

The Current Design, Development, and Challenges of Ankle(-foot) Exoskeletons

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ABSTRACT

The ankle(-foot) exoskeleton focuses on restoring or enhancing movement and mobility in the ankle musculature for individuals with neurological or physical impairments. Beyond mobility, it can improve the functional alignment and support of the skeletal structure. Whether through the integration of artificial intelligence (AI), advanced mechanical designs, or innovative materials, the ankle-foot exoskeleton continues to evolve, significantly improving patient outcomes and overall quality of life. This review outlines the key developments of the ankle-foot orthosis and the various ways it has improved and continues to improve over time in benefiting human life. Additionally, it not only focuses on active exoskeletons but also passive exoskeletons that have been used in the last decade, which could be used as references to find ways to improve the device. Moreover, it outlines the limits and challenges one might encounter in ankle exoskeleton construction, adaptation, or research.

INTRODUCTION

An ankle-foot exoskeleton is a wearable mechanical device designed to improve and assist with the user's lower limb functions. It is most specifically in areas around the ankle joint to assist with movement and rehabilitation (1). These devices are able to detect and process the movement and the anatomy of a human limb, which allows an effective interaction between the user and the exoskeleton device (2). The ankle-foot exoskeleton comes in different types, divided into three categories based on the usage of power; passive, quasi-passive exoskeleton, and powered exoskeleton, which are all able to provide different levels of help (3). Ankle-foot exoskeletons have been designed to become more lightweight to promote natural and safe interactions between the device and the users (4). Exoskeleton technologies are shifting from full-body systems to more specific joints, which allows these devices to become more practical and cost-effective for rehabilitation (5).

The ankle-foot exoskeleton is a crucial medical device that assists people, commonly the elderly or people who have suffered injuries, with walking and even basic movements in their legs. Ankle injuries are

common because it is one of the most injury-prone joints (6). The ankle-foot exoskeleton is able to assist with those struggles by helping create movement, improving coordination, and performance (7, 8). With the current improvements of this medical device, the exoskeleton is adapting to a more natural human dynamic and comfort in human-robot interactions (9). Overall, the importance of ankle-foot exoskeletons can assist in restoring function in disabled or damaged ankle joints.

The ankle-foot exoskeleton is beneficial in several aspects, but most importantly in improving function in the joint. Specifically, when a person suffers injuries, neurological or physical damage, or the joint becomes weak with age, the exoskeleton can provide extra support or restore function (10, 11). Furthermore, the benefits of an exoskeleton provide enhancement in walking function, reduced metabolic cost, and improve a user's performance overall (1, 12).

Recently, rehabilitation faces several problems, which include the difficulty of emulating natural ankle joint movement, as the axes in the joint must be adaptable to each patient and various pathologies (13). Actuators, which play an important role in aiding torque during gait training, are essential but challenging to optimize. The weight of the powered ankle exoskeleton is also a concern because it must remain below 1.25% of the user's body weight per foot for comfort (14). Existing wearable ankle exoskeleton models only assist with dorsiflexion and plantarflexion, while research on inversion and eversion assistance is lacking (15). Experimental results from biomechanical simulations fall short of predictions because of unmodeled kinematic and stride adaptations (16).

Ankle exoskeletons can significantly improve the efficiency of gait rehabilitation by several factors. They can effectively reduce the metabolic cost of walking by using positive power from the ankle joint during the push-off phase. This mimics ankle extension and saves energy, causing the patient to have an easier effort of moving (17). Along with power assistance, the ankle exoskeleton can aid the process of walking for patients with foot-drop by actively facilitating ankle dorsiflexion for foot clearance during the swing phase. This, in turn, can minimize foot slaps at initial contact, which is beneficial, as it helps avoid the patient's tripping and falling (14).

Methodology and Literature Review Search

Our review paper was written using Google Scholar, PubMed, Reaxys, ScienceDirect, and WEB of Knowledge. Also, the studies included in this review were published primarily between 2012 and 2024, with emphasis on studies from the most recent decade. Earlier publications were used only when they provided foundational information related to ankle-exoskeleton design, control, biomechanics, and/or rehabilitation. We included articles when they mentioned ankle or ankle-foot exoskeleton design, control strategies, gait assistance, rehabilitation, biomechanics, human-exoskeleton interaction, energy expenditure, stability, and/or performance. Furthermore, we included publications that mentioned lower-limb exoskeletons, ankle-foot orthoses, and prosthetic systems. Articles that only focused on upper-limb exoskeletons or lower-limb devices that were not related to ankle function were excluded.

