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Review

A survey on soft lower limb cable-driven wearable robots without rigid links and joints

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ABSTRACT

Traditional wearable robots mostly consist of rigid structures connected to the human body. Due to the inherent characteristics of human joints, it is unavoidable that the robot joints have some misalignment with the wearer's biological joints. One solution to the joint misalignment problem in wearable robots is to use soft structures instead of traditional rigid structures as the interface between the robot and the wearer. This survey paper aims to provide an overview of the designs of wearable robots for the lower limbs that do not contain any rigid structures or joints. This study is mainly focused on robots with an electrical cable-driven actuator. The lower limb joint-less robots introduced in this paper were categorized into three main groups, namely exoskeleton-based robots, end-effector-based robots, and exosuits. Application of these devices can be categorized as rehabilitation of patients with gait impairments and power augmentation of healthy users. After a detailed review of the notable designs in each group, a discussion about the advantages and disadvantages indicated that the main drawback of current designs is the limitation on the amount of provided assistive loads. Because the forces are mainly applied in parallel to the human body, the amount of these forces is limited by the wearer's comfort level. In the end, a possible research direction for future researchers is presented in an attempt to address the limitations of current designs.

Contents

1. Introduction

There has been a growing interest among researchers to develop wearable assistive robots in recent decades. Wearable assistive robots are systems that can be worn by humans to support or protect parts of their bodies [1]. They can be divided into two main groups: active devices that use a power source to assist the wearer's motion and passive devices that exploit the wearer's kinematic forces by using passive elements, such as springs or dampers [2]. Wearable robots can be used as rehabilitation devices for patients with neurological disorders, such as spinal cord injuries (SCI) and strokes [3], assistive devices to help the elderly and people with muscle weaknesses in the

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activities of daily life [4] or to augment movement abilities of healthy individuals by reducing the metabolic cost of various tasks [5]. Many wearable robots have been developed for the entire human body [6], the upper extremities of the human body to help with the movement of the torso, arms or hand [7], or the lower extremities of the human body to assist the motion of the legs [8].

One of the most popular choices for the structural design of exoskeletons is using rigid structures, such as the commercially available lower limb rehabilitation device "Lokomat" shown in Fig. 1(a) [3]. Exoskeletons with rigid structures use a series of links and joints parallel to the human body and are connected to it at specific connection points. Rigid exoskeleton designs are usually heavy and add mass and inertia at the distal segments of the user's body that can increase the metabolic cost of movements. One of the significant drawbacks of these rigid exoskeleton designs is the problem of joint misalignment. Due to the complex structure of human joints, it is incredibly challenging to imitate its kinematics precisely. Therefore, the exact location of rotation axes of human joints is almost impossible to locate unless with the help of *in-vivo* imaging techniques [9,10]. Furthermore, some of these joints, such as the elbow and the knee, have varying rotation centers along their range of motion [11]. These challenges make it unavoidable to have some level of misalignment between the joints of traditional rigid exoskeletons, which are mainly simple one-degree-of-freedom rotational joints, and the human biological joints. One popular solution to this problem is to add complex multi-degree-of-freedom mechanisms into the design of exoskeleton joints to compensate for joint misalignments [12]. This could add more weight to the wearable part of the device and decrease its effectiveness. Another solution is to use soft wearable robots instead of rigid exoskeletons. The exosuit, which is depicted in Fig. 1(b), is a good example of these soft exoskeletons that will be further investigated in this paper [13]. These designs employ compliant structures instead of traditional rigid linkages as their interface [14]. Soft wearable devices use various actuators such as pneumatic [15], hydraulic [16], PVC gel [17], electrical cable-driven [13], and Pneumatic Artificial Muscles (PAMs) [18]. The main difference between these two design principles is the fact that exoskeletons with rigid structures can apply higher assistive forces. This characteristic makes them more suitable for situations in which more assistance is required, such as rehabilitation of patients with movement impairments at the early stages of recovery or assisting healthy individuals in more strenuous activities. Conversely, due to the lack of a load bearing structure in soft devices, their assistance level is limited; hence, they are mostly utilized in less demanding situations, such as power augmentation of healthy users in walking or rehabilitation exercises of patients with considerable level of movement abilities.

Several review and survey papers have been published in recent years that were focused on addressing the issues concerning the design and utilization of upper limb [19] and lower limb exoskeletons [20,21]. For example, in [22], the discussion is limited to the classification of joint motions, control systems, and types of actuators used in lower limb rehabilitation exoskeletons in addition to a brief discussion about the joint misalignment problem in these devices. Others have focused on the exoskeletons designed for a specific lower limb joint such as the hip [23], the knee [24], and the ankle joints [25]. Some studies have focused on presenting the state-of-the-art of existing exoskeletons for lower limbs that can be used by elderly people [26] or people who have gait disorders due to neuromuscular impairments [27]. In contrast, others have brought together the methods, metrics, and experimental procedures used to assess robotic-assisted motor skills in lower limbs [28]. There is also a review on the use of compliant elements in the design of lower limb exoskeletons in [14] and the research status of flexible exoskeletons for both upper and lower limbs [29]. Additionally, in [30] a detailed discussion of trends and actuation methods (both fluidic and cable-driven) of soft wearable robots that are used for the upper and lower limbs is presented. According to the findings of this review paper, there has been an increasing trend in popularity toward using cable-driven actuation methods in soft wearable robots in recent years. Moreover, there is a detailed review of the use of cable-driven robots in rehabilitation and their categorization in [31].

This paper aims to provide an overview and categorization of the existing lower limb wearable robot designs that do not have a rigid structure and try to solve the problem of joint misalignment in wearable robots by removing these rigid linkages. Unlike previous reviews and survey papers mentioned in this section, the discussion in this paper will be limited to lower limb devices that are active and use compliant structures that do not restrict the users' motion. Given the significance of cable-driven actuation methods in these devices, the designs reviewed in this paper are limited to the devices that use a cable-driven actuator to transmit forces to the wearer. This paper's discussion will not be limited to assistive and rehabilitative devices, and wearable robots used for power augmentation of healthy users will also be included. Unlike the review paper in [30], the discussion in this paper will not include devices that utilize fluidic actuation methods as is reiterated in the following section. Furthermore, some of the designs aimed at solving the problem of joint misalignment in exoskeletons that are presented in this study cannot be categorized as "soft wearable robots". Finally, a discussion on benefits, limitations, and possible future research directions is presented at the end of this paper.

