rate may significantly affect the system stability with increasing errors

TABLE 6. Summary of reviewed articles for semi-active actuation systems.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Zhang et al. 2015 [73]	Ankle-foot orthosis	Ankle joint torque assistance in sagittal, transverse, and frontal planes provided through an electromagnetic clutch, a spring, and a motor (3 DOF)	Energy store-and-release mechanism with a clutch that then enables and torque is provided by the spring and the motor	N/A
Ohba et al. 2019 [75]	Semiactive ankle-foot orthosis SmartAFO	One DOF linear-motion system through an elastic link mechanism	*Similar to previous	N/A
Hassan et al. 2019 [76]	Semiactive ankle-foot orthosis SmartAFO	Reduces foot slap and supports toe-clearance (1 DOF)	An elastic link mechanism to brake the ankle joint during initial contact mitigating foot-slap. Energy store-and-release mechanism to support toe lift in the swing phase mitigating toe drag.	Increased muscle activity because of the newly introduced AFO

muscle-actuated compliant ankle robotic device able to assist the 4 functional motions while allowing ankle abduction/adduction passively, as shown in Figure. 13(H) [87]. Park *et al.* developed a robotic device that uses pneumatic artificial muscles to mimic the muscle-tendon-ligament-skin system as shown in Figure. 13(I) [88]. Biomimetic to the musculoskeletal system, the device provides active assistance while remaining soft and flexible. Both dorsiflexion-plantarflexion and inversion-eversion motions are assisted while being controlled via a Linear Time-Invariant (LTI) controller. A summary of the reviewed articles is presented in Table. 8.

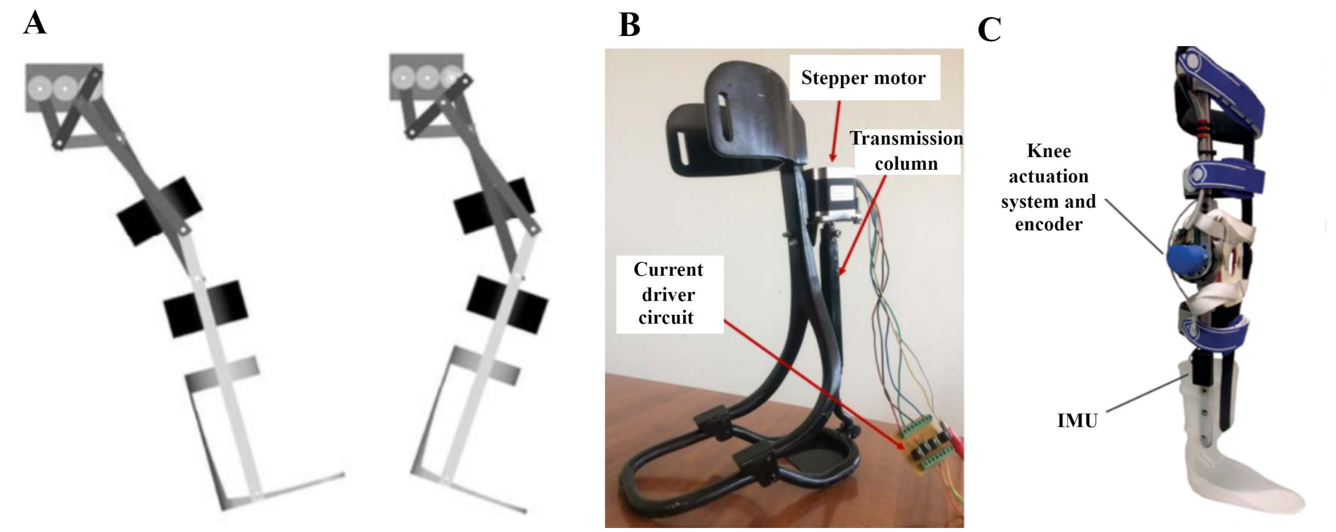

FIGURE 12. Mechanical overview of electric robotic devices, (A) Hip, knee, and ankle joint assisting low-cost robotic device actuated by a motor coupled with four-bar linkage system [77], (B) Ankle joint assisting electro-mechanical low-cost stepper motor actuated robotic device [78], (C) Motor-harmonic drive actuated knee and ankle joint assisting exoskeleton [79].

TABLE 7. Summary of reviewed articles for active actuation of electric (Rigid) robotic devices.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Shah et al. 2011 [77]	Intuitive Leg Assist Device (I-LAD)	Hip articulation (1 DOF) and knee articulation (1 DOF) in sagittal plane with linkage system and AFO that passively prevents foot slap	Mimics the human gait cycle by coupling the actuation of the knee and hip via a dual four-bar linkage system modified from a crank rocker system	N/A
Aboamer et al 2020 [78]	Movement assisting device	Assist ankle dorsiflexion (1 DOF)	Low-cost stepper motor and controller	The device produces a sound due to the mechanical friction
Font-Llagunes et al. 2020 [79]	Modular robotic exoskeleton	Active control of the knee flexion-extension (1 DOF) and passively prevents foot slap	The knee joint consists of a motor-harmonic drive actuation system. The ankle joint is passively actuated through plastic support to prevent drop foot during gait	Needs an emergency stop button and a more powerful motor for safety

d: ACTIVE ACTUATION OF CABLE-DRIVEN ROBOTIC DEVICES

Pneumatic artificial muscles and tendon-driven actuators can only produce a force in one direction, hence requiring antagonistic pairs of actuators to be able to produce both dorsiflexion and plantarflexion forces. Three articles were identified and discussed below.

Kwon *et al.* developed a robotic AFO which uses soft wearable material with a cable-pulling bidirectional mechanism utilizing one motor as shown in Figures.14 (A) and 14(B) [92]. Actuators and sensors are precisely embedded onto the orthosis to avoid slippage and unwanted pressure applied onto the user's skin. In another study, Xia *et al.* developed a portable soft ankle exoskeleton that assists the impaired limb at push-off and stabilizes inversion-eversion of the ankle joint, as shown in Figure. 14(C) [93]. The robotic device delivers the assistive propulsive force through a bidirectional cable-driven actuation system. It stabilizes inversion-eversion using small and lightweight gear motors which deliver a counter-electromotive force. T-Flex is another bio-inspired AFO actuation presented by Manchola *et al.*, which mimics the behavior of the antagonist muscles by adjusting the stiffness of bio-inspired tendons according to the gait cycle, as seen in Figure. 14(D) [94]. A summary of the reviewed articles is presented in Table. 9.

e: ACTIVE ACTUATION WITH SERIES ELASTIC ACTUATORS

To ensure safe Human-Robot interaction, compliant actuators have been introduced to recent drop foot robotics. Series elastic actuators (SEA), in particular, allow the decoupling of the inertia and friction of the actuator and transmission system from the load, thereby allowing active engagement of the patient whilst receiving therapy [72]. Six articles were identified and discussed below.

Polinkovsky *et al.* developed a prototype of an active AFO using a SEA where a motor controlling the motor arm in series with a pre-tensioned spring assist plantarflexion and dorsiflexion, as shown in Figure. 15(A) [95]. To provide an assistive robotic device that simultaneously assists the motion of the ankle and the knee joints of pediatric subjects, Rossi *et al.* developed an active knee-ankle orthosis that assists gait using series elastic actuators as shown in Figure. 15(B) [96].Moltedo *et al.* developed

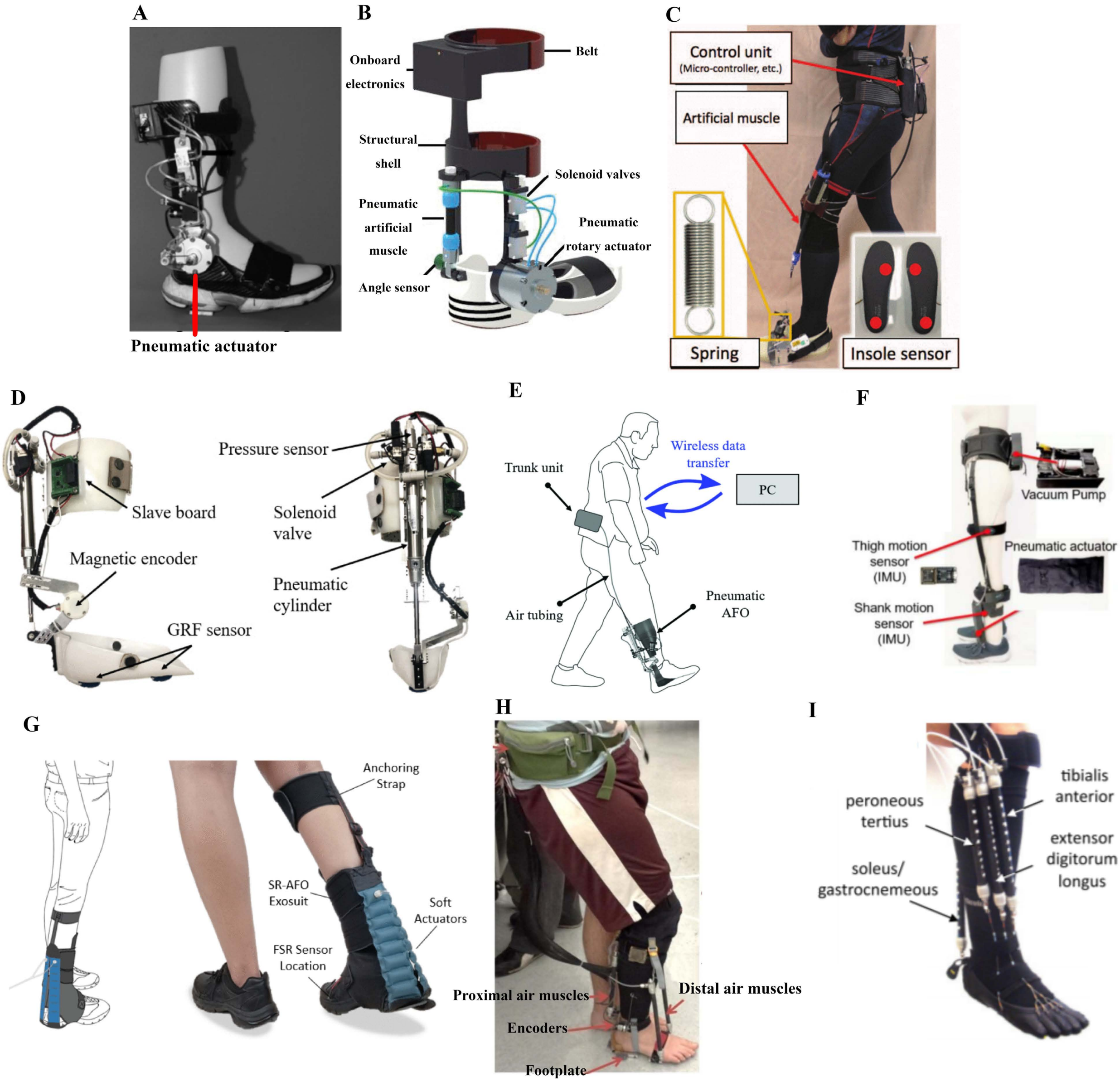

FIGURE 13. Mechanical overview of pneumatic robotic devices, (A) Pneumatic rotational actuator ankle assisting robotic device [80], (B) Pneumatic artificial muscle and pneumatic rotational actuator ankle assisting robotic device [81], (C) McKibben-type artificial muscle aligned in series with a tension spring AFO [82], (D) Portable powered AFO with compact custom compressor [83], (E) Optimized portable powered AFO [84], (F) Soft pneumatically actuated AFO exosuit [85], (G) Soft pneumatically actuated AFO exosuit [86], (H) Artificial muscle actuated compliant ankle robotic device [87], (I) Pneumatic artificial muscles mimicking muscle-tendon-ligament-skin system [88].