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Articles that did not provide a good amount of information related to the design, control, biomechanics, or performance of ankle-foot exoskeletons were also not included. Search terms included “ankle exoskeleton,” “ankle-foot exoskeleton,” “lower-limb exoskeleton,” “ankle rehabilitation,” “powered ankle exoskeleton,” “passive ankle exoskeleton,” and “exoskeleton gait assistance”.

2. Considerable Factors in the Design of Ankle-Foot Exoskeletons

2.1. Human-Centered Design

This control system is initialized based on the most common requirements of a “standard human model,” which then evolves during its performance by effectively using the feedback collected from the wearer to support different body shapes and assistance needs (13). Ankle exoskeletons with different degrees of freedom (DoF) impact gait kinematics and stability (18). They occur when the joint is taken beyond its functional range of motion, and they can be present in athletes as well as in people living a sedentary lifestyle (2). Moreover, bone fractures or neurological disabilities caused by strokes and other serious disorders make the ankle rehabilitation process long and torturous (19). “Human-in-the-loop” (HIL) optimization has been employed as a method to tune assistive device parameters on a subject-specific basis (Figure 1) (7). It minimizes a physiological cost function while an individual is using the device (20). A compact, lightweight prosthesis emulator system (a high-speed data loop that tells the test robot how it is interacting with the ground and the user) with high torque accuracy, fast response, and precise center of pressure control meets the biomechanical requirements of the biological ankle. The prosthesis emulator system is aimed at enhancing balance and reducing energy expenditure, supporting the advancement of autonomous prosthetic devices to improve mobility and quality of life in individuals with lower-limb amputation (21). Additive manufacturing (AM), or the industrial process for three-dimensional (3D) printing, has become increasingly prevalent in the development of custom prosthetic devices for individual patients, thereby improving patient satisfaction (22). An ankle exoskeleton that uses a data-driven kinematic model to continuously estimate the phase, phase rate, stride length, and ground incline states during locomotion, which matches human torques observed in a multiactivity database of ten able-bodied subjects (23).

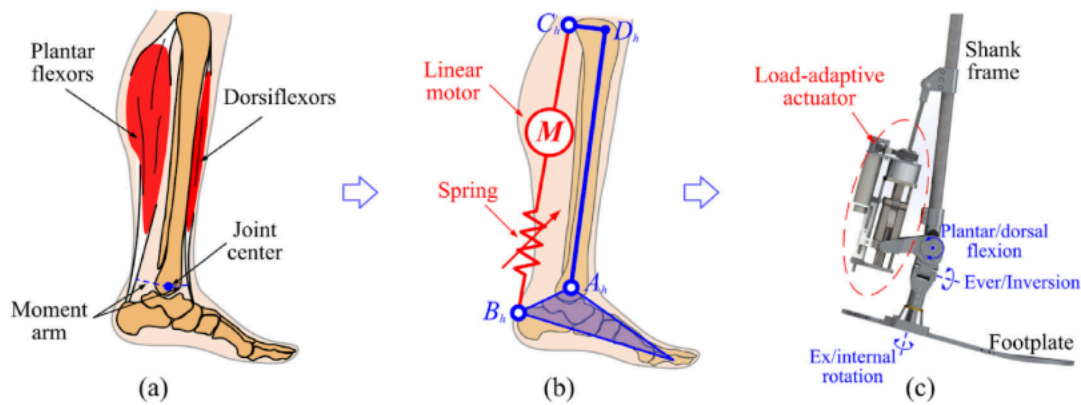


Figure 1. Conceptual design of the ankle exoskeletons. (a) musculoskeletal model and (b) equivalent mapping model of human ankle joint; (c) the CAD model of the ankle exoskeleton (48).

2.2. The Mechanical Components of Ankle Assistive Devices

The mechanical components of ankle assistive devices are designed to help with joint movement while attempting to reduce user discomfort. Some designs include brushless DC motors that bidirectionally actuate each ankle joint through a chain-to-cable transmission system (Figure 2). This allows for precise torque application based on the real-time approximations of the biological ankle moment (17). Some mechanical systems can reduce the physical burdens that are on the user by positioning the motor and driver off-board and linking them to the wearable unit through a Bowden cable. This is able to help lower the inertia and allows the joint to be able to move in a more natural way (24). Some other designs take passive mechanical routes. They integrate a pneumatic artificial muscle (PAM) aligned with the Achilles tendon, which releases and stores energy during movement. The sequencing mechanism controls the timing of the release to support gait phases (25). In the powered ankle exoskeletons, linear actuators such as motor-driven ball screws combined with a series of elastic components are used to enhance the propulsion during heel lift and push-off. These systems include safety features like backdrivability and multi-loop control so they can ensure smooth and adaptive support (26).