2. Methods

Based on what was presented in the introduction of this paper, a detailed review of lower limb cable-driven robotic designs that did not use any rigid links and joints is carried out in this study. Given the growing popularity of cable-driven actuation methods, which was also shown in [30], it was decided that the scope of this review paper was to remain limited to the devices that utilized this actuation method. Hence, studies that used other actuation methods, such as pneumatic, hydraulic, PVC gel, and Pneumatic Artificial Muscles (PAMs), were excluded from the discussion of this paper. Furthermore, only those devices that are designed for the assistance of the lower limbs of the human body are considered in this study. In this review, a cable-driven lower limb soft wearable robot is defined as an active wearable robot that does not have any rigid linkage structure that requires alignment to the human joints aimed at assisting the motion of the lower limbs via a cable-driven actuation system. The devices that fit into this category are included in this review paper.

To this aim, an extensive search in the PubMed electronic database, IEEE Xplore digital library, Science Direct, and Google Scholar was carried out to find relevant studies from 2000 until 2020. Only peer-reviewed articles were considered in this paper. The keywords used for the initial search include: "cable", "wire", "rehabilitation", "assistance", "lower limb", "exosuit", "robot", "cable-driven", "soft wearable robots", and their combinations. The papers that included these terms in their title, abstract, or list of keywords were selected. The initial search resulted in finding over 300 papers that were further screened to eliminate irrelevant and duplicate results. Afterwards, the respective websites of each relevant research group were searched to find further studies related to the scope of this paper. After collecting the relevant papers, an extensive search among the studies which have cited them was carried out to find any other relevant designs. Finally, 84 papers from 29 research groups, which included 34

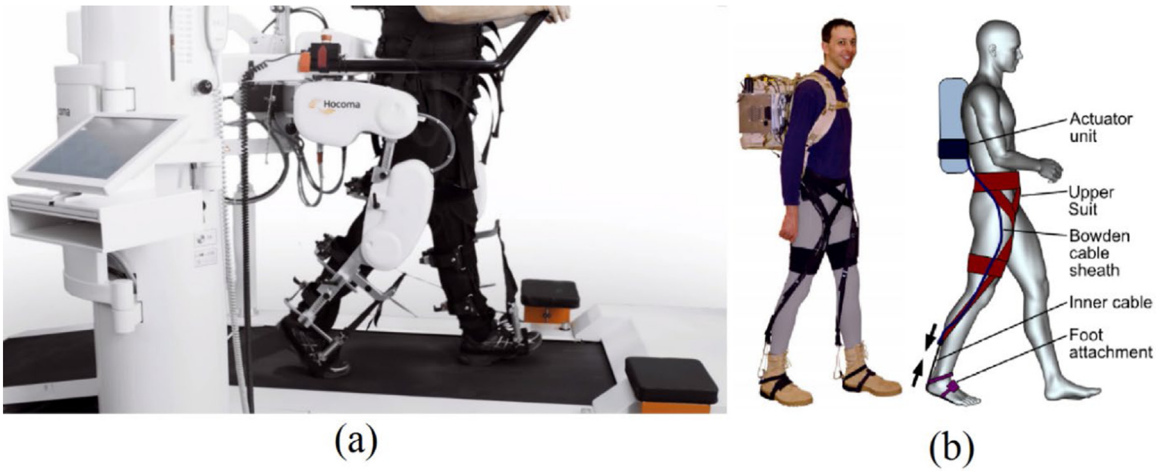

Fig. 1. (a) lower limb rehabilitation exoskeleton robot Lokomat Hocoma, (b) lower limb soft wearable exosuit [13].

unique designs, were chosen based on the following inclusion and exclusion criteria.

Papers that fulfilled the following criteria were included in this study;

- The device used a power source and active actuators to provide assistance.
- The device used compliant structures for its interface to the user.
- The device was designed to assist the lower limbs, namely the hip, the knee, the ankle joints, or any combination of them.
- The device used a cable-driven actuation system

The following criteria were used to exclude a study from this paper;

- The device used any form of rigid structure that required an alignment of its joints to the biological joints of the wearer.
- The study did not present any significant contribution to the design or control strategy of previously mentioned devices.

Fig. 2 shows an overview of the wearable devices that met the abovementioned criteria. The bar chart in part (a) of Fig. 2 indicates a clear increasing trend in the interest of different research groups to design and develop soft cable-driven lower limb robots that do not attach any rigid structure to the wearer. Based on the results obtained by this search procedure, the devices that were chosen for this review paper were divided into three separate categories based on their structural design, namely End-effector-based robots, Exoskeleton-based robots, and Exosuits. Although a more detailed discussion of the structural design and relevant examples of each category is presented in the remainder of this paper, a brief definition of each group is given in this section to further clarify this categorization. End-effector-based robots are attached to each leg via a single cuff which acts as the end-effector of the robot, through which the assistive forces are applied to the human body. Conversely, exoskeleton-based robots use multiple cuffs as attachment points to various segments of the lower limbs in order to provide assistive torques to individual joints. Similarly, exosuits use several anchor points to the human body to apply assistive forces. However, while these cuffs are not connected to each other in exoskeleton-based robots, the anchor points of exosuits are connected via textile-based structures. Consequently, exosuits are not put in the same category as the exoskeleton-based robots. Moreover, part (b) of Fig. 2 shows a pie chart of the percentages of unique designs for either category. It can be seen from the pie chart that the majority of research groups have preferred exosuit designs over other types of wearable robots for the lower limbs.

3. Exoskeleton-based robots

Exoskeleton-based cable-driven robots for lower limbs that do not use a rigid structure are used for various purposes, such as rehabilitation of patients with neuromuscular disorders and reducing the metabolic cost of human gait. These wearable robots actuate the lower limb joints by applying forces to cuffs worn on the wearer's body through cables. Depending on the design of these cuffs and cable routings, the applied forces are able to generate a torque around one or multiple lower limb joints. It is worth noting that straps or links should not connect the two cuffs worn on either side of a joint in these devices. In this section, some of the most significant designs of exoskeleton-based cable-driven robots without a rigid structure are reviewed in two sections, namely those devices used for rehabilitation and assistive purposes and those used for power augmentation of healthy users.

3.1. Rehabilitation and assistance

Jin et al. [32] introduced the first cable-driven leg exoskeleton without a rigid structure that is capable of generating bidirectional torques on the hip and the knee joints, named Cable-driven Active Leg EXoskeleton (C-ALEX). This robot is shown in Fig. 3(a). The primary purpose of this wearable robot was to assist patients in post-stroke rehabilitation exercises. To generate bidirectional torques on the hip and the knee joints, the first design of C-ALEX used four cables actuated by four AC electric motors mounted on a fixed structure. It comprises three cuffs connected to the waist, the thigh, and the shank of the wearer with cables routed through them [32]. Thigh and shank cuffs were tightly connected to the wearer's limbs and made of 3D printed ABS plastic with a sparse interior to lower their weight (0.57 kg for the shank and 0.06 kg for the thigh). This design allowed the continuous application of hip and knee flexion/extension torques throughout the exercise. An assist-as-needed controller with a tendon tension planner was presented that utilized a tunnel-like force field around the target path and assisted the ankle of the wearer to move on a prescribed target path by controlling the tension in the cables. An experiment in [32] on six healthy subjects evaluated the effectiveness of the preliminary design of the robot. Even though C-ALEX was primarily designed for use in treadmill trainings, it was revised in [33] to be used over-ground by utilizing a movable