the spindle-driven compliant MACCEPA (Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator) towards providing a lightweight, high torque actuator, as shown in Figure. 15(C) [97], [98]. In another study, Kirtas *et al.* developed an ankle-foot orthosis which is controlled by an adaptive backstepping controller actuated using a SEA along with a lever mechanism and an orthotic shoe [56]. The orthosis was designed to be wearable and portable using battery packs as a power source. Chen *et al.* proposed a robotic AFO with a Series Elastic Actuator (SEA) and a magneto-rheological (MR) brake, with which the MR brake is utilized to regulate the AFO's viscosity and generate a large braking torque of 21.8 Nm with low power of 8.8 Watts, as shown in Figure. 15(D) [99]. A summary of the reviewed articles is presented in Table. 10.

f: ACTIVE ACTUATION WITH VARIABLE STIFFNESS ACTUATORS

Even though SEA presents several advantages over stiff actuators, it has limited adaptability due to the constant spring stiffness. Moreover, using a SEA requires the robot's natural frequency to match with that of the desired motion frequency for optimal energy efficiency. Further limitations include the SEA's inability to compensate between large force bandwidth

TABLE 8. Summary of reviewed articles for active actuation of pneumatic robotic devices.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Shorter et al. 2011 [80]	Portable powered AFO (PPAFO)	Provides both ankle plantar flexion and dorsiflexion assistance (1 DOF)	Bi-directional pneumatic actuator	N/A
Ulkir et al. 2018 [81], [89]	Pneumatic ankle-foot orthosis (PAFO)	Assists ankle dorsiflexion-plantar flexion (1 DOF)	The compact actuator structure produces high torque assistance. Lightweight and untethered modular design	N/A
Hong et al. 2019 [82]	Pneumatic ankle-foot orthosis (PAFO)	Assists ankle dorsiflexion (1 DOF)	The McKibben-type artificial muscle that supports heel rocker function with a tension spring	Small response time resulting in abrupt knee and ankle motion. Tension spring needs to be compatible
Kim et al. 2020 [83]	Pneumatic ankle-foot orthosis (PAFO)	Assists ankle dorsiflexion (1 DOF)	A lightweight portable soft exosuit with garment-like functional textile anchors and cable-based transmission	Relatively low mechanical output. Not accurately timed assistance led to the hindrance during ankle push-off state
Kim et al. 2020 [84]	Pneumatic ankle-foot orthosis (PAFO)	Assists ankle dorsiflexion (1 DOF)	Wearable custom compressor is worn at the trunk of the body. The compression rate of the custom compressor was optimized to the rate of consumption required to power the active AFO	Relatively low mechanical output. Ankle kinematic data was slightly delayed due to unsynchronized assistive forces
Salmeron et al. 2020 [85]	Pneumatic ankle-foot orthosis (PAFO)	Assists ankle dorsiflexion (1 DOF)	Origami actuator is simple and inexpensive with a high force to mass ratio. The use of negative pressure offers a safer way of actuation. Ergonomic	N/A
Thalman et al. 2020 [86], [90]	A soft robotic ankle-foot orthosis (SR-AFO) exosuit	Assists ankle plantarflexion (1 DOF)	A sock-like garment fabricated from compliant fabrics. It is lightweight and form-fitting	Needs increased current speed of actuation to allow for faster actuation to support faster walking
Murphy et al. 2014 [87]	Pneumatic ankle-foot orthosis (PAFO)	Assists ankle dorsiflexion-plantar flexion and inversion-eversion (2 DOF)	3 pneumatic muscles used to make a lightweight, compliant ankle robotic device	Rigid and weighted footplate
Park et al. 2014 [91]	Pneumatic ankle-foot orthosis (PAFO)	Controls varied sagittal and medio-lateral ankle motions such as dorsiflexion, plantarflexion, inversion, and eversion (2 DOF).	Has multiple artificial muscle-tendon units that mimic not only the morphology but also the functionality of the biological muscles	N/A

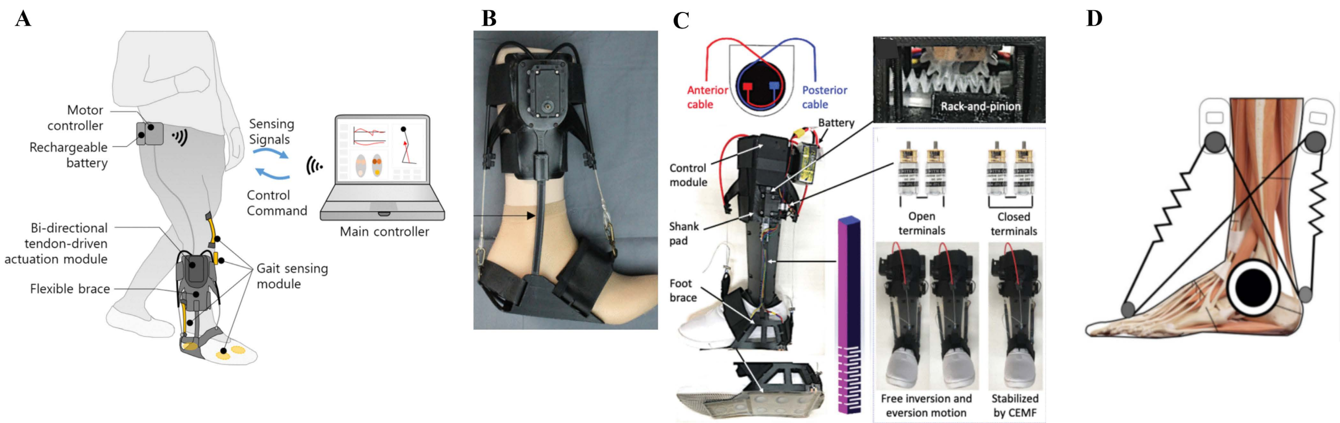

FIGURE 14. Mechanical overview of cable-driven robotic devices, (A) Soft wearable AFO with a cable-pulling bidirectional mechanism [92], (B) Close-up profile of soft wearable AFO with a cable-pulling bidirectional mechanism [92], (C) Portable soft ankle exoskeleton with bi-directional cable-driven actuation [93], (D) T-Flex with stiffness adjusting mechanism of bio-inspired tendons [94].

and force resolution [72]. Capable of adjusting their intrinsic compliance dynamically according to different tasks, variable stiffness actuators (VSAs) have recently emerged to overcome some of these limitations [72]. Four articles were identified and discussed below.

Gu *et al.* designed a compact and portable variable stiffness mechanism for an AFO as shown in Figure. 16(A) [100]. Assistance is delivered through a pneumatic transmission with an air pump. The stiffness modulation mechanism is driven using control hardware. Robotic devices, which

TABLE 9. Summary of reviewed articles for active actuation of cable-driven robotic devices.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Kwon et al. 2019 [92]	Soft ankle foot orthosis	Assists ankle dorsiflexion-plantar flexion (1 DOF)	A cable-pulling mechanism in both directions with a single motor. Powered by a rechargeable battery and communicates with the main controller wirelessly.	No improvement in swing time and step length asymmetry. The abnormality of the non-paretic side in the hemiplegic gait was not corrected. Lateral shifting of the weight during walking
Xia et al. 2020 [93]	Soft ankle-foot orthosis	Foot propulsion assistance in sagittal plane (1 DOF), and inversion-eversion stabilization during walking for stroke patients	Bi-directional cable-driven actuation system and portable	N/A
Manchola et al. 2019 [94]	T-Flex	Ankle plantar flexion and dorsiflexion assistance (1 DOF)	Mimics the behavior of the antagonist muscles through adjusting the stiffness of bio-inspired tendons according to the gait cycle	N/A

incorporate variable stiffness actuators, allow for the optimal match between the user's gait deficiencies and the AFO's ankle stiffness. To enhance kinematic compatibility, Sanchez- Manchola *et al.* developed a gait assisting and rehabilitation device which includes six actuated degrees of freedom along the sagittal plane of the hip, knee, and ankle joints with a variable-stiffness 2 DOF hip joint, as well as, one passive degree of freedom along the frontal plane of the hip joint as shown in Figure. 16(B) [101]. At the hip joint, the variable stiffness system provides assistance modular to the user's level of disability. At the ankle joint, variable stiffness is implemented according to the user's step-to-step gait variations. In another study, Rodriquez *et al.* designed an AFO which aids passive ankle joint stiffness without limiting its range of motion using a negative stiffness mechanism generated by a spring-loaded CAM follower mechanism [102]. The AFO was designed to be compact through a design that generates a large torque with a small moment arm, as shown in Figure. 16 (C). Yu *et al.* developed a knee-ankle foot robotic device that is modular according to the user's gait impairments, as shown in Figure. 16(D) [103]. Assistance is delivered through two compact compliant force controllable linear actuators, with one placed at the ankle and the other placed at the knee. Two sets of springs are used to control the force of the actuator which transmits the linear force from a ball screw nut to an output linkage. The first set of springs consists of soft linear springs to provide the assistive torque, while the other set includes torsional springs for providing the output torque. This allows the actuator to possess a high force control range and bandwidth [103]. A summary of the reviewed articles is presented in Table. 11.

D. CLINICAL FEASIBILITY

The research findings made it possible to describe the design aspects of 72 lower-limb robotic assistance devices for drop foot. 21 studies evaluating specific design aspects through experimental trials with respect to clinical feasibility and safe Human-Robot interface are discussed in the section below.

1) CLINICAL FEASIBILITY OF SEATED GAIT TRAINING ROBOTIC DEVICES

Robotic rehabilitation provides a viable potential alternative to therapist-aided rehabilitation, where robot-assisted tasks can provide customized therapy to patients suffering from movement deficiencies, such as drop foot and beyond. Platform-based systems are a prime example of robotic reha- bilitation systems which can help alleviate muscle spasticity and improve ankle joint performance safely and effectively [105]. The following case studies demonstrate the clinical feasibility of such systems in chronic post-stroke hemiparesis patients compared with healthy elderly [106], as well as poststroke patients with hemiplegic spastic muscles [105], [107]. These case studies collectively aim to shed light on the efficacy and Human-Robot safe interaction of seated robotic training for drop foot impairment based on various biomechanical measures captured before and post therapy.

For seated gait training robotic devices in [29], where the PNF technique is used to utilize maximum static flexibility within training the ankle joint, the effectiveness of PNF on ankle plantar flexors spasticity was investigated by Zhou *et al.* [105] in a 3-month study conducted to measure the effect of PNF on spasticity, where the paretic limb was used as experimental group and the normal limb as control group. The study proved that the PNF training robotic device improved the biomechanics of the paretic limb in reference to the normal limb. It also showed improvements in muscle strength, muscle control, timed up-and-go training, and walking at normal and fast speeds.

A study on the device developed in [30] was performed, where the custom automatic bi-axial Ankle Movement Trainer (AMT) was used to measure the ankle stiffness along the subtalar and talocrural axes in older adults. This study validated the ATM, confirming the significant correlation it had with clinical measurements of older adult's active ankle range of motion [106].