2.2.1 The Type of Actuator and Motor

Ankle exoskeletons use various actuator types, which include pneumatic muscle actuators (PMAs), a series of elastic actuators (SEAs), a variable stiffness actuator (VSA), motor actuators, and hydraulic actuators, designed to assist plantar flexion, dorsiflexion, or both (14). SEAs are commonly chosen when required stability, while electric motors provide strong torque, and artificial muscles or Bowden cables help reduce weight (27). Electric actuators deliver power through a transmission system and are often part of self-contained devices that have onboard power and control. Pneumatic actuators use recycled exhaust

gas between flexion cycles, while hydraulic actuators, while powerful, are limited due to the difficulty of the body (28).

Load adaptive actuators incorporate nonlinear springs to adjust stiffness based on the external load and joint angle (29, 30). SEAs and VSAs dominate current designs, though the nonlinear torque-to-weight relationship and the lack of standard technical data make it hard to see the optimal configurations. Many actuator systems rely on trial-and-error design, and choosing the right elastic component type, and spring stiffness and spring stiffness remains a challenge (31).

2.3. Sensors and Controllers

The ankle exoskeletons had three major components in torque: the amount of weight it can sustain, the propulsive plantar flexor torque, and the swing (14). Additionally, the sensing that is applied in an exoskeleton is utilized for joint torque prediction from multiple channels of electromyography (EMG) signals (Figure 2) (32). Specifically, the tendon-driven flexible exoskeleton (T-FLEX) utilizes an inertial sensor and a statistical algorithm to estimate the gait accurately and quickly (Figure 4). Other research, like Leal-Junior et al., references the plastic optical fiber inertial measurement unit (POF-IMU) sensor, using angular velocities measured by the inertial measurement unit (IMU) gyroscope to compensate for the physical phenomenon of the plastic optical fiber (POF) sensor (33). Other parts, such as the composition of the skeleton, like the adaptive myoelectric controller for robotic ankle exoskeletons, adjust actuation gain in real time based on users' muscle signals. This personalized approach aims to enhance walking efficiency by reducing metabolic cost and improving user comfort. Overall, the sensing and the automation mechanics of the ankle exoskeleton try to aid in the improvement of comfort, mobility, and accessibility of using the device, so it adapts to its environment (34).

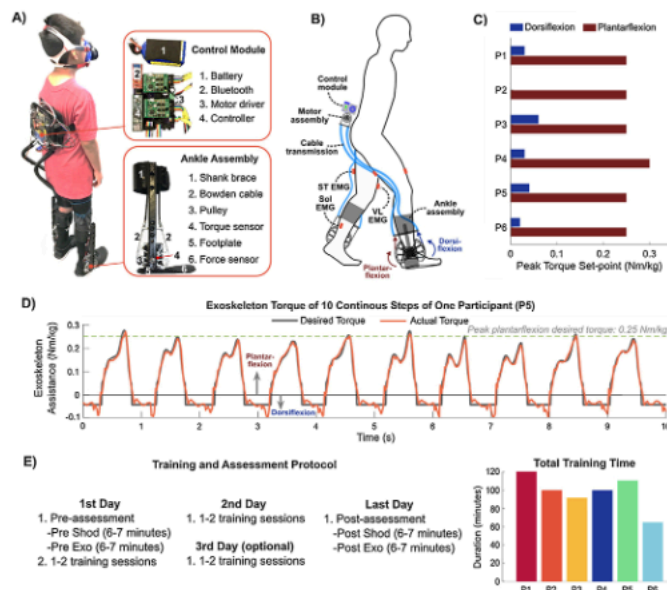


Figure 2. Experimental setup and design. A) Exoskeleton ankle assembly and control module. B) Electromyography (EMG) of the soleus (Sol), vastus lateralis (VL), and semitendinosus (ST) was monitored bilaterally when participants walked with the ankle exoskeleton. C) Plantarflexion and dorsiflexion torque set-points for each participant. D) Desired and actual torque profiles of ten continuous steps from one participant. E) Experimental protocol for training and assessment and total training time (ranged from 65 to 120 minutes) with the exoskeleton across the cohort (51).