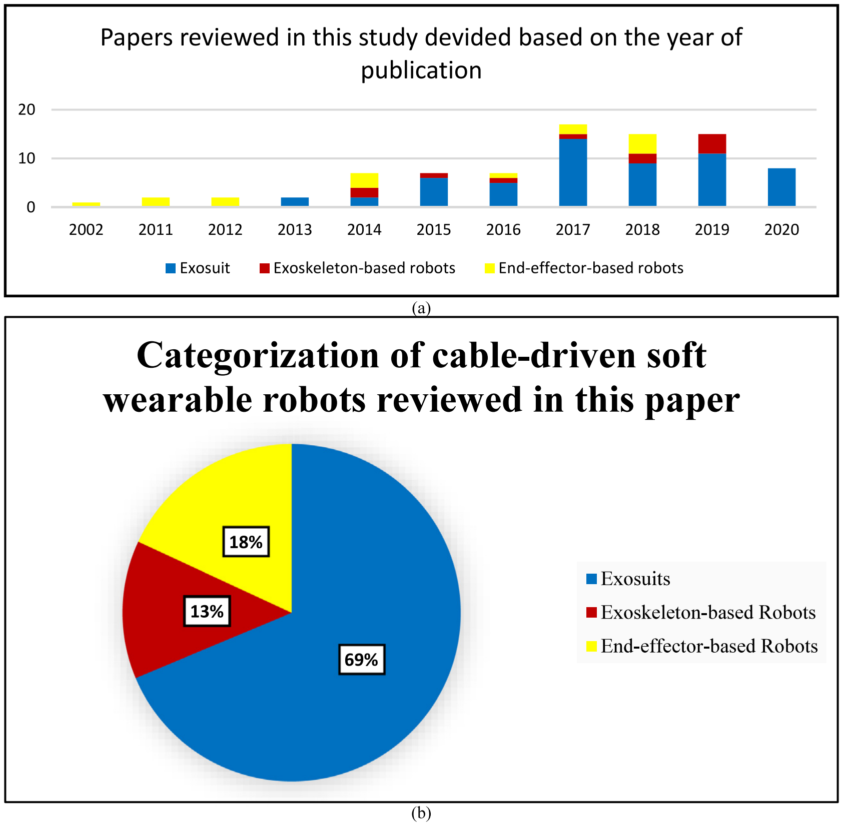

Fig. 2. (a) the annual total number of unique designs of lower limb cable-driven soft wearable robots from the year 2002 to 2020, (b) the relative shares of each category from the total number of unique designs.

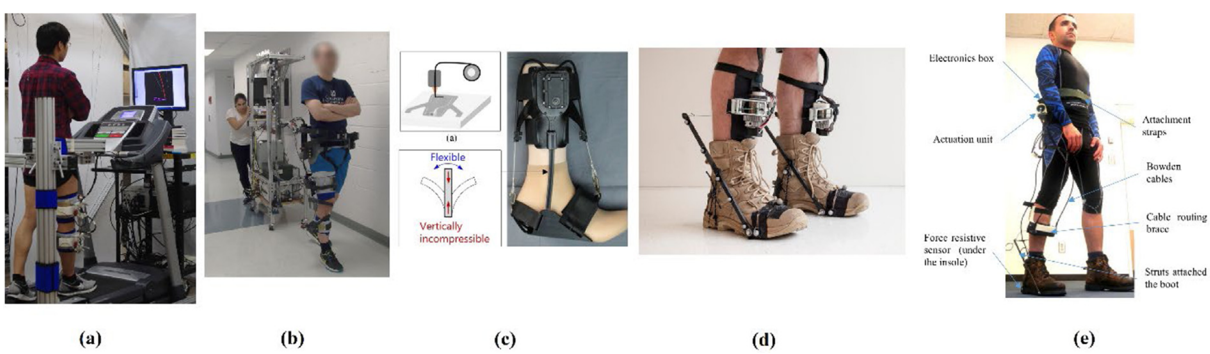

Fig. 3. Exoskeleton-based cable-driven robots for the lower limbs. (a) C-ALEX's first design [32], (b) C-ALEX with portable actuation unit for over-ground walking [33], (c) soft robotic ankle foot orthosis for post-stroke patients [34], (d) Autonomous Ankle Exoskeleton [35], and (e) Walking Augmentation Ankle Exoskeleton (WAXO) [36].

actuation platform. It is shown in Fig. 3 (b). Further experiments on nine healthy subjects in [37] were carried out to investigate the device's capability in human retraining of gait. The results showed a promising adaptation of gait after training.

Other research groups have also presented exoskeleton-based cable-driven robots to assist patients with gait impairments. For instance, in [34] a soft robotic ankle foot orthosis for post-stroke patients is presented. Unlike the previously mentioned C-ALEX, this robot can only apply assistive torques to a single joint, namely the ankle joint. Since post-stroke patients accompanied by hemiplegia experience muscular weakness of their ankle joints, which induces degradation of propulsion force during the stance phase and reduced clearance during the swing phase due to foot-drop [34], designing a wearable robot that can properly assist the ankle joint during walking could increase patients' ability to perform the activities of daily life with more confidence. To this end, the soft ankle foot orthosis of [34], which is depicted in Fig. 3(c), was designed as an inexpensive, lightweight, and easy to wear device that assists both dorsiflexion and plantarflexion via a bidirectional tendon-driven actuator mounted on the patient's leg. Two flexible, 3D-printed columns were added to either side of the device connecting the shank and the heel pads in order to prevent vertical compression while allowing free rotation of the joint. Because these flexible columns do not require any alignment to the wearer's joint, and they only add to the stiffness of the device without restricting the natural motion of the joint, this device was included in this review paper. A real-time gait phase detection algorithm based on foot–ground contact information and IMU sensors and a three-stage assistive force generation method were used to control this device. Preliminary experiments on one post-stroke patient showed improvements in both gait propulsion and foot-drop prevention. Similarly, in [40] a wearable ankle robot prototype for assistance to foot-drop developed at the University of Bath is presented. The actuation

Table 1
An overview of lower limb exoskeleton-based cable-driven wearable robots.