Evaluating the efficiency of the Compliant Ankle Rehabilitation Robot (CARR) developed in [33] for clinical applications, a case study on a stroke patient was performed

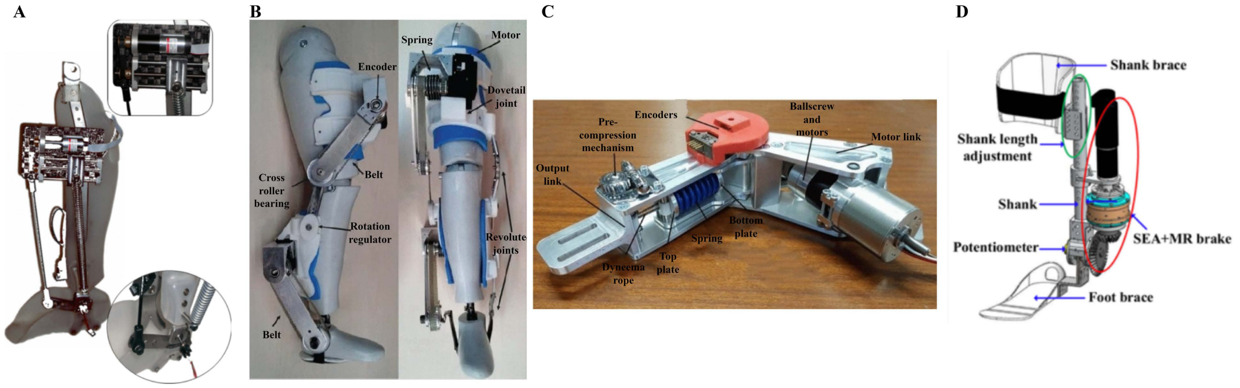

FIGURE 15. Mechanical overview of active robotic devices with series elastic assistance, (A) Active AFO using a SEA consisting of a motor and pre-tensioned spring [95], (B) Knee-ankle orthosis actuated through series elastic actuators [96], (C) Compliant spindle-driven MACCEPA [97] [98], (D) AFO with a series elastic actuator (SEA) and a magneto-rheological (MR) brake [99].

TABLE 10. Summary of reviewed articles for active actuation with series elastic assistance.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Polinkovsky et al. 2012 [95]	An AFO using a SEA prototype	Assists ankle plantar flexion and dorsiflexion (1 DOF)	SEA with a motor controlling the motor arm in series with a pre-tensioned spring	The device is speed limited
Rossi et al. 2014 [96]	Knee-ankle orthosis	Assists ankle dorsiflexion and plantar flexion (1 DOF) and/or assists knee flexion-extension (1 DOF)	Permits the control of the force and the emulation of different stiffness	Torque signal was distorted
Moltedo et al. 2019 [97], [98]	Compliant actuator	Assists ankle dorsiflexion and plantar flexion (1 DOF)	Spindle-driven MACCEPA	Need for more advanced benchmarking techniques of series elastic actuators' behavior under dynamic condition
Kirtas et al. 2021 [56]	Actuator system	Ankle assistance along the sagittal plane (1 DOF)	Adaptive backstepping controller actuated using a SEA along with a lever mechanism and an orthotic shoe	N/A
Chen et al. 2021 [99]	Ankle foot orthosis	Assists ankle dorsiflexion and plantar flexion (1 DOF)	A robotic AFO with a SEA and MR brake,	Needs an electric motor with a larger power to increase the power output of the SEA and needs lightweight materials

TABLE 11. Summary of reviewed articles for active actuation with variable stiffness actuation.

Authors/Year	Robotic Device Specification	Method of Rehabilitation	Novelty	Limitations
Gu et al. 2015 [100]	Ankle foot orthosis	Assists dorsiflexion and plantar flexion of ankle joint (1 DOF)	A portable stiffness modulation mechanism utilizing pneumatic stiffness	N/A
Sanchez-Manchola et al. 2018 [101]	Ankle foot orthosis	Assists in the sagittal plane for hip (1 DOF), knee (1 DOF), and ankle joints (1 DOF) with additional passive DOF at hip joint	An exoskeleton with a variable-stiffness 2 DOF hip joint with intersecting axes	Affects hip and knee kinematics
Rodriguez et al. 2018 [102]	Ankle foot orthosis	Assist ankle dorsiflexion and plantar flexion (1 DOF) while compensating for passive stiffness	Negative stiffness mechanism generated by a spring-loaded CAM follower mechanism	nAFO cannot reach the required maximum negative torque because of the stick-slip of the gas-spring and the CAM design
Yu et al. 2013 [103]	Pneumatic ankle-foot orthosis (PAFO)	Asissts ankle dorsiflexion-plantar flexion (1 DOF)	Pneumatic artificial muscle and pneumatic rotary actuator	N/A

by Zhu *et al.* The results demonstrated effective assistance of the CARR and accurate trajectory tracking throughout the training [107].

2) CLINICAL FEASIBILITY OF OVER-GROUND GAIT TRAINING ROBOTIC DEVICES

Over-ground rehabilitation robotic systems motivate motor relearning by employing actual over-ground training. The following clinical case studies were selected for demonstrating the clinical feasibility and Human-Robot safe interaction capability of these devices. They included patients with motor function loss and spastic ankles due to either spinal cord injury [108] or post-stroke patients with hemiparesis [109]–[111]. Treadmill training was performed for all of the discussed clinical studies, with one study incorporating an interactive visual task to evaluate its efficiency

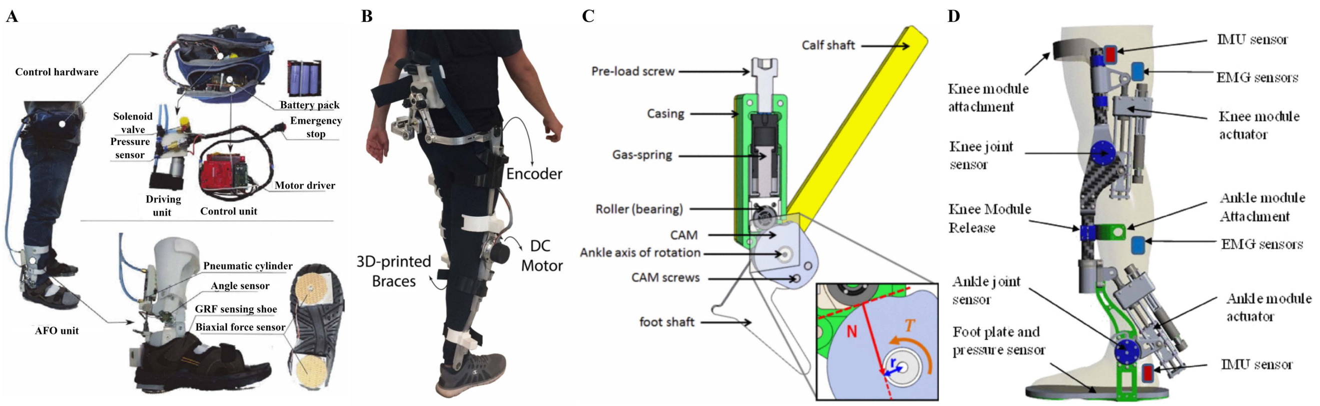

FIGURE 16. Mechanical overview of active robotic devices with variable stiffness actuators, (A) Compact and portable AFO with variable stiffness mechanism [100], (B) Hip, knee, and ankle joint assisting and rehabilitation robotic device with variable stiffness at knee and ankle joint [101], (C) AFO using negative stiffness mechanism [102], (D) Variable impedance knee-ankle foot robotic device [104].

at improving the user's gait kinetics (dorsiflexion and plantar flexion moments). Key performance indicators included adequate toe clearance during the swing phase of gait and foot placement during the stance phase [109], ankle range-of motion [108], EMG values of the hip abductors, medial hamstrings, soleus, rectus femoris, vastus medialis and tibialis anterior muscles [110], as well as gait kinetics [112].

In [109], a case study was performed on a patient with hemiparesis examining the use of Thera-Band with BWSTT. The Thera-Band, a commercialized elastic resistance band used as a treatment intervention during BWSTT, was placed around the hemiparetic lower extremity to help with dorsiflexion and eversion movements during the swing phase, in addition to assistance with the placement of the foot during stance phase. The study confirmed that the Thera-Band with BWSTT was able to aid in foot clearance during swing and in properly positioning the limb during stance without the need for manual assistance or an AFO.

The LOCOMAT system, a treadmill training robotic device that trains the impaired limb using the user's body weight and the provided treadmill speed, was tested in the work of Mirbagheri *et al.* to determine the effects of locomotor training on patients suffering from drop foot [108], [113]. Ten patients with ankle spasticity were trained for 4 weeks [108]. The results indicated that treadmill training reduced the patients' reflex stiffness by 65%, and the intrinsic (muscular) stiffness by 60%, while it increased the patients' maximum voluntary contraction by 93% and 180% for the ankle extensor and flexor muscles, respectively [108]. A continuation of the study presented a linear regression line using the resulting changes in ankle spasticity over the ankle range of motion [113]. With these results, two recovery classes were distinguished. Modeling the results showed that not only did the treadmill training reduce ankle spasticity and improve its volitional control, but it was also able to improve the spastic ankle's abnormal variance of reflexes [113].

In another study, the effect of pelvic mediolateral corrective force using treadmill training as proposed by [36] resulted in enhanced muscle activity and gait symmetry of post-stroke patients suffering from hemiparesis [110]. This study also demonstrated that this type of assistance was able to improve the muscle activity of the impaired leg and enhance the pelvic displacement symmetry.

In [112], the Anklebot developed in [10] was used along with an interfaced game to provide training for post-stroke patients based on interactive visual tasks. The interactive task consisted of a soccer video game with which movement in the game was controlled by the user's volitional ankle torque. Ankle rehabilitation was attained with the game's adaptive auto-adjust to task difficulty, promoting cooperative learning.

3) CLINICAL FEASIBILITY OF THE PERCEPTIVE SYSTEMS OF ROBOTIC DEVICES

In general, AFOs rely on perceptive components integrated within the system to identify the user's phase of gait. The following case studies were selected to demonstrate the clinical feasibility and Human-Robot safety interaction capability in AFOs which integrate various sensors, including foot pressure insole sensors, footswitches, IMUs, and EMG systems [24]. The sensors ensure safe and effective Human-Robot interaction by providing the robot controller with real-time kinematic data for real-time control and modulation.

For example, in [26], an over-ground and stairs gait training robotic device was used for sub-acute stroke survivors to evaluate improvement in functional gait. To validate the perceptive system developed in [26] which measures gait patterns and estimates walking intentions, a randomized control trial conducted by Yeung *et al.* investigated the therapeutic impact of a portable robotic device which detects the user's movement intentions [63]. This study showed that 20-session robotic device training was able to enhance gait independence, motor recovery, walking speed, and limb stability during loading response.

Another study investigated the gait feedback approach developed by [24], consisting of a two-layer model measuring both gait phases and ankle angle. They concluded that this is significantly accurate in recognizing the phase of gait (above 95%), as well as short delay responses (below 20 ms,) and minimal errors in angle measurement (below 3.5°) [24].