2.3.1. Force Measurement

Lower limb exoskeleton robots help with walking movements through mechanical force by identifying the wearer's walking intention. When the exoskeleton robot is lightweight and comfortable to wear, the stability of walking increases, and energy can be used efficiently (27). Bougrinat et al. presented in this paper a way to develop an ankle exoskeleton with a minimum added distal mass while it can provide at least 30 Nm of assistive plantarflexion torque. The proposed exoskeleton uses Bowden cables to transmit the mechanical force from the actuation unit to the carbon fiber struts fixed on the boot. The low added distal mass is the main design characteristic of both powered and passive ankle exoskeletons, which have demonstrated an improvement in walking efficiency (17). Shifting ankle-foot gearing regulates the speed of plantarflexor (i.e., calf muscle) contraction, which influences the economy of force production (35). Active or powered prostheses can generate an external force through an actuator and therefore can mimic intact limb functional characteristics (2,11,36). More recently, advanced methods to adapt the position/torque-current location, such as the knee or the ankle, and automatically detect terrains or locomotion modes have become more common, but these are largely still limited to laboratory settings (37).

2.3.2 Angle Measurement

An understanding of ankle anatomy and biomechanics was essential to define travel distances and joint rotation angles for replicating natural gait patterns in the exoskeleton design (Figure3) (6). The exoskeleton incorporated three degrees of freedom (3DOF); the rehabilitation exoskeleton can move, rotate, and control the foot in all three distinct geometric planes of the foot in motion, allowing control of ankle joint movement across all planes. This facilitated smoother, more natural motion, contributing to more effective rehabilitation (38). To ensure appropriate assistive torque during neutral standing, the actuator rope was adjusted for each participant so that the resting spring length corresponded to an ankle angle 13° more plantarflexed than neutral. This configuration provided approximately 5–10% of the total ankle torque measured during standing balance tasks. The ankle's spring-like behavior was modeled using quasi-stiffness, calculated as the local slope of the moment-angle curve at various phases of the gait cycle. This metric captured the combined influence of tendons, muscle (active and passive), and connective tissues acting across the joint (39). To estimate joint angles while walking, IMU sensors were placed on the thigh and shank. Gyroscope and accelerometer data were collected as participants walked at 1–2.5 km/h while wearing the exoskeleton. A feedforward neural network, implemented in MATLAB, used

speed-dependent weights to estimate the angles of the knee, talocrural, and subtalar joints in real time (40).

2.3.3. Speed, Direction, and Actuation Timing During Movement

Ankle exoskeleton performance is related to how it manages speed, direction, and actuation timing during movement (41, 42, 43). Passive and active designs must consider different parameters such as speed, acceleration, and translation movements to support dorsiflexion and plantarflexion effectively (41, 44). Devices usually focus actuation on the talocrural axis while allowing passive motion at the subtalar joint, using mechanisms like ball-screws and brushless motors to support controlled motion (44). The study shows that the timing and magnitude of assistive torque significantly affect gait stability, with late push-off timing that reduces variability, while high power levels increase instability (42). Additionally, walking speed, ground irregularities, and body weight influence the mechanical stiffness of the ankle, which makes it require systems that can adapt to resistance accordingly (45). To meet these demands, modern exoskeletons must implement adaptive controllers that respond to changing walking speeds and user-specific gait patterns (43).

3. Types of Ankle Exoskeletons

3.1. Passive Ankle Exoskeleton Device

Passive exoskeletons (passive ankle foot orthosis) are suitable for augmentation on the ankle joint as the power on the ankle has a negative period where energy can be stored and a positive period where the stored energy can be released (17). Purely passive exoskeletons are lightweight and energy-neutral and are those that do not rely on an external power source. Instead of drawing energy out of the gait cycle itself, one ankle exoskeleton has been shown to reduce the metabolic cost of human walking using purely passive elements (46, 47). The one-way clutch exoskeletons mimic the Achilles tendon and function and assist in jumping (48). Passive prostheses rely on a fixed spring and offer basic functionality, and are commonly used as they are inexpensive and implement cushioning during gait. Unfortunately, those passive ankle-foot prostheses are still unable to mimic able-bodied performance during daily activities as they fail to provide sufficient range of motion and net positive joint work (36).

In kinematics, motor control, and energetics, researchers have developed design and control principles to reduce the energetic demand of walking and improve the quality of gait (49). Spring stiffness needs to be optimized for the exoskeletons to reduce muscular effort (50). The TD is a prototype in the development process of an innovative passive ankle prosthesis classified as energy storing and releasing foot (Figure 4). The novelty of the foot compared to most prostheses currently being used by people with an amputation is the articulating ankle joint (36).