Name/ Institution	Tethered/ Untethered	Joints	Number of actuators	Applications	Experiments
C-Alex [32,33]	Both	Hip and knee flexion and extension	4 electrical cable-driven (each leg)	Gait rehabilitation of post-stroke patients	• Preliminary experiments on 6 healthy subjects [32] • Effects of weight compensation on 12 healthy subjects [38] • Assessment of over-ground performance on 8 healthy young adults [33] • Investigating the retraining of human gait of 9 healthy subjects [37] • Preliminary assessment of adding Augmented Reality (AR) headset to the device in over-ground walking on three groups, each containing 8 healthy participants [39]
Ankle-foot-orthosis [34]	Untethered	Ankle plantarflexion and dorsiflexion	1 bi-directional electrical tendon-driven (one leg)	Rehabilitation of post-stroke gait	• Feasibility tests on 1 post-stroke patient [34]
University of Bath [40]	Untethered	Ankle dorsiflexion	1 electrical cable-driven (one leg)	Rehabilitation of foot-drop	• Preliminary validation of the device and the control system on 1 healthy subject [40]
Autonomous Ankle Exoskeleton [41]	Untethered	Ankle plantarflexion	1 electrical cable-driven (one leg)	Power augmentation of loaded and unloaded walking	• Evaluation of energy consumption of loaded level treadmill walking of 7 healthy subjects [41] • Evaluation of metabolic effects of unloaded treadmill walking of 2 healthy subjects [42] • Evaluation of metabolic, kinetic, and kinematic effects of unloaded level treadmill walking of 6 healthy subjects [35]
WAXO [36]	Untethered	Ankle plantarflexion	1 electrical cable-driven (one leg)	Power augmentation of walking	• Evaluation of muscle activity of 1 healthy subject in treadmill walking [36]

module in this device is mounted on the shank and provides assistance to the foot-drop during walking through the textile strap which is attached to the shoe of the wearer. This device, however, does not have the mentioned flexible columns and the two attachment points on the patient's leg are completely disconnected; thus, removing the problem of joint misalignment. The two-level controller designed for this device is comprised a high-level gait event detection algorithm based on Bayesian method and a low-level PID controller that controls the robot based on the references generated by the higher level. This system controls the device in two modes, namely the assistive mode to prevent foot drop and the transparent mode that allows the user to move without the intervention of the robot.

3.2. Power augmentation of healthy users

Exoskeleton-based cable-driven robots for the lower limbs also have the potential to be used for power augmentation of healthy subjects. For example, an active autonomous ankle exoskeleton was designed by Mooney et al. [41] that comprised a pair of fiberglass struts attached to each boot and coupled to the heel of the boot via a lightweight inextensible cord, which is depicted in Fig. 3(d). Unidirectional actuators mounted on the anterior shank segments applied a force to the proximal end of the struts that was then converted to a torque about the human ankle joint. A battery and control package was worn on the waist to reduce distal mass on the wearer's leg. A biomechanically inspired timing-based controller initiated push-off assistance at 43% of the gait cycle and provided slack in the cable during the swing phase. Therefore, this portable single-joint assistive device only provided active assistance during a limited period in the gait cycle. An experiment in [41] on seven healthy male subjects, walking on a treadmill and carrying a 23 kg weight, showed a significant reduction in metabolic power of walking by $8 \pm 3\%$. Another experiment in [42] on two healthy subjects walking on a treadmill showed a 6% to 11% reduction in metabolic cost of unloaded walking. Further experiments on six healthy participants in [35] reiterated these results by showing an $11 \pm 4\%$ reduction in metabolic cost of walking and a significant reduction in the positive power of the hip, the knee, and the ankle joints. By reducing the added mass of a robot on the wearer's limbs, the metabolic benefits of a wearable device could increase. To this aim, Bougrinat et al. [36] introduced walking augmentation ankle exoskeleton (WAXO), which is illustrated in Fig. 3(e), to assist the ankle joint of healthy users with minimal added distal mass compared to other devices. Thus, the actuation unit of WAXO was attached to the waist of the user, utilizing Bowden cables to move the carbon fiber struts attached to the boot. The optimization of the device's mass resulted in a total mass of 2045 g for the entire robot, 348 g of which was placed distally on the wearer's leg. The device provided ankle joint plantarflexion torques at the end of the stance phase. Experimental walking results for one healthy subject showed a reduction in muscle activity and a potential reduction in metabolic cost of walking by $7.2 \pm 2.6\%$.

An overview of the exoskeleton-based cable-driven robots described in Sections 3.1 and 3.2 is presented in Table 1.

4. End-effector-based robots

Unlike exoskeleton-based cable-driven robots, there is another type of cable-driven robots that actuate the lower limbs by moving a single end-effector cuff connected to the leg of the wearer via cables. Hence, these robots cannot actuate each lower limb joint independently. All of the end-effector-based lower limb robots reviewed in this section are used in rehabilitation exercises.

One advantage of this group of robots compared to exoskeleton-based robots is their ability to assist the wearer in performing rehabilitation exercises other than walking. One example of these types of exercises is the Straight Leg Rise (SLR) exercise.

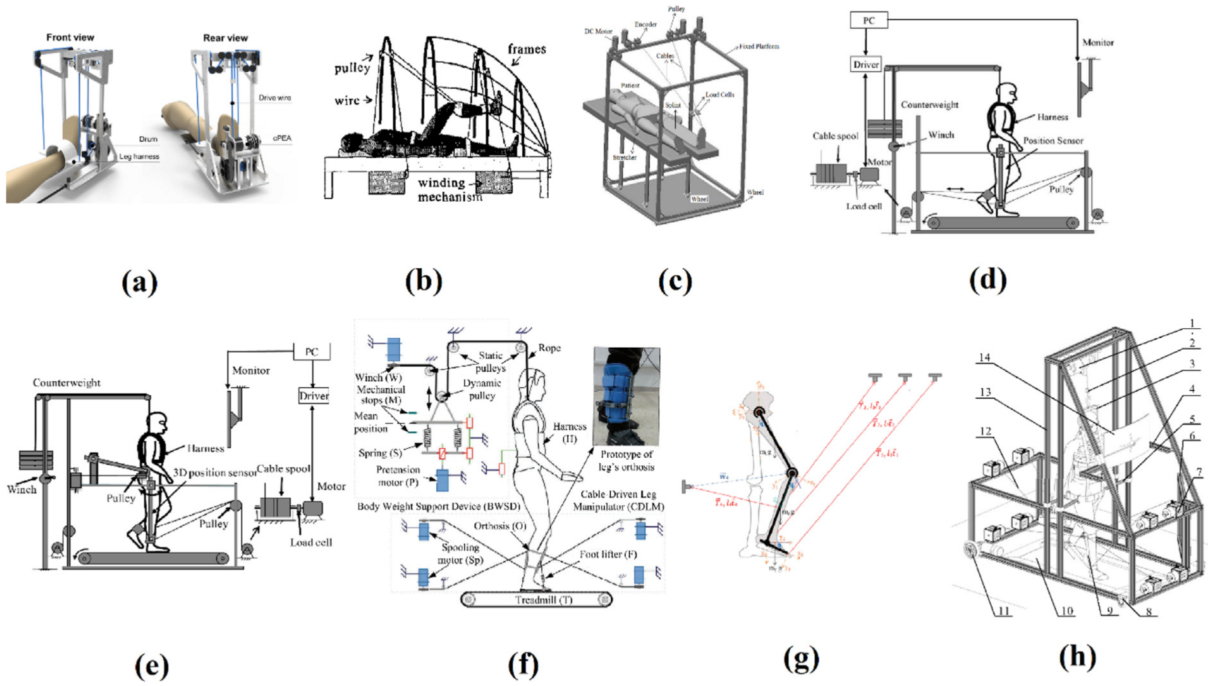

Fig. 4. End-effector-based cable-driven robots for the lower limbs. (a) wire-driven robotic device with SEA [43], (b) wire-driven leg rehabilitation system [44], (c) cable-driven parallel manipulator [45], (d) CaLT [46], (e) 3DCaLT [47], (f) CDLT [48], (g) cable-driven robot of [49], (h) MCLR [50].