4) CLINICAL FEASIBILITY OF THE CONTROL SYSTEMS OF ROBOTIC DEVICES

Control systems are incorporated with AFOs to regulate the user's level and rate of adaptations to the assistive device, hence mimicking the central nervous system [114]. Control strategies regulate the active device's torque, stiffness, impedance for a safe and efficient Human-Robot interaction [114]. The experimental trials discussed include healthy subjects in order to assess the control strategy's tracking performance [114] and identify optimal control references [115], [116], [114]. One paretic patient was employed in Arnez-Paniagua et al's study to further evaluate the efficiency of tracking performance for a drop foot patient.

A pretest on healthy subjects and a modeling test on a patient were performed to generate the control rule for drop speed and the estimation rule for walking speed in [115],which proved the successful control of the foot movement during different gait cycles [115]. Another form of the previous work was performed by Adiputra *et al.*, where the control reference parameters were measured for different subjects at different walking speeds to apply average ankle torque and ankle angular velocity onto a magnetorheological brake [116].

Arnez-Paniagua *et al.* experimentally tested the control method developed by [62], which relies on the torque generated by the user, on three healthy subjects and one paretic patient. The results demonstrated the control design's success at different walking speeds and different gait sub-phase duration proportions [62], [114], [117]. This study was able to successfully track the reference trajectory's performance within a few steps and reduce the muscular activities of the tibialis anterior and gastrocnemius muscles.

5) CLINICAL EFFICACY OF SEMI-ACTIVE ACTUATED ROBOTIC DEVICES

Semi-active AFOs are designed to overcome the challenges inherent to passive AFOs, as they provide better ankle joint range-of-motion, accelerated functional recovery, reduced muscle disuse atrophy, and reduced excessive knee flexion during the loading response phase of gait [118]. To evaluate the clinical feasibility and Human-Robot safe interface of hybrid AFOs in comparison with passive AFOs, [118] used an innovative spring damper placed posterior to the ankle joint on 15 drop foot patients. The performance indicators included several balance-related tests, such as the self- reported balance confidence (ABC) test, Timed Up and Go Test (TUG), and Berg Balance Scale (BBS) test [118]. The spring damper mechanism involved modular constant force springs and modifiable series hydraulic shock absorbers. Placed posterior to the ankle joint, the mechanism did not obstruct the ankle joint. Activities-Specific Balance Confidence Scale (ABC), Berg Balance Scale (BBS), and Timed Up and Go (TUG) tests were conducted on fifteen right-side drop foot patients. The spring damper mechanism resisted plantar flexion at initial contact to loading response, increased the ankle's range of motion from midstance to terminal stance, and prevented plantarflexion during the swing phase. The results of the balance confidence tests showed that the AFO improved the ABC scale, increased the single-leg standing task for the BBS scale, and improved TUG due to the increased ankle ROM and the energy storage and release mechanism.

6) CLINICAL FEASIBILITY OF ELECTRIC (RIGID) ACTUATED ROBOTIC DEVICES

Given that post-stroke patients often suffer from muscle weakness, active AFOs allow for better gait adaptation to the robotic device's assistive moment [119]. The following clinical study evaluated post-stroke patients' gait adaptations to powered AFO (PAFO) gait training therapy. The study focused on the user's interaction with the output assistive force, where it was essential for users to learn how to store and release energy timely and efficiently during gait training [119]. Three post-stroke patients were recruited, and the outcome measurements used to evaluate gait adaptation included temporal, kinematic, and kinetic parameters. The actuated assistance of the (PAFO) was achieved through a robotic tendon actuator, consisting of a DC motor coupled with a lead-screw and lead-nut, along with a series spring. This study showed that the robotic device was able to improve gait cadence, ankle range of motion, and ankle power generation, with which the output was greater than the power input from the robotic device. Additionally, motion capture data confirmed the improvement of the sound limb.

7) CLINICAL FEASIBILITY OF PNEUMATIC ACTUATED ROBOTIC DEVICES

Soft exosuits, made of soft material and fabrics, provide assistive devices with interfaces that are more ergonomic, conformal, and compliant [120]. The following studies demonstrate the clinical feasibility and safe Human-Robot interaction using soft exosuits to assist post-stroke patients whilst maintaining natural gait [82], [111], [120], [121]. The exosuit's impact on the venous flow profile of the superficial femoral vein was also explored [111]. Performance indicators included ankle kinetics and time average mean velocity, as well as volumetric flow rate of the venous flow

In [82], a pneumatically actuated McKibben-type artificial muscle, aligned in series with a tension spring, was devel- oped to provide the user with the high dorsiflexion force needed during the swing phase of gait. Clinical trials of the developed robotic device proved its ability to provide high dorsiflexion forces with immediate drop foot improvement [82].

Bae *et al.* tested the validity of a soft robotic device to be used to assist chronic stroke patients [120]. The study confirmed that the exosuits successfully tracked post-stroke gait, provided assistive force at the appropriate times, and improved key gait parameters. Similarly, Awad *et al.* studied the implications of a soft robotic exoskeleton on the assistance and rehabilitation of post-stroke patients' gait deficits [121]. Their study showed that soft exoskeletons can provide faster overground gait and increase the distance traveled.

Since stroke patients are more likely to suffer from deep vein thrombosis and joint contracture, Low *et al.* studied the effect of a soft exosuit on the blood flow in the users' lower limbs [111]. The study demonstrated that the device enhanced venous blood flow while still assisting ankle motion.

V. DISCUSSION

The most significant motion deficit suffered by drop foot patients is the uncontrolled dorsiflexion of the ankle. This is primarily why most rehabilitation devices in literature focus on assisting the ankle motion in the sagittal plane. All the designs reviewed here share the main objective of improving drop foot deficit. Their different approaches hence focus on either training the muscle weakness in dorsiflexion or providing movement assistance through foot drop resistance. In the pursuit of advanced robotic devices, it is vital to mimic or rehabilitate the function of the impaired muscle without hindering the users' physiological range of motion, nor compromising their safety, comfort, or balance. Moreover, many of these advanced robotic devices provide additional functional features in order to rehabilitate the impairment regardless of the level of impairment, and/or follow the user's motion irrespective of the type of walking surface, ground inclination, external disruptions/perturbations, and user's step-to-step variations.

Some of these additional functional features include:

1) Interactive and adaptive training
2) Additional degrees of freedom
3) Adjustability to variations in gait
4) Adjustability to different levels of impairment
5) Alternative power supplies
6) Modular stiffness mechanisms
7) Smart sensors and control systems for optimal and safe Human-Robot interaction

VI. REMAINING ISSUES AND FUTURE DIRECTION

For an AAFO to efficiently assist and rehabilitate motion deficits, several key requirements must be addressed, including the insurance of safety/comfort of the user, maintaining a lightweight structure, offering modularity and adaptability to motion, as well as providing sufficient assistive torque(s) to restore motion deficits. Compliance, a key prerequisite for safe Human-Robot interaction, can be maintained through proper compliant actuation and structure to multiple degrees of freedom, real-time gait trajectory tracking and assistance, as well as minimal added mass [97]. The current body of literature reflects several gaps in the compliance of current robotic devices in association with the fundamental mechanisms of gait, variations of gait, gait therapy, and underlying neural pathways of patients suffering from drop foot deficit. Some of the main issues which remain open areas of research for user-compliant assistance/rehabilitation include the degrees of freedom; gait pattern variability; balance and stability; restrictive and bulky designs; as well as inflexible sensor components. The following addresses these issues and attempts to delineate the future direction of advanced robotic devices for drop foot.

A. DEGREES OF FREEDOM

The optimal number of degrees of freedom remains a contentious issue when designing robotic assistive devices. For example, the parallel two-UPS/RRR ankle rehabilitation robot developed by Dong *et al.*, as discussed above, provides patient-active exercise only in the uniaxial direction, which limits its effectiveness in terms of providing multi-axis patient-active exercises [35]. On the other hand, some experts argue that using a smaller number of actuators, as compared to the DOFs anatomically present, may be advantageous to avoid the need for precise alignment of the robotic device with the user's joint axes [38].

Another challenge arising with increasing the actuated DOF is due to the fact that added electric components tend to be heavy, rigid, and bulky, hence limiting the freedom of the limb in natural physiological motions. For example, in the work of Liu *et al.*, to balance the gravity of the motor for dorsiflexion assistance and the gearbox for eversion assistance of the robotic device, a large torque was required [31].

Overall, a robotic device's safety factor is greatly impacted by the device's compliance with the user during therapy, as well as the device's center of rotation coinciding with the physiological joint's center of rotation. By implementing multiple DOF, safety is better ensured through the synergistic movement of the lower limb [35].More future work is needed for determining the optimal number of degrees of freedom towards safe, lightweight robust effective systems.

B. VARIABILITY OF GAIT PATTERN

The complexity and variability of human gait lead to challenges in its faithful emulation. During gait, the user is prone to changing their pattern and shifting their center of gravity which, if not compensated with real-time gait assistance, can cause resistance to assistive devices. Systems which lack real-time adaptability have demonstrated a negative effect on the ankle's propulsive force, compelling compensated muscle contractions [83], causing lateral shifting of the weight during gait [92], delaying peak phase shift and reducing maximum toe-clearance [37], and causing abrupt foot strike and excessive knee flexion [82], [83].

One approach, with which the perturbations within the gait cycle were reduced, was to overcome the speed limitations of the DC motor [56]. Changing to a faster DC motor helped overcome this limitation with the trade-off of increasing power consumption. This was demonstrated in the modular robotic exoskeleton developed by Font-Llagunes *et al.*, incorporating a stronger motor to ensure a safer design in assisting with the knee's full extension to support the patient's weight [79].

Regarding the algorithm developed which emulates the rhythmic movements of gait using PCPG, it is worthy to note that constant phase-resetting needs to be performed since gait cycles are not perfectly identical. As stated in the reviewed study [49], a major drawback to the required phase resetting is the need to increase the speed of phase recovery to provide a smooth transition between gait cycles in order to ensure natural gait and user comfort [49]. This was also reflected in the work of Arnez-Paniagua *et al.*, where an error from the constant change of the initial position of the ankle joint during the swing sub-phase resulted in a negative influence on the adaptive performance [62].

In general, more work is needed on real-time detection algorithms, in conjunction with control systems, to provide assistance at proper timing. With post-stroke patients, detecting different gait patterns of patients, as well as individual gait pattern differences, ensures safer interaction with the assistive intervention and more efficient rehabilitation. Moreover, devices which lack precise trajectory tracking systems are more likely to experience undesired responses to unknown interaction forces [56].

C. BALANCE AND STABILITY

The use of additional assistive devices, such as canes, during robot-assisted rehabilitation is another area open to further research. The incorporation of external support with the robotic systems should be evaluated carefully considering the effect on the joint kinematics and kinetics. For example, to maintain balance and help the patients stand straight during robot-assisted gait training, a walking cane was used in the work of Yeung *et al.*, a front handrail in the work of Hsu *et al.*, and a wheeled walker and bilateral crutches in the work of Choi *et al.* [26], [57], [110]. Despite their benefits in terms of affording added measures of safety, these interventions, on the downside, influenced the walking patterns and the biomechanics of gait of the participants and studies show that they may over time trigger over-reliance which could affect motor relearning.