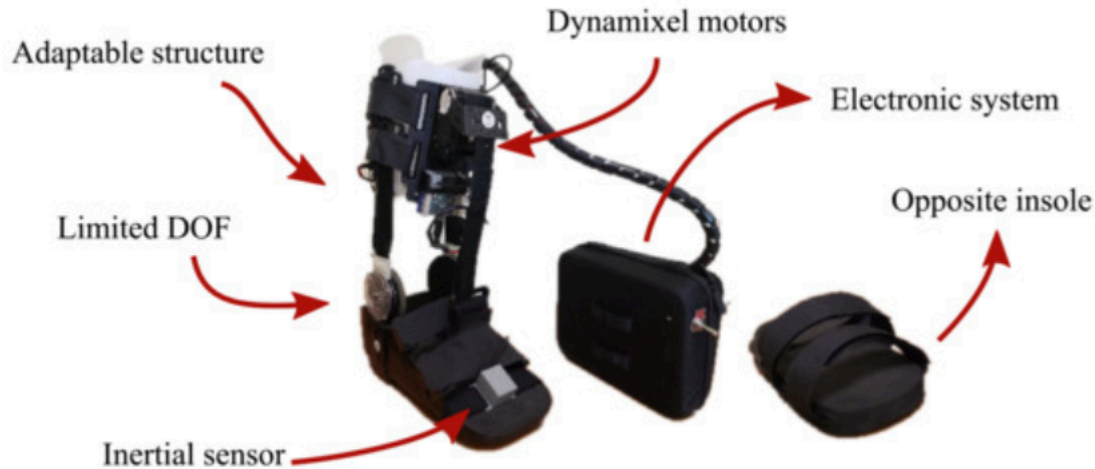


Figure 4. The actuation system of the T-FLEX exoskeleton was implemented on the passive orthotic structure. The insole of the left part is added to the non-paretic limb to compensate for the effect due to the device's use (24).

3.2. Designs, Systems, and Applications

Active (powered) ankle exoskeletons are wearable robotic devices that are designed to assist with joint flexion and extension by applying controlled forces or torques (51). These devices include rehabilitation systems like AssistOn-Ankle, which use series-elastic actuation and adaptable kinematics to enhance user control and familiarity during treatment (52). Designs often rely on electric actuators with belt, Bowden cable, or harmonic drives, and combine passive energy elements to improve joint performance (45). A common classification splits active ankle devices into prostheses, orthoses, rehabilitation robots, and powered exoskeletons, which are often used in clinical rehab settings to support repeated walking exercises for patients who suffer from neurological conditions (53, 54). Mobile versions can help with plantarflexion, lower muscle activity, and maintain high torque tracking over prolonged periods, even outside treadmill environments (55). Because these systems provide positive work, they require precise control interfaces that ensure efficient motion while still balancing weight and power output (56).



Figure 5. Demonstration of the Dephy ExoBoot (DpEp45 exoskeleton which shows a carbon fiber footplate combined into an ankle-high boot. The footplate is attached to a shank-mounted assembly consisting of a unidirectional actuator (51).

3.3. Smart Ankle-Foot Exoskeleton

Smart ankle-foot exoskeletons (ankle-foot orthoses (AFOs)) are engineered to be lightweight, compliant, and adaptable. Their design incorporates adjustable carbon fiber plates and cuffs that align with the user's ankle joint axis, which minimizes unwanted forces and enhances comfort during use (57). This compact and adaptable configuration allows the smart AFO to function autonomously. Evidence from the related ankle interventions, like functional electrical stimulation and elastic orthoses, suggests that enabling faster walking speeds post-stroke can add to the benefits of propulsion-targeting smart AFOs (58).