SLR exercise comprises a movement that keeps the leg straight and lifts around the hip joint supposed to train the lower limb muscles related to walking [51]. Lee et al. [43] developed a wire-driven robotic device with series elastic actuators that provided assistive forces to the lower limbs in SLR exercises. It is shown in Fig. 4(a). This device was capable of simultaneously providing force measurement and assistance, using its series elastic design. The effectiveness of a robust force control was evaluated with experiments on one healthy participant and one patient with lower limb impairments [43]. However, the first lower limb end-effector-based device used with the patient lying down instead of standing upright was introduced by Homma et al. [44], which is illustrated in Fig. 4(b). It used a wire-driven actuator to create lower limb motions by moving the robot's end-effector cuffs. A critical characteristic of this type of robot is its tendency to be low-cost and easy to manufacture. A low-cost, end-effector-based robot used for stroke patients while sitting was developed in [45,52], and is shown in Fig. 4(c). It performed individual movements of the hip, the knee, or the ankle joints by using one or up to three cables. However, evaluation experiments on patients have not been reported for this device.

Other end-effector-based robots are mainly used for gait rehabilitation exercises, usually on a treadmill. The first design was a device named CaLT, introduced by Wu et al. [46] and depicted in Fig. 4(d). CaLT was a novel cable-driven robotic locomotor training system that provided assistive or resistive forces to the legs during treadmill training. These forces were applied to the legs with four cables driven by four motors through custom-made cuffs connected to the ankle. These cuffs were the end-effectors of the robot that could create motion in both legs of patients by using the four independent cables. CaLT included one load cell for each cable and two custom-made 3D position sensors that consisted of a detection rod, two universal joints, two potentiometers, and one linear position transducer. Thus, it was able to measure the position of the ankle, which was coincident with the position of the robot's end-effector. The controller of CaLT could provide assistive or resistive forces in the cables, proportional to the kinematic error of the ankle point, and automatically adjust the amount of this force based on the kinematic performance of the patient. Backdrivability of the device and the fact that the gait trajectory was not fixed were its essential features. Preliminary tests on ten chronic Spinal Cord Injury (SCI) patients showed the effectiveness of CaLT in retaining gait variability. A long-term experiment on one SCI patient proved that the device could improve over-ground gait speed and the kinematic performance of patients [46]. CaLT could also be used for the rehabilitation of post-stroke patients. An experiment with seven chronic hemiparetic stroke patients wearing the device, which applied forces during pre-swing through mid-stance phases of gait, indicated the feasibility of CaLT in improving locomotor function in patients post-stroke [53]. A study on ten subjects with SCI showed that the aftereffects of using CaLT would transfer to over-ground walking more effectively with a resistive force perturbation rather than an assistive one [54]. Another study indicated that SCI patients with higher functioning showed better results with resistive force perturbation [55]. However, an experiment on 30 post-stroke patients showed better results for assistive force perturbation [56]. The design of CaLT was revised to be used for children with Cerebral Palsy (CP). This new design was called 3DCaLT and included two additional motors that could provide controlled forces to the patient's pelvis via cables [47]. This device is illustrated in Fig. 4(e).

There are other examples of end-effector-based robots used for walking rehabilitation. For example, Lamine et al. [48] proposed a gait training machine composed of a bodyweight support device and a cable-driven parallel robot named Cable-Driven Legs Trainer (CDLT), which is shown in Fig. 4(f). It controlled the pose of the patient's limb through an orthosis placed on the patient's leg. It could help patients in treadmill walking training using an active cable-driven leg manipulator, which consisted of an orthosis placed around the leg and a foot-lifter positioned between the orthosis and the foot, stabilizing the ankle joint when the foot was off the ground. It consisted of four cables to create 3 degrees of freedom for each leg. Moreover, Faqihi et al. [49] designed a cable-driven robot with four cables connect to each shank and ankle to move the leg in the sagittal plane. It is depicted in Fig. 4(g).

Table 2
An overview of lower limb end-effector-based cable-driven wearable robots.

Name/ Institution	Tethered/ Untethered	End-effector placement	Number of actuators	Application	Experiments
Lee et al. [43]	Tethered	At the shank near the ankle joint	1 electrical wire-driven series elastic (cPEA: compact planetary geared elastic actuator) (one leg)	Rehabilitation, Straight Leg Raise (SLR) exercise	• Validation of the design on 1 healthy subject and 1 patient [43]
Homma et al. [44]	Tethered	At the top (near the knee joint) and the bottom (near the ankle joint) of the shank	2 electrical wire-driven (fixed for 1-DOF and moving for 2-DOF setups) (one leg)	Rehabilitation of the hip and knee joints with patients lying down	• Validation of the 1-DOF system on a test dummy and 1 male subject [44]
Barbosa et al. [45]	Tethered	At the ankle joint [45], or both at the ankle and the knee joints [52]	1 up to 6 electrical cable-driven (one leg)	Rehabilitation of gait impairments in patients with Cerebral Palsy (CP) and stroke (patients lying down)	• Preliminary validation experiments on an anthropomorphic wooden puppet [45]
CaLT [46]	Tethered	At the bottom of the shank (near the ankle joint)	2 electrical cable-driven per leg	Rehabilitation of patients with incomplete Spinal Cord Injury (iSCI) and post-stroke	• 10 subjects with chronic iSCI in one experimental session to test the characteristics of the device and 1 subject with chronic iSCI in repeated testing sessions over 8 weeks to test improvements in locomotor function [46] • Feasibility test of assistive force at the ankle in robot-assisted treadmill training on 7 subjects with chronic stroke [53] • Evaluation of aftereffects of assistance and resistance perturbations during robot-assisted treadmill training to over-ground walking on 10 subjects with iSCI in two sessions [54] • Determination of the effectiveness of cable-driven resistance treadmill training on improvements of locomotor functions with 10 chronic iSCI patients divided into two groups [55] • Determination of the effects of assistive and resistive perturbations on locomotor improvements in post-stroke patients with 30 subjects with chronic stroke divided into two groups [56]
3DCaLT [47]	Tethered	At the bottom of the shank (near the ankle joint) and at the pelvis	2 electrical cable-driven per leg and 2 electrical cable-driven for the pelvis	Rehabilitation of children with Cerebral Palsy (CP), post-stroke patients, and those with incomplete Spinal Cord Injury (iSCI)	• 5 children with CP were tested for 6 weeks of long-term gait training [47] • Evaluation of the effectiveness of applying a mediolateral corrective force to the pelvis to improve gait symmetry on 15 subjects with post-stroke hemiparesis [57] • Evaluation of the effects of applying controlled assistive force to the pelvis in medial–lateral direction on improving lateral balance control with 10 subjects with iSCI [58] • Evaluation of the effectiveness of pelvis perturbations compared to treadmill walking on improving balance control and gait stability of 14 subjects with iSCI [59]
CDLT [48]	Tethered	At the shank	4 electrical cable-driven (one leg)	Rehabilitation of patients with Spinal Cord Injury (SCI) and stroke	–
Faqihi et al. [49]	Tethered	At the shank and foot	4 electrical cable-driven (one leg)	Lower limb rehabilitation in the sagittal plane	–
MCLR [50]	Untethered	At the top and bottom of the shank	4 electrical cable-driven per leg	Lower limb rehabilitation	• Demonstrating the effectiveness of the proposed control strategy with experiments on actuators [50]