D. RESTRICTIVE AND BULKY DESIGN

Lightweight and compact designs remain on the top of the objective tree list for all devices interfacing with the human body, especially during load-bearing activities. Many theoretically functional design prototypes rapidly lose footing in clinical experiments due to the user's compensation to the added distal mass. For example, in the semi-active robotic device developed by Hassan *et al.*, the walking experiment results showed increased muscle activity when assisting with foot slap, which was due to the newly introduced AFO which increased the user's engagement when walking [76]. In the design by Murphy *et al.*, where the assisting robotic device was actuated by artificial pneumatic muscles, the robot's rigid flat footplate increased plantar flexion during the stance and swing phases of gait, hence altering the biomechanics [87]. The plantar flexion increase during stance was due to the foot plate's rigidity which did not support the function of the heel and forefoot rockers, while that during swing was due to the weight of the footplate. The footplate proposed in this design also resulted in increased eversion during the stance phase to apply contact at the lateral side of the foot and end of swing phase for safe ground contact at heel strike. Further examples include evidence of the soft exosuit being restrictive as demonstrated in the work of Bae *et al.* in the form of decrease in the stride length seen in all participants [120]. More research is warranted in this area to provide safe, patient-driven, user-centered lightweight and compact designs.

E. INFLEXIBLE SENSOR COMPONENTS

Although the rapid explosion in sensor technology has tremendously aided the design and development of robotic and assistive and rehabilitative devices, some designs remain vulnerable due to sensor limitations that can hinder smooth and accurate data collection, hence affecting accurate and safe torque transmission or rehabilitation. For example, during the use of insole sensors to measure the phases of gait, foot slipping within the shoe or user slipping on the surface may disrupt the kinematic and kinetic measurements and interfere with the feedback needed for assistance [38].

He *et al.* used a combination of neural EEG and musculoskeletal EMG for their exoskeleton to provide the user with optimal assistance [46]. However, the Human-Robot interface interfered with the EMG placement, hence lowering the decoding accuracy for the lower limb EMG activity. This limitation, along with head movement-related artifacts which could potentially contaminate EEG signals, rendered the device less effective.

Another study, in which Casas *et al.* embedded an optical strain sensor into biomimetic tendon actuators [48], suffered from the challenge of using the sensor to measure the motion without influencing the tendon's mechanical properties. Indeed, the embedding technique affected the sensor's performance, where the surface conditions of the tendon caused sensor detachment leading to inaccurate data.

Overall, sensors will continue to play a big role in the future of robotic rehabilitation, and hence novel, lightweight, flexible, accurate, and precise sensors are needed to fill that gap.

F. FUTURE DIRECTION

The authors believe that the future of robotic assistive devices should align well with the envisioned futuristic world of 4P medicine, by designing devices and systems that can be **P**ersonalized, **P**articipatory, **P**reventive and **P**redictive. This warrants a bio-inspired multifactorial integrative approach in the development of device structure, mechanisms, actuation, perception, and control.

The development of device structure and mechanisms can benefit from design extension into assistance of movements beyond those in the sagittal plane, in alignment with the physiological joint degrees of freedom. Structure can also be enhanced through the use of smart novel lightweight materials, with enhanced mechanical properties, towards compact and lightweight structures. The new generation of devices should provide users with better balance, stability, comfort, natural gait and importantly optimal human-device interface. For added stability and balance, the scope of assistance should transcend traditional control of the hip, knee, and ankle joints, to include assisting and stabilizing the spine and pelvis, again inspired by the integrative synergy observed in physiological movement.

Development in actuation should be focused on realizing more compact, efficient, lightweight, and large power-to-weight ratio actuators. Having actuation mechanisms that conform to the human body without risking the users' safety or comfort, would serve as a great advancement in the field of robotic devices for drop foot. The authors suggest further exploration of solutions that combine technologies of twistedcable-actuation and variable stiffness actuation.

Embedded sensors in smart devices used for capturing various physiological signals (EMG, ECG, EEG, IMUs, etc.) must adhere to the highest standards of precision and accuracy, in addition to light weight, compactness and interface adaptability. Advancement in perception systems and control techniques are required towards enhanced sensors that conform to human limbs, avoiding limitations such as sensor slippage, interface interference, and detachment. Moreover, it is anticipated that including human perception in bilateral interactive systems would significantly enhance the usability and effectiveness of robotic wearable devices. Future control systems which can provide real-time assistance with gait subevent adaptive control are highly desirable to provide the user with a natural smooth gait regardless of variability in the gait pattern or the environment. Finally, recent technological advancements in the field of computing afford the unprecedented opportunity to enhance current robotic systems by integrating them with empathetic AI, VR, and serious gaming towards robust multifaceted rehabilitation assistive solutions for drop foot motion deficits and beyond.

VII. CONCLUSIVE REMARKS

The objective of this work was to review and summarize the designs, working principles, and applications of robotic devices for drop foot assistance and rehabilitation which were proposed in literature in the last decade. The main contribution is providing a functional summary that can be beneficial for both research and clinical communities, alike, by shedding light on the available designs and technologies, as well as the remaining gaps and limitations for treating drop-foot abnormalities. It is noteworthy that several review articles have already been published on the design and application of ankle-foot orthoses. In spite of their value, these studies were found to be either outdated or lacked an extensive review on the different robotic technologies currently available for treating drop-foot abnormalities. The current review includes some of the important traditional designs highlighted by those reviews (designs that are safe, lightweight, wearable, comfortable, provide balance and stability, etc.), but also goes beyond to explore advanced functional features, including interactive and adaptive training, additional degrees of freedom, adjustability to variations in gait, adjustability to different levels of impairment, alternative power supplies, modular stiffness mechanisms, and smart sensors and control systems for optimal and safe Human-Robot interaction. Obviously, many constraints and limitations arise when one attempts to combine all these functional features into one robotic device. On the other hand, such a bio-inspired integrative design would provide a paradigm shift in the world of rehabilitation robotics and add great value to the future of advanced robotic devices for the assistance and rehabilitation of a wide spectrum of movement pathologies, including drop foot.

REFERENCES

[1] M. Błażkiewicz, I. Wiszomirska, K. Kaczmarczyk, G. Brzuszkiewicz-Kuźmicka, and A. Wit, "Mechanisms of compensation in the gait of patients with drop foot," *Clin. Biomech.*, vol. 42, pp. 14–19, Feb. 2017.

[2] S. L. Nori and J. M. Das, "Steppage gait," PubMed, Nat. Library Med., Bethesda, MD, USA, Tech. Rep., Aug. 2021.

[3] I. Wiszomirska, M. Błażkiewicz, K. Kaczmarczyk, G. Brzuszkiewicz-Kuźmicka, and A. Wit, "Effect of drop foot on spatiotemporal, kinematic, and kinetic parameters during gait," *Appl. Bionics Biomech.*, vol. 2017, pp. 1–6, Apr. 2017.

[4] G. M. Lyons, T. Sinkjær, J. H. Burridge, and D. J. Wilcox, "A review of portable FES-based neural orthoses for the correction of drop foot," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 10, no. 4, pp. 260–279, Dec. 2002.

[5] L. Saunders, "Illustrated orthopedic physical assessment," *Physiotherapy*, vol. 88, no. 9, p. 572, Sep. 2002.

[6] J. Perry and J. M. Burnfield, *Gait Analysis: Normal and Pathological Function*, 2nd ed. San Francisco, CA, USA: Slack, 2010.

[7] K. Daniilidis, E. Jakubowitz, A. Thomann, S. Ettinger, C. Stukenborg-Colsman, and D. Yao, "Does a foot-drop implant improve kinetic and kinematic parameters in the foot and ankle?" *Arch. Orthopaedic Trauma Surg.*, vol. 137, no. 4, pp. 499–506, Apr. 2017.

[8] J. A. Blaya and H. Herr, "Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 12, no. 1, pp. 24–31, Mar. 2004.

[9] E. Pourhoseingholi, H. Saeedi, M. Kamali, and M. Jalali, "The effect of articulated AFO with hydra pneumatic damper in biomechanical characteristic of drop foot: A pilot study," *Med. J. Islamic Republic Iran*, vol. 34, p. 115, Sep. 2020.

[10] A. Roy, H. I. Krebs, J. E. Barton, R. F. Macko, and L. W. Forrester, "Anklebot-assisted locomotor training after stroke: A novel deficit-adjusted control approach," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2013, pp. 2175–2182.

[11] S. Prenton, K. Hollands, and L. Kenney, "Functional electrical stimulation versus ankle foot orthoses for foot-drop: A meta-analysis of orthotic effects," *J. Rehabil. Med.*, vol. 48, no. 8, pp. 646–656, 2016.

[12] R. Jiménez-Fabián and O. Verlinden, "Review of control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons," Med Eng Phys., vol. 34, no. 4, pp. 397–408, May 2012, doi: 10.1016/j.medengphy.2011.11.018.

[13] D. Adiputra, N. Nazmi, I. Bahiuddin, U. Ubaidillah, F. Imaduddin, M. A. Rahman, S. Mazlan, and H. Zamzuri, "A review on the control of the mechanical properties of ankle foot orthosis for gait assistance," *Actuators*, vol. 8, no. 1, p. 10, Jan. 2019. [Online]. Available: https://www.mdpi.com/2076-0825/8/1/10

[14] T. Yan, M. Cempini, C. M. Oddo, and N. Vitiello, "Review of assistive strategies in powered lower-limb orthoses and exoskeletons," *Robot. Auto. Syst.*, vol. 64, pp. 120–136, Feb. 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921889014002176

[15] W. Huo, S. Mohammed, J. C. Moreno, and Y. Amirat, "Lower limb wearable robots for assistance and rehabilitation: A state of the art," *IEEE Syst. J.*, vol. 10, no. 3, pp. 1068–1081, Sep. 2016.

[16] M. Alam, I. A. Choudhury, and A. B. Mamat, ''Mechanism and design analysis of articulated ankle foot orthoses for drop-foot,'' *Sci. World J.*, vol. 2014, pp. 1–14, Apr. 2014.

[17] M. Hamedi, P. Salimi, A. Aliabadi, and M. Vismeh, ''Toward intelligent ankle foot orthosis for foot-drop, a review of technologies and possibilities,'' in *Proc. 2nd Int. Conf. Biomed. Eng. (ICoBE)*, Mar. 2015, pp. 1–6.

[18] M. Alam, I. A. Choudhury, and A. B. Mamat, ''Mechanism and design analysis of articulated ankle foot orthoses for drop-foot,'' *Sci. World J.*, vol. 2014, Apr. 2014, Art. no. 867869, doi: 10.1155/2014/867869.

[19] L. P. Kenney, B. W. Heller, A. T. Barker, M. L. Reeves, T. J. Healey, T. R. Good, G. Cooper, N. Sha, S. Prenton, and D. Howard, ''The design, development and evaluation of an array-based FES system with automated setup for the correction of drop foot,'' *IFAC-PapersOnLine*, vol. 48, no. 20, pp. 309–314, 2015.

[20] I. Díaz, J. J. Gil, and E. Sánchez, ''Lower-limb robotic rehabilitation: Literature review and challenges,'' *J. Robot.*, vol. 2011, pp. 1–11, Nov. 2011.

[21] S. Mohammed, Y. Amirat, and H. Rifai, ''Lower-limb movement assistance through wearable robots: State of the art and challenges,'' *Adv. Robot.*, vol. 26, nos. 1–2, pp. 1–22, 2012, doi: 10.1163/016918611X607356.