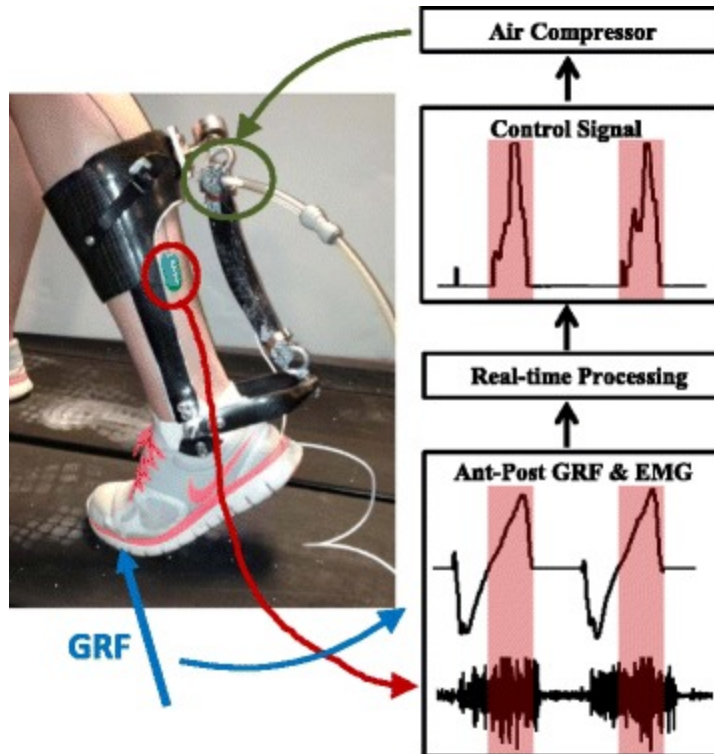


Figure 6. Illustration of a proportional myoelectric propulsion (PMP) controlled ankle exoskeleton. Soleus electromyography EMG and anterior-posterior ground reaction force (GRF) signals are used to regulate magnitude and timing of plantarflexion assistance, activated only during stance when an anterior GRF is present (highlighted region) (69).

Optimizing the mass and mass distribution of powered ankle-foot orthoses is important for accurately mimicking natural joint kinetics, reducing net joint moments and overall muscle forces, and preventing muscle fatigue or disuse by considering individual muscle activity (59). Additionally, actuator stiffness and the timing of push-off onset significantly affect device performance and the metabolic cost of walking. Stiffer actuators and earlier push-off timings tend to reduce stance time but require longer adaptation periods for users (60). The performance of smart AFOs depends on multiple factors related to their specific actuation setups, making direct comparisons across different studies challenging (61).

4. Application of Devices

4.1. Rehabilitation/Physical Therapy

In early research, the purpose of ankle rehabilitation robot research is simply to lose weight and to fit the different demands of training modes. A bed-type robot and an exoskeleton robot have been developed,

aiming at multi-joint coordination training (62). The device for rehabilitation is significant as diseases such as stroke and spinal cord injuries can cause muscle weakness, spasticity, poor control of ankle joint movements, or even deformity (8, 63). Overground gait training with a powered ankle exoskeleton improves walking speed, stride length, and muscle activation in cerebral palsy (CP) by assisting plantar and dorsiflexion, increasing ankle power and gait efficiency (64).

Untethered ankle exoskeleton assistance influences balance-related gait parameters in older adults without compromising stability, supporting further investigation for enhancing mobility while minimizing fall risk (65). Elastic ankle exoskeletons can mitigate age-related declines in walking efficiency by optimizing muscle operating lengths and lowering metabolic cost (66). Dual-mode ankle exoskeletons can potentially assist as a mobility aid for acute high-intensity activities and resistance, having potential as a functional gait training tool (67). It was found that devices such as an active prosthesis can enhance amputees' quality of life (Figure 5) (68). Short-term use may reduce energy cost and could facilitate greater accumulation of walking exercise and improve mobility, particularly for highly impaired individuals (69, 70).

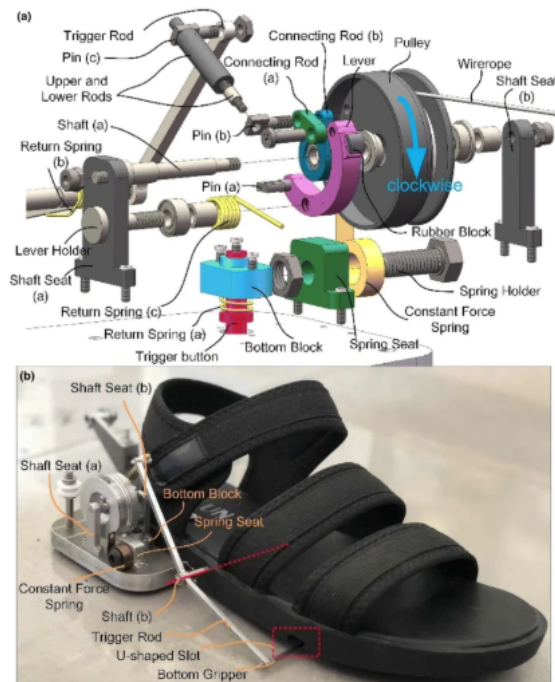


Figure 7. (a) Schematics showing the assembly structure of the clever clutch. (b) Prototype of the proposed Powered Ankle-Foot Exoskeleton (64).