Although this design consisted of cables connected to the shank and the ankle of the patients, it is still considered an end-effector-based cable-driven robot because it did not move the hip, knee, and ankle joints separately. A simulation of the computed torque controller designed for this device was presented in [49], while no further experiments on its prototypes were reported. However, not all end-effector-based robots are tethered. Zou et al. [50,60] presented a movable cable-driven lower limb rehabilitation robot (MCLR) for gait training and over-ground walking training in different assistive modes, which is shown in Fig. 4(h). Four cable-driven units, capable of realizing 3 degrees of freedom of the lower limbs in the sagittal plane by moving the shank as the end-effector of the robot, make up the active cable-driven part of the MCLR. The entire device, including a bodyweight support system, was mounted on a movable chassis.

An overview of the devices reviewed in Section 4 is also presented in Table 2.

5. Exosuit

Another approach to solve the problems of traditional rigid exoskeletons, such as joint misalignment, kinematic restrictions on lower limb motions, and high added inertia, is using "exosuits". An exosuit is defined as a wearable device that consists of an integrated garment that includes attachment points to the body, a structured textile that transmits loads across the body, and actuated segments that can reduce their relative length to provide tensile forces in the suit [61]. The main difference between exosuits as wearable robots and traditional exoskeletons is that exosuits do not contain any rigid elements to support compression loads across the joints. Instead, the wearer's bone structure tolerates all of the compressive forces generally encountered by the body, plus the forces generated by the suit [13]. The first exosuit design was introduced by Asbeck et al. [62] and was meant to augment selected lower limb muscles by adding impulses of power at certain joints and at the right phases of the gait cycle. The first prototype of this novel concept used cable-driven electrical actuators and fabrics that were anchored to bony landmarks near the surface of the skin to apply moments to the hip and the ankle joints of the wearer. It was shown that the exosuit added minimal inertia, mechanical impedance, and kinematic restrictions. This exosuit design utilized cable-driven electrical actuators because they are easier to control and use readily available batteries as power sources, which are beneficial for untethered designs. The main difference between exosuits and exoskeleton-based cable-driven robots, which have been reviewed in detail in Section 3, is that exosuits use textile-based structures to connect the attachment points of the device together, whereas the cuffs of exoskeleton-based robots are completely separated. This characteristic makes it possible for exosuits to actuate one joint (mono-articular exosuits) or multiple joints (multi-articular exosuits) using a single actuator. As a result, it is possible to reduce the overall weight of the exosuit by reducing the number of actuators. It also makes it possible to design portable exosuits. The original motivation behind the development of exosuits was to augment the movement abilities of healthy individuals, but these devices were later utilized in assisting the elderly and performing rehabilitation exercises for patients with neuromuscular disorders caused by stroke, etc. In the next two sections, a review of the exosuit designs is provided, which are separated based on whether they were used for power augmentation of healthy individuals or rehabilitation and assistive purposes.

5.1. Power augmentation of healthy users

In 2013, a new multi-articular exosuit was introduced by Asbeck et al. [62] that used Bowden cable-driven actuators. It is shown in Fig. 5(a). The design of this exosuit made it possible to simultaneously provide torques on multiple joints, which reduced the total number of required actuators and consequently the weight of the system. The exosuit's assistance was achieved by duplicating the force generated by biological muscles from 40% to 60% of the gait cycle and remaining transparent through the rest of the cycle. Due to the near symmetry of the moments at the ankle and the hip during this period in the gait cycle, the multi-articular architecture of the exosuit activated ankle plantarflexion and hip flexion via a single load path. The total mass of the portable system was reduced in the second version of the device to 10.1 kg [13]. It was shown that the device was able to decrease the gross metabolic cost of walking with minimal restrictions to the wearer's natural gait. An updated version of this device with a compact actuation unit and a new control approach was shown to significantly reduce the metabolic rate of walking by 11%–15% [63]. Further experiments were conducted on healthy individuals using this device to evaluate its effectiveness in reducing the metabolic cost of unloaded treadmill walking. In [64], an experiment on 7 healthy participants walking on a treadmill at a speed of 1.5 meters per second while wearing the exosuit was presented that was aimed at isolating and characterizing the relationship between assistance magnitude and the metabolic cost of walking. The results of this study proved that increasing the assistance level in the exosuit led to a decrease in the metabolic cost of the wearer, with a maximum of $22.83 \pm 3.17\%$ reduction in metabolic cost of walking compared to when the exosuit did not provide any assistance. Another experiment on 7 healthy subjects walking on a treadmill was conducted in [65] to compare the effects of continuously varying assistance magnitude with discrete step conditions in finding the optimal actuation parameters for each robot and wearer. The findings of this study suggested that since there was no difference in biomechanical parameters between all conditions, the biomechanical parameters can be recorded with the shortest protocol condition (single continuous sweep protocol). Moreover, the effects of this device on reducing the metabolic cost of loaded walking was evaluated on 8 healthy subjects with an experiment in which they walked on a treadmill while carrying a 23-kg backpack [66]. The results of this study indicated a significant reduction in metabolic rate by 11 to 15% in all conditions in which the exosuit provided assistance to the wearer. The same research group at the Harvard University designed another multi-articular exosuit, which consisted of two load paths for each leg: a multi-articular ankle plantarflexion and hip flexion load path and a monoarticular hip extension load path [67]. In order to minimize the number of actuators needed for the four load paths of this exosuit, one motor was used to actuate the same load path of both legs [68]. This exosuit is depicted in Fig. 5(b). Performance of this exosuit design was evaluated on the metabolic cost reduction of loaded treadmill walking of healthy subjects. For instance, in [69], an experiment was conducted on 7 healthy individuals wearing the exosuit while carrying a load equal to 30% of their body mass. This study showed metabolic cost reductions of as high as $14.2 \pm 6.1\%$ compared to when the exosuit was worn but did not provide any assistance. Similarly, another experiment on 8 healthy subjects walking on a treadmill while carrying a 23.8-kg backpack showed significant metabolic cost reductions [70]. In addition to proving minimal changes to the natural kinematics of participants due to wearing the exosuit, a comparison between the mono-articular (hip extension) and multi-articular (ankle plantarflexion and hip flexion) parts of this exosuit design indicated a greater average metabolic cost reduction for the multi-articular segment of the exosuit designs (14.6% compared to 4.6%). A new version of this multi-articular exosuit was presented in [71]. It was redesigned for over-ground walking, and a new online parameter tuning method was utilized in the controller for this new version [72].