[22] J. Kim, S.-J. Kim, and J. Choi, ''Real-time gait phase detection and estimation of gait speed and ground slope for a robotic knee orthosis,'' in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, Aug. 2015, pp. 392–397.

[23] V. Nalam and H. Lee, ''Environment-dependent modulation of human ankle stiffness and its implication for the design of lower extremity robots,'' in *Proc. 15th Int. Conf. Ubiquitous Robots (UR)*, Jun. 2018, pp. 112–118.

[24] L. Meng, U. Martinez-Hernandez, C. Childs, A. A. Dehghani-Sanij, and A. Buis, ''A practical gait feedback method based on wearable inertial sensors for a drop foot assistance device,'' *IEEE Sensors J.*, vol. 19, no. 24, pp. 12235–12243, Dec. 2019.

[25] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, ''Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement,'' *PLoS Med.*, vol. 6, no. 7, 2009, Art. no. e1000097.

[26] L.-F. Yeung, C. Ockenfeld, M.-K. Pang, H.-W. Wai, O.-Y. Soo, S.-W. Li, and K.-Y. Tong, ''Randomized controlled trial of robot-assisted gait training with dorsiflexion assistance on chronic stroke patients wearing ankle-foot-orthosis,'' *J. NeuroEng. Rehabil.*, vol. 15, no. 1, pp. 1–12, Dec. 2018.

[27] A. Karime, H. Al-Osman, W. Gueaieb, J. M. Alja'am, and A. El Saddik, ''E-Wobble: An electronic wobble board for ankle and toe rehabilitation,'' in *Proc. IEEE Int. Symp. Med. Meas. Appl. (MeMeA)*, May 2011, pp. 366–369.

[28] S. Zuo, J. Li, M. Dong, X. Zhou, W. Fan, and Y. Kong, ''Design and performance evaluation of a novel wearable parallel mechanism for ankle rehabilitation,'' *Frontiers Neurorobot.*, vol. 14, p. 9, Feb. 2020.

[29] Z. Zhou, Y. Zhou, N. Wang, F. Gao, K. Wei, and Q. Wang, ''A proprioceptive neuromuscular facilitation integrated robotic ankle–foot system for post stroke rehabilitation,'' *Robot. Auto. Syst.*, vol. 73, pp. 111–122, Nov. 2015.

[30] S. Cho, H. Lee, and H. Kim, ''Development and evaluation of ankle muscle trainer with malleolar and subtalar movement actuators and underfoot reaction force sensors during active ankle dorsi-plantarflexion,'' in *Proc. 16th Int. Conf. Control, Autom. Syst. (ICCAS)*, Oct. 2016, pp. 971–975.

[31] Q. Liu, X. Zhang, W. Shang, C. Wang, Z. Lin, T. Sun, J. Ye, G. Chen, J. Wei, and Z. Wu, ''Design and characterization of the MKA-IV robot for ankle rehabilitation,'' in *Proc. IEEE Int. Conf. Real-Time Comput. Robot. (RCAR)*, Aug. 2018, pp. 544–549.

[32] L. Moreira, S. M. Cerqueira, J. Figueiredo, J. Vilas-Boas, and C. P. Santos, ''AI-based reference ankle joint torque trajectory generation for robotic gait assistance: First steps,'' in *Proc. IEEE Int. Conf. Auto. Robot Syst. Competitions (ICARSC)*, Apr. 2020, pp. 22–27.

[33] M. Zhang, S. Q. Xie, X. Li, G. Zhu, W. Meng, X. Huang, and A. J. Veale, ''Adaptive patient-cooperative control of a compliant ankle rehabilitation robot (CARR) with enhanced training safety,'' *IEEE Trans. Ind. Electron.*, vol. 65, no. 2, pp. 1398–1407, Feb. 2018.

[34] M. Zhang, J. Cao, S. Q. Xie, G. Zhu, X. Zeng, X. Huang, and Q. Xu, ''A preliminary study on robot-assisted ankle rehabilitation for the treatment of drop foot,'' *J. Intell. Robot. Syst.*, vol. 91, no. 2, pp. 207–215, Aug. 2018.

[35] M. Dong, W. Fan, J. Li, X. Zhou, X. Rong, Y. Kong, and Y. Zhou, ''A new ankle robotic system enabling whole-stage compliance rehabilitation training,'' *IEEE/ASME Trans. Mechatronics*, vol. 26, no. 3, pp. 1490–1500, Jun. 2021.

[36] T. Watanabe, T. Tono, Y. Nakashima, K. Kawamura, J. Inoue, Y. Kijima, Y. Toyonaga, T. Yuji, Y. Higashi, T. Fujimoto, and M. G. Fujie, ''Analysis of interaction between therapist and hemiplegic patient for control of lateral pelvic motion during robotic gait training,'' in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2013, pp. 2663–2668.

[37] J. Fong, H. Rouhani, and M. Tavakoli, ''A therapist-taught robotic system for assistance during gait therapy targeting foot drop,'' *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 407–413, Apr. 2019.

[38] A. Roy, H. I. Krebs, D. J. Williams, C. T. Bever, L. W. Forrester, R. M. Macko, and N. Hogan, ''Robot-aided neurorehabilitation: A novel robot for ankle rehabilitation,'' *IEEE Trans. Robot.*, vol. 25, no. 3, pp. 569–582, Jun. 2009.

[39] W. Liu, ''Developing a novel gait training device using a minimally-required-assistance principle,'' *Frontiers Biomed. Devices*, vol. 40789, Apr. 2018, Art. no. V001T03A018.

[40] T. Susko, K. Swaminathan, and H. I. Krebs, ''MIT-Skywalker: A novel gait neurorehabilitation robot for stroke and cerebral palsy,'' *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 10, pp. 1089–1099, Oct. 2016.

[41] A. Roy, C. Chornay, L. W. Forrester, C. E. Hafer-Macko, and R. F. Macko, ''Quantifying human autonomy recovery during ankle robot-assisted reversal of foot drop after stroke,'' in *Proc. IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics (Biorob)*, Aug. 2018, pp. 523–530.

[42] Y.-R. Mao, W. L. Lo, Q. Lin, L. Li, X. Xiao, P. Raghavan, and D.-F. Huang, ''The effect of body weight support treadmill training on gait recovery, proximal lower limb motor pattern, and balance in patients with subacute stroke,'' *BioMed Res. Int.*, vol. 2015, pp. 1–10, 2015.

[43] M. M. Mirbagheri, L. L. Ness, C. Patel, K. Quiney, and W. Z. Rymer, ''The effects of robotic-assisted locomotor training on spasticity and volitional control,'' in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Jun. 2011, pp. 1–4.

[44] L.-F. Yeung, C. Ockenfeld, M.-K. Pang, H.-W. Wai, O.-Y. Soo, S.-W. Li, and K.-Y. Tong, ''Design of an exoskeleton ankle robot for robot-assisted gait training of stroke patients,'' in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 211–215.

[45] T. Wang, C. Wang, J. Wei, J. Xia, Z. Sun, Q. Liu, L. Duan, X. Zhang, Y. Wang, and J. Long, ''Development of an ankle detection platform for foot drop rehabilitation,'' in *Proc. IEEE 9th Annu. Int. Conf. CYBER Technol. Autom., Control, Intell. Syst. (CYBER)*, Jul. 2019, pp. 407–412.

[46] Y. He, K. Nathan, A. Venkatakrishnan, R. Rovekamp, C. Beck, R. Ozdemir, G. E. Francisco, and J. L. Contreras-Vidal, ''An integrated neuro-robotic interface for stroke rehabilitation using the NASA X1 powered lower limb exoskeleton,'' in *Proc. 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug. 2014, pp. 3985–3988.

[47] N. B. Bolus, C. N. Teague, O. T. Inan, and G. F. Kogler, ''Instrumented ankle–foot orthosis: Toward a clinical assessment tool for patient-specific optimization of orthotic ankle stiffness,'' *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 6, pp. 2492–2501, Dec. 2017.

[48] J. Casas, A. Leal-Junior, C. R. Díaz, A. Frizera, M. Múnera, and C. A. Cifuentes, ''Large-range polymer optical-fiber strain-gauge sensor for elastic tendons in wearable assistive robots,'' *Materials*, vol. 12, no. 9, p. 1443, May 2019.

[49] M. Duvinage, R. Jiménez-Fabián, T. Castermans, O. Verlinden, and T. Dutoit, ''An active foot lifter orthosis based on a PCPG algorithm,'' in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Jun. 2011, pp. 1–7.

[50] K. Anam and A. A. Al-Jumaily, ''Active exoskeleton control systems: State of the art,'' *Proc. Eng.*, vol. 41, pp. 988–994, Jul. 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1877705812026732

[51] M. Kanthi, H. S. Mruthyunjaya, and V. I. George, ''Fuzzy logic control for active ankle foot orthosis,'' in *Proc. IEEE Int. Conf. Fuzzy Syst. (FUZZ-IEEE)*, Jul. 2013, pp. 1–6.

[52] M. George, P. Hegde, and K. Hegde, ''Embedded controller design for active ankle foot orthosis using fuzzy logic,'' *J. Adv. Res. Dyn. Control Syst.*, vol. 10, pp. 57–64, Jan. 2018.

[53] T. Kikuchi, S. Tanida, T. Yasuda, and T. Fujikawa, ''Automatic adjustment of initial drop speed of foot for intelligently controllable ankle foot orthosis,'' in *Proc. IEEE/SICE Int. Symp. Syst. Integr.*, Dec. 2013, pp. 276–281.

[54] Y. Zhuang, Y. Leng, J. Zhou, R. Song, L. Li, and S. W. Su, ''Voluntary control of an ankle joint exoskeleton by able-bodied individuals and stroke survivors using EMG-based admittance control scheme,'' *IEEE Trans. Biomed. Eng.*, vol. 68, no. 2, pp. 695–705, Feb. 2021.

[55] J. F. Guerrero-Castellanos, H. Rifaï, V. Arnez-Paniagua, J. Linares-Flores, L. Saynes-Torres, and S. Mohammed, "Robust active disturbance rejection control via control Lyapunov functions: Application to actuated-ankle–foot-orthosis," *Control Eng. Pract.*, vol. 80, pp. 49–60, Nov. 2018.

[56] O. Kirtas, Y. Savas, M. Bayraker, F. Baskaya, H. Basturk, and E. Samur, "Design, implementation, and evaluation of a backstepping control algorithm for an active ankle–foot orthosis," *Control Eng. Pract.*, vol. 106, Jan. 2021, Art. no. 104667.

[57] H. Choi, "Assistance of a person with muscular weakness using a joint-torque-assisting exoskeletal robot," *Appl. Sci.*, vol. 11, no. 7, p. 3114, Mar. 2021.

[58] U. Martinez-Hernandez, A. Rubio-Solis, V. Cedeno-Campos, and A. A. Dehghani-Sanij, "Towards an intelligent wearable ankle robot for assistance to foot drop," in *Proc. IEEE Int. Conf. Syst., Man Cybern. (SMC)*, Oct. 2019, pp. 3410–3415.

[59] J. Lopes, C. Pinheiro, J. Figueiredo, L. P. Reis, and C. P. Santos, "Assist-as-needed impedance control strategy for a wearable ankle robotic orthosis," in *Proc. IEEE Int. Conf. Auto. Robot Syst. Competitions (ICARSC)*, Apr. 2020, pp. 10–15.