4.2 Industrial and Occupational Applications

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For industrial applications, these exoskeletons help reduce fatigue and strain from prolonged standing or walking. Innovations in actuators and power systems are making these exoskeletons more comfortable and effective for both rehabilitation and industrial applications (71). Passive exoskeletons are effective in industrial work, rehab, elderly care, military, and sports (72). Robotic orthoses (hereon referred to as orthoses) have the potential to provide effective rehabilitation because they are computer-controlled mechanical devices that are worn in parallel with the body and are designed to actively assist the user in moving their impaired limbs through a series of exercises (73). The potential of the exoskeleton in clinical applications includes its cost-effectiveness, ease of use, and high accuracy of movement control to make this device a promising solution for restoring the functions of the lower extremities in patients (74). With appropriate risk mitigation strategies, adequate standards, comprehensive reporting of adverse events, and regulatory oversight, powered exoskeletons may one day allow individuals with gait disabilities to safely and independently ambulate (75).

5. Challenges and Future Perspectives

5.1. Technological Limitation

Current powered exoskeletons face major limitations such as heavy motors and battery packs, short battery life, and bulkiness, making them difficult to wear and limiting user independence (47, 11, 76). Many designs do not adapt well to uneven terrain, which causes skin irritation, gait instability, and increased energy use (76). Passive exoskeletons address some of these issues by drawing energy from the user's gait, but the understanding of how exoskeletons reduce metabolic cost remains complex because of the nonlinear interaction between human and machine (77, 78). Additionally, rigid, complex structures, lack of adduction-abduction support, and poor user-centered design continue to limit widespread acceptance and commercialization (13).

Technological and biomechanical challenges continue in accurate control of tuning, comfort, and safety, and the ability to customize one's own movement for diverse users (79). Issues like misalignment, inaccurate motion tracking, and interface discomfort from deformable human tissues end up complicating effective design (78). Current modeling techniques like inverse dynamics often underestimate actual muscle work, while stability proxies like hop height may not capture true balance (80, 57). Moreover, preset motion patterns can conflict with users' natural gait adaptations, which stresses the need for more flexible and individualized systems (81). These technological limitations hinder exoskeleton performance, comfort, and user satisfaction.

5.2 Medical Limitation

While it is true that ankle exoskeletons have great effectiveness in rehabilitation, their effectiveness is limited by medical factors. Post-stroke patients often experience difficulties in walking, which makes gait rehabilitation important to them. Devices such as unpowered ankle-foot orthosis (AFOs), powered

platforms, and portable powered exoskeletons are all examples that can support and help with recovery (82). It is shown that passive exoskeletons can reduce the metabolic costs by about 7% at moderate speeds; however, the stiffness tuning of the exoskeleton is crucial, as the benefit of the exoskeleton is mostly speed- dependent, and it may reduce under varying gait conditions (40). A limitation, such as patient-specific factors, is a huge factor in limiting the effectiveness of the exoskeleton, as exoskeletons are designed to be able to fit and function properly to align with the patient's biomechanics. If an exoskeleton cannot fit and align with the patient, it could possibly increase difficulty in movement (83). In addition, more limitations are placed as studies that are conducted on young and healthy adults; this could limit the generalization of the results (84). All this research can tell us that while the ankle exoskeleton could help with the outcomes in rehabilitation, its effectiveness could possibly have a limitation.

5.3. Future Perspective

Modern ankle exoskeleton technology has made significant progress but still faces important limitations. Current control systems often rely on simple sensors like a single heel strike detector, which limits robustness (17). Future improvements may include multisensory fusion and advanced torque control techniques. Additionally, the use of innovative materials like thermoplastics and carbon fiber could lead to lighter, stronger, and more flexible designs that may enhance energy efficiency and prevent muscle atrophy (76). Optimization of exoskeleton mass and alignment, especially for devices acting simultaneously on the knee and ankle, is crucial for improving metabolic cost and user comfort (85).

Research efforts should focus on enhancing simulation models to include 3-D kinematic adaptations and better metabolic cost predictions, accelerating development cycles (16, 86). Experimental characterization combined with iterative design and prototyping will be important to advance functionality and performance in real-world settings (87, 88). Evaluation of metrics that consider symmetry, coordination, ergonomics, stability, and safety is essential for meaningful comparisons and improvements (89). Additionally, understanding human-robot interaction through data will help in achieving better adaptability and integration (90). Expanding studies on diverse tasks and exploring the muscular and postural effects of exoskeleton use will provide better insights into optimizing assistive technologies for everyday and occupational activities (91).

5.3.1 Limitations of this Review

This review has methodological limitations. Due to the use of a non-systematic search approach, the selection of studies may have demonstrated publication bias and may not have covered all relevant discussion regarding the development of ankle(-foot) exoskeletons. Publication bias may have influenced the given evidence, including the technological and medical limitations of the devices reviewed.