The same research group at the Harvard University had also presented a mono-articular hip extension assistance exosuit [73], which is depicted in Fig. 5(c). This fully portable hip exosuit provided torques in the sagittal plane of up to 30% of the nominal biological torques for level-ground walking. Several experiments on healthy subjects were carried out using this exosuit to evaluate the effectiveness of various control methods in different experimental conditions. For instance, in [77], a new force controller

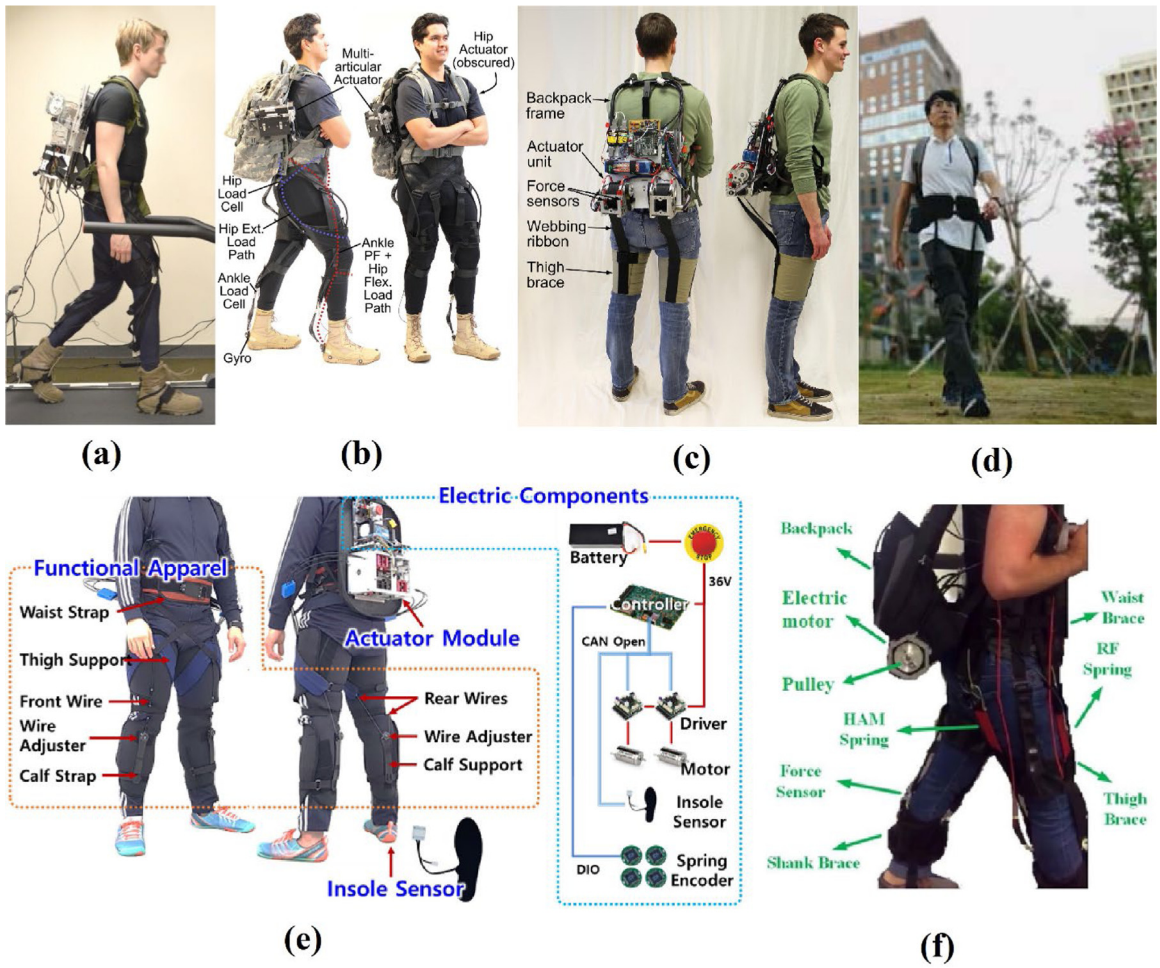

Fig. 5. Exosuits used for power augmentation of healthy users (a) multi-articular (ankle plantarflexion and hip flexion) exosuit [62], (b) multi-articular (ankle plantarflexion, hip flexion and hip extension) exosuit [68], (c) mono-articular hip extension exosuit [73], (d) SIAT Soft Exosuit (SSEX) [74], (e) knee exosuit of Lee et al. [75], (f) Sharbafi et al. [76].