[60] D. Adiputra, M. A. A. Rahman, U. Ubaidillah, D. D. D. P. Tjahjana, P. J. Widodo, and F. Imaduddin, "Controller development of a passive control ankle foot orthosis," in *Proc. Int. Conf. Robot., Autom. Sci. (ICORAS)*, Nov. 2017, pp. 1–5.

[61] R. Kochhar, M. Kanthi, and R. K. Makkar, "Neuro-fuzzy controller for active ankle foot orthosis," *Perspect. Sci.*, vol. 8, pp. 293–297, Sep. 2016.

[62] V. Arnez-Paniagua, H. Rifai, S. Mohammed, and Y. Amirat, "Adaptive control of an actuated ankle foot orthosis for foot-drop correction," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 1384–1389, Jul. 2017.

[63] L.-F. Yeung, C. C. Y. Lau, C. W. K. Lai, Y. O. Y. Soo, M.-L. Chan, and R. K. Y. Tong, "Effects of wearable ankle robotics for stair and over-ground training on sub-acute stroke: A randomized controlled trial," *J. NeuroEng. Rehabil.*, vol. 18, no. 1, pp. 1–10, Dec. 2021.

[64] W. Meng, Q. Liu, Z. D. Zhou, Q. S. Ai, B. Sheng, and S. Q. Xie, "Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation," *Mechatronics*, vol. 31, pp. 132–145, Oct. 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957415815000501

[65] W. M. dos Santos and A. A. G. Siqueira, "Optimal impedance control for robot-aided rehabilitation of walking based on estimation of patient behavior," in *Proc. 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2016, pp. 1023–1028.

[66] R. Huang, Z. Pengl, H. Cheng, J. Hu, J. Qiu, C. Zou, and Q. Chen, "Learning-based walking assistance control strategy for a lower limb exoskeleton with hemiplegia patients," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 2280–2285.

[67] Z. Peng, R. Luo, R. Huang, T. Yu, J. Hu, K. Shi, and H. Cheng, "Data-driven optimal assistance control of a lower limb exoskeleton for hemiplegic patients," *Frontiers Neurorobotics*, vol. 14, p. 37, Jul. 2020.

[68] T. Lee, I. Kim, and Y. S. Baek, "Design of a 2DoF ankle exoskeleton with a polycentric structure and a bi-directional tendon-driven actuator controlled using a PID neural network," *Actuators*, vol. 10, no. 1, p. 9, Jan. 2021. [Online]. Available: https://www.mdpi.com/2076-0825/10/1/9

[69] S. Aole, I. Elamvazuthi, L. Waghmare, B. Patre, and F. Meriaudeau, "Improved active disturbance rejection control for trajectory tracking control of lower limb robotic rehabilitation exoskeleton," *Sensors*, vol. 20, no. 13, p. 3681, Jun. 2020. [Online]. Available: https://www.mdpi.com/1424- 8220/20/13/3681

[70] Y. Long, Z. Du, L. Cong, W. Wang, W. Dong, and Z. Zhang, "Active disturbance rejection control based human gait tracking for lower extremity rehabilitation exoskeleton," *ISA Trans.*, vol. 67, pp. 389–397, Mar. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0019057817300277

[71] R. Jiménez-Fabián and O. Verlinden, "Review of control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons," *Med. Eng. Phys.*, vol. 34, no. 4, pp. 397–408, May 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1350453311003092

[72] Y. Shao, W. Zhang, Y. Su, and X. Ding, "Design and optimisation of load-adaptive actuator with variable stiffness for compact ankle exoskeleton," *Mechanism Mach. Theory*, vol. 161, Jul. 2021, Art. no. 104323.

[73] C. Zhang, Y. Zhu, J. Fan, J. Zhao, and H. Yu, "Design of a quasi-passive 3 DOFs ankle-foot wearable rehabilitation orthosis," *Bio-Med. Mater. Eng.*, vol. 26, pp. S647–S654, Aug. 2015.

[74] M. I. Awad, D. Gan, A. Az-zu'bi, J. Thattamparambil, C. Stefanini, J. Dias, and L. Seneviratne, "Novel passive discrete variable stiffness joint (pDVSJ): Modeling, design, and characterization," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2016, pp. 1808–1813.

[75] T. Oba, H. Kadone, M. Hassan, and K. Suzuki, "Robotic ankle–foot orthosis with a variable viscosity link using MR fluid," *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 2, pp. 495–504, Apr. 2019.

[76] M. Hassan, K. Yagi, H. Kadone, T. Ueno, H. Mochiyama, and K. Suzuki, "Optimized design of a variable viscosity link for robotic AFO," in *Proc. 41st Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2019, pp. 6220–6223.

[77] B. Shah, D. McNally, K. Patel, S. Frone, and S. Sutaria, "Design and fabrication of an intuitive leg assist device to address lower extremity weakness," in *Proc. IEEE 37th Annu. Northeast Bioeng. Conf. (NEBEC)*, Apr. 2011, pp. 1–2.

[78] M. A. Aboamer, N. A. R. Mohamed, and B. Alrashide, "Low-cost electromechanical bionic model for foot drop gait disability," in *Proc. 2nd Int. Conf. Comput. Inf. Sci. (ICCIS)*, Oct. 2020, pp. 1–3.

[79] J. M. Font-Llagunes, U. Lugrís, D. Clos, F. J. Alonso, and J. Cuadrado, "Design, control, and pilot study of a lightweight and modular robotic exoskeleton for walking assistance after spinal cord injury," *J. Mech. Robot.*, vol. 12, no. 3, Jun. 2020, Art. no. 031008.

[80] K. A. Shorter, Y. Li, E. A. Morris, G. F. Kogler, and E. T. Hsiao-Wecksler, "Experimental evaluation of a portable powered ankle-foot orthosis," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBS)*, Aug. 2011, pp. 624–627.

[81] O. Ulkir, G. Akgun, and E. Kaplanoglu, "Mechanical design and analysis of a pneumatic ankle foot orthosis," in *Proc. Electr. Electron., Comput. Sci., Biomed. Eng. Meeting (EBBT)*, Apr. 2018, pp. 1–4.

[82] J.-C. Hong, S. Suzuki, Y. Fukushima, K. Yasuda, H. Ohashi, and H. Iwata, "Development of high-dorsiflexion assistive robotic technology for gait rehabilitation," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2018, pp. 3801–3806.

[83] S. J. Kim, Y. Na, D. Y. Lee, H. Chang, and J. Kim, "Pneumatic AFO powered by a miniature custom compressor for drop foot correction," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 8, pp. 1781–1789, Aug. 2020.

[84] S. J. Kim, J. Park, W. Shin, D. Y. Lee, and J. Kim, "Proof-of-concept of a pneumatic ankle foot orthosis powered by a custom compressor for drop foot correction," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2020, pp. 747–753.

[85] L. J. Salmeron, G. V. Juca, S. M. Mahadeo, J. Ma, S. Yu, and H. Su, "An untethered electro-pneumatic exosuit for gait assistance of people with foot drop," *Frontiers Biomed. Devices*, vol. 83549, Apr. 2020, Art. no. V001T09A009.

[86] C. M. Thalman, T. Hertzell, and H. Lee, "Toward a soft robotic ankle-foot orthosis (SR-AFO) exosuit for human locomotion: Preliminary results in late stance plantarflexion assistance," in *Proc. 3rd IEEE Int. Conf. Soft Robot. (RoboSoft)*, May 2020, pp. 801–807.

[87] P. Murphy, G. Adolf, S. Daly, M. Bolton, O. Maurice, T. Bonia, C. Mavroidis, and S.-C. Yen, "Test of a customized compliant ankle rehabilitation device in unpowered mode," in *Proc. 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug. 2014, pp. 3057–3060.

[88] Y.-L. Park, B.-R. Chen, N. O. Pérez-Arancibia, D. Young, L. Stirling, R. J. Wood, E. C. Goldfield, and R. Nagpal, "Design and control of a bio-inspired soft wearable robotic device for ankle–foot rehabilitation," *Bioinspiration Biomimetics*, vol. 9, no. 1, Jan. 2014, Art. no. 016007.

[89] O. Ulkir, G. Akgun, A. Nasab, and E. Kaplanoglu, "Data-driven predictive control of a pneumatic ankle foot orthosis," *Adv. Electr. Comput. Eng.*, vol. 21, no. 1, pp. 65–74, 2021.

[90] C. M. Thalman, J. Hsu, L. Snyder, and P. Polygerinos, "Design of a soft ankle-foot orthosis exosuit for foot drop assistance," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2019, pp. 8436–8442.

[91] Y.-L. Park, B.-R. Chen, D. Young, L. Stirling, R. J. Wood, E. Goldfield, and R. Nagpal, "Bio-inspired active soft orthotic device for ankle foot pathologies," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2011, pp. 4488–4495.

[92] J. Kwon, J.-H. Park, S. Ku, Y. Jeong, N.-J. Paik, and Y.-L. Park, "A soft wearable robotic ankle-foot-orthosis for post-stroke patients," *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2547–2552, Jul. 2019.