5.3.2 Gait Improvement

The gait control method has been used in lower-limb exoskeletons to assist the user to move according to a predefined trajectory (25, 26). With the predefined gait, a classification algorithm was developed to control the exoskeleton for rehabilitation (27). Based on the zero moment point method, a gait adjustment method was proposed to improve the stability of the stance leg during walking (28, 92). During gait, the human ankle both bends with ease and provides push-off forces that facilitate forward motion (93). The system utilized force sensors to identify gait phases and used motion sensors to measure leg tilting angle and leg angular velocity for classifying walking conditions in real-time for the current step. It was designed as a gait training device to facilitate stroke patients in varying terrains according to their walking intention (94). Powered exoskeletons influence neuromuscular patterns, offering insights into gait modulation and potential therapeutic benefits (95). A recent study has shown that the metabolic rate of human walking can be reduced by a lightweight elastic ankle exoskeleton (48).

CONCLUSION

Ankle-foot exoskeletons or ankle-foot orthoses (AFOs) have improved significantly in recent years. Advanced materials, robotics, and sensor systems have led to significant improvements in ankle exoskeletons. Ankle exoskeletons have evolved to not only act as support but also as a system that can aid human mobility. One of the main advantages of current ankle exoskeletons is gait phase assistance, energy efficiency, and enhanced balance. Recent advances in technologies allowed ankle exoskeletons to aid in more personalized and responsive support for a wide range of motion and circumstances. There are still key problems that remain in ankle exoskeletons. The problems include excessive weight, limited joint freedoms, and the need for complex customization, which requires specific functions. In addition, an insufficient standardized protocol requires specific functions.

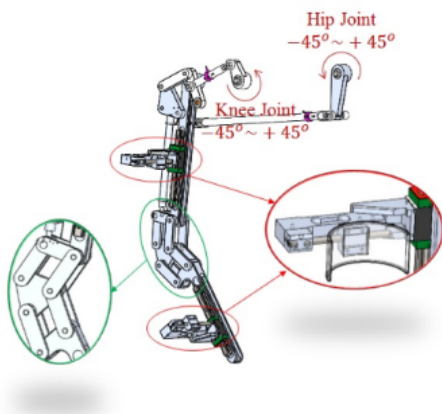


Figure 3. Mechanical structure of the lower-limb exoskeleton, showing the hip and knee joint mechanisms. Adapted from Cao et al. (95).

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Table 1. Comparative Analysis of Key Ankle Exoskeleton Studies on Objectives, Designs, and Experimental Outcomes.

Author(s), year, title	Aim of Study	Design Features	Results
Tang X, Wang X, Ji X; A wearable lower limb exoskeleton: reducing the energy cost of human movement	This study was to identify the advantages that ankle exoskeletons have for a patient regarding endurance, mass, volume, and cost. It lists the main points of existing research and provides improvement measures that are appropriate for practical application.	They used a wearable ankle exoskeleton prototype and assigned people to walk with and without it to measure and compare how much energy the body used in each condition to test if the device makes walking more convenient and efficient.	The lower limb exoskeleton increased the power amplification and reduced the metabolic cost compared to unassisted walking. It overall showcased stability and comfort.
Kalita Bhaben, Narayan Jyotindra, Dwivedy Santosha Kumar, 2020, Development of Active Lower Limb Robotic-Based Orthosis and Exoskeleton Devices: A Systematic Review	The aim of this study was to review existing lower-limb orthosis and exoskeleton devices, focusing on design, actuation, and control strategies. It reviews current advancements and identifies areas that need improvement.	The authors used a systematic literature review, analyzing already developed lower-limb exoskeletons and devices. These systems were categorized based on joint types, actuation modes, and control strategies.	The study found that a wide variety of exoskeleton designs exist, but no single best option has emerged. Devices vary in mechanical structures, control systems, and actuator types. They also concluded that many systems assist gait, especially for elderly and impaired users; however, high cost and complexity are barriers.
Gonzalez S, Stegall P, Cain SM, Siu HC, Stirling L, et al. Assessment of a powered ankle exoskeleton on human stability and balance.	The aim of this study was to examine balance and stability in exoskeletons that are designed to assist human motion.	Participants were asked to complete a task in their own shoes and when they wore the exoskeleton. Data were collected and analyzed through their inertial measurement units and through an analyzed pool level and the individual level.	Results showed that exoskeletons had mixed effects on stride stability metrics, and it was observed that stride duration increased when wearing the exoskeleton. Stride length, stride speed, stride stability, and balance were not affected by the exoskeleton state. It was concluded that each

			individual participant had no correlation in results. However, recommend including balancing tasks for exoskeleton evaluation.
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