[93] H. Xia, J. Kwon, P. Pathak, J. Ahn, P. B. Shull, and Y.-L. Park, "Design of a multi-functional soft ankle exoskeleton for foot-drop prevention, propulsion assistance, and inversion/eversion stabilization," in *Proc. 8th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Nov. 2020, pp. 118–123.
[94] M. Manchola, D. Serrano, D. Gómez, F. Ballen, D. Casas, M. Munera, and C. A. Cifuentes, "T-FLEX: Variable stiffness ankle-foot orthosis for gait assistance," in *Proc. Int. Symp. Wearable Robot.*, in Biosystems & Biorobotics, vol. 22, 2019, pp. 160–164.
[95] A. Polinkovsky, R. J. Bachmann, N. I. Kern, and R. D. Quinn, "An ankle foot orthosis with insertion point eccentricity control," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2012, pp. 1603–1608.
[96] S. Rossi, F. Patanè, F. D. Sette, and P. Cappa, "WAKE-Up: A wearable ankle knee exoskeleton," in *Proc. 5th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics*, Aug. 2014, pp. 504–507.
[97] M. Moltedo, T. Baček, K. Langlois, K. Junius, B. Vanderborght, and D. Lefeber, "Design and experimental evaluation of a lightweight, high-torque and compliant actuator for an active ankle foot orthosis," in *Proc. Int. Conf. Rehabil. Robot. (ICORR)*, Jul. 2017, pp. 283–288.
[98] M. Moltedo, G. Cavallo, T. Baček, J. Lataire, B. Vanderborght, D. Lefeber, and C. Rodriguez-Guerrero, "Variable stiffness ankle actuator for use in robotic-assisted walking: Control strategy and experimental characterization," *Mechanism Mach. Theory*, vol. 134, pp. 604–624, Apr. 2019.
[99] B. Chen, B. Zi, Z. Wang, Y. Li, and J. Qian, "Development of robotic ankle–foot orthosis with series elastic actuator and magneto-rheological brake," *J. Mech. Robot.*, vol. 13, no. 1, Feb. 2021, Art. no. 011002.
[100] G. M. Gu, S. Kyeong, D.-S. Park, and J. Kim, "SMAFO: Stiffness modulated ankle foot orthosis for a patient with foot drop," in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, Aug. 2015, pp. 543–548.
[101] M. Sanchez-Manchola, D. Gomez-Vargas, D. Casas-Bocanegra, M. Munera, and C. A. Cifuentes, "Development of a robotic lower-limb exoskeleton for gait rehabilitation: AGoRA exoskeleton," in *Proc. IEEE ANDESCON*, Aug. 2018, pp. 1–6.
[102] K. Rodriguez, J. de Groot, F. Baas, M. Stijntjes, F. van der Helm, H. van der Kooijl, and W. Mugge, "Passive ankle joint stiffness compensation by a novel ankle-foot-orthosis," in *Proc. 7th IEEE Int. Conf. Biomed. Robot. Biomechatronics (Biorob)*, Aug. 2018, pp. 517–522.
[103] H. Yu, S. Huang, N. V. Thakor, G. Chen, S.-L. Toh, M. S. Cruz, Y. Ghorbel, and C. Zhu, "A novel compact compliant actuator design for rehabilitation robots," in *Proc. IEEE 13th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2013, pp. 1–6.
[104] H. Yu, M. S. Cruz, G. Chen, S. Huang, C. Zhu, E. Chew, Y. S. Ng, and N. V. Thakor, "Mechanical design of a portable knee-ankle-foot robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2013, pp. 2183–2188.
[105] Z. Zhou, Y. Sun, N. Wang, F. Gao, K. Wei, and Q. Wang, "Robot-assisted rehabilitation of ankle plantar flexors spasticity: A 3-month study with proprioceptive neuromuscular facilitation," *Frontiers Neurorobot.*, vol. 10, p. 16, Nov. 2016.
[106] H. Kim, S. Cho, and H. Lee, "Reliability of bi-axial ankle stiffness measurement in older adults," *Sensors*, vol. 21, no. 4, p. 1162, Feb. 2021.
[107] G. Zhu, X. Zeng, M. Zhang, S. Xie, W. Meng, X. Huang, and Q. Xu, "Robot-assisted ankle rehabilitation for the treatment of drop foot: A case study," in *Proc. 12th IEEE/ASME Int. Conf. Mech. Embedded Syst. Appl. (MESA)*, Aug. 2016, pp. 1–5.
[108] M. M. Mirbagheri, C. Patel, and K. Quiney, "Robotic-assisted locomotor training impact on neuromuscular properties and muscle strength in spinal cord injury," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2011, pp. 4132–4135.
[109] D. Veneri, "Combining the treatment modalities of body weight support treadmill training and thera-band: A case study of an individual with hemiparetic gait," *Topics Stroke Rehabil.*, vol. 18, no. 4, pp. 402–416, Jul. 2011.
[110] C.-J. Hsu, J. Kim, R. Tang, E. J. Roth, W. Z. Rymer, and M. Wu, "Applying a pelvic corrective force induces forced use of the paretic leg and improves paretic leg EMG activities of individuals post-stroke during treadmill walking," *Clin. Neurophysiol.*, vol. 128, no. 10, pp. 1915–1922, Oct. 2017.
[111] F.-Z. Low, J. H. Lim, J. Kapur, and R. C.-H. Yeow, "Effect of a soft robotic sock device on lower extremity rehabilitation following stroke: A preliminary clinical study with focus on deep vein thrombosis prevention," *IEEE J. Transl. Eng. Health Med.*, vol. 7, pp. 1–6, 2019.
[112] A. V. Krishna, S. Chandar, R. S. Bama, and A. Roy, "Novel interactive visual task for robot-assisted gait training for stroke rehabilitation," in *Proc. 7th IEEE Int. Conf. Biomed. Robot. Biomechatronics (Biorob)*, Aug. 2018, pp. 402–407.
[113] M. M. Mirbagheri, X. Niu, M. Kindig, and D. Varoqui, "The effects of locomotor training with a robotic-gait orthosis (Lokomat) on neuromuscular properties in persons with chronic SCI," in *Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Aug. 2012, pp. 3854–3857.
[114] V. Arnez-Paniagua, H. Rifaï, Y. Amirat, M. Ghedira, J. M. Gracies, and S. Mohammed, "Adaptive control of an actuated ankle foot orthosis for paretic patients," *Control Eng. Pract.*, vol. 90, pp. 207–220, Sep. 2019.
[115] T. Kikuchi, S. Tanida, T. Yasuda, and T. Fujikawa, "Development of control model for intelligently controllable ankle-foot orthosis," in *Proc. 35th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Jul. 2013, pp. 330–333.
[116] D. Adiputra, M. A. A. Rahman, U. Ubaidillah, S. A. Mazlan, N. Nazmi, M. K. Shabdin, J. Kobayashi, and M. H. M. Ariff, "Control reference parameter for stance assistance using a passive controlled ankle foot orthosis—A preliminary study," *Appl. Sci.*, vol. 9, no. 20, p. 4416, Oct. 2019.
[117] V. Arnez-Paniagua, H. Rifai, Y. Amirat, S. Mohammed, M. Ghedira, and J. M. Gracies, "Modified adaptive control of an actuated ankle foot orthosis to assist paretic patients," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 2311–2317.
[118] E. Pourhoseingholi and H. Saeedi, "Role of the newly designed ankle foot orthosis on balance related parametersin drop foot post stroke patients," *J. Bodywork Movement Therapies*, vol. 26, pp. 501–504, Apr. 2021.
[119] J. Ward, T. Sugar, A. Boehler, J. Standeven, and J. R. Engsberg, "Stroke survivors' gait adaptations to a powered Ankle–Foot orthosis," *Adv. Robot.*, vol. 25, no. 15, pp. 1879–1901, Jan. 2011.
[120] J. Bae, S. M. M. De Rossi, K. O'Donnell, K. L. Hendron, L. N. Awad, T. R. T. D. Santos, V. L. De Araujo, Y. Ding, K. G. Holt, T. D. Ellis, and C. J. Walsh, "A soft exosuit for patients with stroke: Feasibility study with a mobile off-board actuation unit," in *Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR)*, Aug. 2015, pp. 131–138.
[121] L. N. Awad, P. Kudzia, D. A. Revi, T. D. Ellis, and C. J. Walsh, "Walking faster and farther with a soft robotic exosuit: Implications for post-stroke gait assistance and rehabilitation," *IEEE Open J. Eng. Med. Biol.*, vol. 1, pp. 108–115, 2020.

NOUR AL-RAHMANI received the B.S. degree in biomedical engineering from Khalifa University, Abu Dhabi, United Arab Emirates, in 2020, where she is currently pursuing the M.S. degree in biomedical engineering.

She worked an internship at the Institute of BioRobotics, Scuola Superiore Sant'Anna, Pontedera Pisa, Italy. She worked as a Teaching Assistant in various courses with the Department of Biomedical Engineering. Her current research interests include variable stiffness actuators, compliant ankle-foot-orthosis designs, and human–robot interaction.

DHANYA MENOTH MOHAN received the bachelor's degree in mechatronics engineering from Anna University, India, and the master's degree in computer control and automation from Nanyang Technological University, Singapore. She has held research positions at Nanyang Technological University and Rolls-Royce Corporate Laboratory in Singapore for several years and was involved in both academic and industrial research and development projects. She is currently a Research Associate at the Healthcare Engineering and Innovation Center, Khalifa University, Abu Dhabi. Her research interests include mechatronic systems, robotics control, biomechanics, and machine learning.

MOHAMMAD I. AWAD (Member, IEEE) received the master's degree in mechanical engineering from the Jordan University of Science and Technology, in 2011, and the Ph.D. degree in robotics from Khalifa University, in 2018. He had established his career starting in 2007 in research and development in robotics and automation field in both industry and academic as he worked as an Industrial Consultant as well as a Teaching and Research Assistant at the Jordan University of Science and Technology. In 2010, he had joined the King Abdullah II Design and Development Bureau (KADDB) and served as a Product Development Engineer. He is currently a Postdoctoral Research Fellow with the Center of Autonomous Robotics Systems (KUCARS) and the Healthcare Engineering and Innovation Center (HEIC), Khalifa University. Since 2012, he has been involved in several research projects in variable stiffness actuators, compliant manipulation, haptics interfaces design, and rehabilitation exoskeletons. He is a member of ASME, IEEE RAS, and IET.

SABAHAT ASIM WASTI received the bachelor's degree in medicine and Surgery from the Khyber Medical College, Peshawar, Pakistan. He moved to the U.K. for postgraduate studies, in 1984. After obtaining the membership of Royal College of Ireland, he completed Rehabilitation Medicine training at Leeds Teaching Hospital. He then became a Consultant in rehabilitation medicine at Sheffield Teaching Hospitals, Sheffield, U.K., where he served for nearly nine years before moving to the United Arab Emirates to take up the position of a Senior Consultant Post in physical medicine and rehabilitation at Sheikh Khalifa Medical City, in 2007. He is currently a Staff Physician with the Neurological Institute, Cleveland Clinic Abu Dhabi. He has served in both the public and private sectors in the United Arab Emirates and spearheaded the development of rehabilitation services in both. He served on as a British Society of Rehabilitation Representative in Consensus Reference Group for Multiple Sclerosis Guidelines, commissioned by the National Institute of Clinical Excellence. He is recognized for promoting the cause of neurorehabilitation in particular and widely respected by his peers. He is well known for his views on cultural and ethical variances and the implications of these on neurorehabilitation. He also serves as a Regional VP, WFNR (Gulf Region), Chair Service Development SIG, and the Co-Chair Ethics SIG, WFNR. He has also served as the chair for several conferences and frequently delivers invited lectures.

IRFAN HUSSAIN received the B.E. degree in mechatronics engineering from Air University, Pakistan, the 2nd level master's degree in automatica and control technologies from the Politecnico di Torino, Italy, the M.S. degree in mechatronics engineering from the National University of Sciences and Technology, Pakistan, and the Ph.D. degree in robotics from the University of Siena, Italy. He was a Postdoctoral Researcher at the Robotics Institute, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates. He also worked as a Postdoctoral Researcher at Siena Robotics and System Laboratory (SIRSLab), Italy. He worked as a Research Assistant at Gyeongsang National University, South Korea, from 2012 to 2013. He was an Intern Engineer with Centro Ricerche Fiat (CRF), Italy. He worked as an Assistant Manager of engineering with Trojans, Pakistan, from 2008 to 2011. He is currently an Assistant Professor of robotics and mechanical engineering at Khalifa University. His research interests include variable stiffness actuators, extra robotic limbs, medical robotics, wearable haptics, grasping, soft robotics, exoskeletons, and prosthesis. He was an Associate Editor of the RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)-18.

KINDA KHALAF received the B.S. *(summa cum laude)* and M.S. (Hons.) degrees in mechanical engineering and the Ph.D. degree in biomechanics/computational biomechanics, specializing in biomaterials, and dynamic modeling and control from The Ohio State University (OSU), USA. She has held faculty appointments in engineering and medicine at several prestigious universities, including the University of Miami and the American University of Beirut and currently works as an Associate Chair with the Department of Biomedical Engineering, Khalifa University, Abu Dhabi. She has numerous publications in the areas of musculoskeletal biomechanics, computational biomechanics, and neuromusculoskeletal modeling and control. She is on the list of International Who Is Who of Professionals. She is a Founding Member of the IEEE EMBC in the United Arab Emirates and a member of many professional organizations. She has been awarded various awards and honors, including the prestigious National Merit Scholar and Khalifa Award for Education.