aimed at improving force tracking capabilities of the device was tested on one healthy subject in a treadmill walking experiment in which an off-board actuation unit was utilized for the exosuit. The results of this test indicated a root mean error of force tracking equal to 1.7% of the desired peak force. Another experiment in [78] was carried out on 8 healthy subjects walking on a treadmill, while carrying a 23-kg backpack wearing this mono-articular exosuit, aimed at determining how the timing of hip assistance affects the positive mechanical power, the biological joint power, and the metabolic cost. The results of this study showed a significant reduction in metabolic cost for all assistive profiles compared to the unpowered condition of up to 8.5 $\pm$ 0.9% of mean reduction. Also, an IMU-based iterative controller, which was aimed at determining the onset timing of actuation based on an estimate of maximum hip flexion angle, was presented and tested on 8 healthy subjects in loaded (23-kg backpack) treadmill walking experiments [79]. The results of this experimental study showed that the proposed algorithm could reliably deliver assistance to the wearer, and a metabolic reduction was observed for all four assistive profiles tested in this study with varying percentages from a minimum of 5.7% up to 8.5%. Preliminary evaluation of the effects of this exosuit design in unloaded over-ground walking was performed on one healthy subject in [80]. The ability of the system to accurately control the peak force and its timing to the desired value was shown in this study. Furthermore, in [81], the effects of this device in unloaded over-ground walking and jogging were evaluated on 3 healthy subjects. It was proven that this exosuit was capable of robustly delivering the specified peak forces to the wearer for both conditions. A switching admittance–position control algorithm was proposed and tested on 3 healthy subjects in treadmill walking and jogging [82]. Tracking force profiles were accurately conducted for both conditions in this study as well. Moreover, this exosuit has been tested in running experiments. In [83], for example, a single participant experiment was presented with an untethered hip exosuit that resulted in a metabolic rate reduction of 9.3% for walking and 4.0% for running on a treadmill. The control system in this study was able to automatically switch between walking and running conditions. Another experiment on this exosuit design was carried out in [84] with the aim to isolate the relationship between assistance profile and metabolic cost reduction. In this study, 8 healthy subjects participated in an unloaded treadmill running experiment in which two hip assistive profiles were used, namely a profile that mimics the biological hip moment based on reference data and another one that is inspired by simulation study. The results of this study indicated the superiority of the second method as metabolic cost reductions of 9.1 $\pm$ 2.2% compared to powered-off condition and 5.4 $\pm$ 4.2% compared to not wearing the exosuit were observed. In [85], an online classification algorithm was presented for this device to identify walking and running conditions. This algorithm was validated with experiments on 6 healthy subjects on treadmill and 8 participants outdoors. The method showed a 99.99% accuracy for various speeds, slopes, on treadmill and over-ground, and loaded and unloaded conditions. Also, the metabolic cost reduction of wearing the exosuit during running compared to not wearing the suit was 3.9%, and the metabolic cost reductions of walking and running with the exosuit powered-on compared to powered-off were 12.2% and 8.2%, respectively. Finally, a long-term study was conducted in [86] to investigate the energetic adaptations of using this exosuit over multiple sessions. 8 healthy subjects participated in 5 sessions of treadmill walking while carrying a 20.4-kg load over 20 days. Mean metabolic cost reductions in the first and the fifth sessions were 6.2 $\pm$ 3.9% and 10.3 $\pm$ 4.7%, respectively, which proves that the metabolic cost reduction is preserved.

Other research groups have also developed exosuits for power augmentation of healthy users. Hu et al. [74] have presented a cable-driven wearable robot named SIAT Soft Exosuit (SSEX), which was designed to assist human hip extension. It is shown in Fig. 5(d). Preliminary experiments on 5 healthy volunteers wearing the exosuit showed the effectiveness of the proposed device in gait phase detection. An auto-pretension method was presented in [87] to reduce system latency in SSEX. In [75], an exosuit system was proposed that assisted stair ascent and descent by supporting the power of the knee joint, which is illustrated in Fig. 5(e). The front and rear wires of this exosuit transmitted forces for the knee extension and flexion motions using one actuator per leg. A novel Series Elastic Tendon Actuator (SETA) was introduced in [88] and used in this exosuit that performed the agonist and antagonist function of the human muscles using two internal wires as well as elastic elements to measure human–robot interaction forces. Experimental results showed an overall decrease in muscle activity while using this exosuit [75]. In addition to these mono-articular designs for the hip and the knee joints, Sharbafi et al. [76] have developed a biarticular exosuit that could reduce the total metabolic cost of motion by 12% in simulations. This device is shown in Fig. 5(f).

5.2. Rehabilitation and assistance

Bae et al. [89] introduced the first application of soft exosuits to rehabilitate post-stroke patients. The device used for this study was a unilateral multi-articular soft exosuit that consisted of a multi-articular ankle plantarflexion and hip flexion module and a mono-articular ankle dorsiflexion module actuated with an off-board actuation unit. It is shown in Fig. 6(a). Experiments on three post-stroke hemiparesis patients walking on treadmill indicated an increase in step time and stance time symmetry index with averages of 6.26% and 3.52%, respectively, and a decrease in stride time by 11.43%, which proved feasibility of the exosuit for post-stroke gait assistance and training [89]. In [90], a study was conducted using this device to determine whether similar benefits could be observed in over-ground trainings. 9 patients with hemiparetic stroke participated in this study which involved walking over-ground while wearing the soft exosuit in both powered-on and powered-off conditions. The results of this experiment indicated an improvement in push-off, an increase in paretic side's propulsion impulse and average positive ankle power, a decrease in average negative ankle power, and a 5.2° increase in maximal ankle dorsiflexion which assisted foot clearance during the swing phase. 7 individuals with chronic stroke participated in another treadmill walking experiment using this exosuit [91]. The results of this study showed a 10.43 $\pm$ 1.48% decrease in net metabolic power spent by participants, an increase in symmetry of body's center of mass power and a reduction in circumduction and hip hiking of 20 $\pm$ 5% and 27 $\pm$ 6%, respectively. Similarly, a single-session study on 8 individuals in chronic phase of stroke recovery on a treadmill resulted in immediate changes in the kinematic strategy used by the patients to advance the paretic limb in the form of a reduction in hip hiking and circumduction [92]. In [93], an experiment on 6 patients in the chronic phase after stroke was conducted to evaluate the exosuit-induced changes in over-ground walking speed, distance and energy expenditure. The results of this study showed no substantial change in patients' gait while the exosuit was unpowered, and in the powered condition, improvements in over-ground walking speed in 10-meter walking test with the median of 0.14 $\pm$ 0.06 meters per second and walking distance during a 6-minute walking test with a median of 32 $\pm$ 8 meters were observed. Likewise, another study on 6 post-stroke patients in over-ground walking resulted in increases in the walking speed in 10-meter walking test with the median of 0.12 $\pm$ 0.02 meters per second and walking distance during a 6-minute walking test with a median of 30 $\pm$ 12 meters were observed [94]. An optimized version of the multi-articular exosuit, with a new waist belt, a quick lacing mechanism integrated into the calf wrap, and a new optimized controller, showed a 50% decrease in electrical energy consumption while preserving its ability to provide consistent assistance force profiles [95]. An offline assistance optimization scheme, which was sensitive to step-to-step variability in gait, was introduced for this exosuit [96]. A multi-scale clinical trial with 44 post-stroke hemiparesis patients was conducted on a similar exosuit named ReStore, which assisted ankle plantarflexion and dorsiflexion over-ground and on a treadmill [97]. This device is depicted in Fig. 6(b). In addition to no reported device-related falls or serious adverse events and a low rate of device malfunction, the 5-day experiment resulted in improvements in both device-assisted and unassisted maximum walking speed of patients with respective averages of 0.01 $\pm$ 0.03 and 0.07 $\pm$ 0.03 meters per second. A tethered, lightweight, hinge-free wearable robot for knee extension assistance in post-stroke or cerebral palsy patients was introduced by the same research group, which is illustrated in Fig. 6(c) [98]. It combined soft textile exosuit components with integrated rigid components. In order to increase the moment arm of the knee extensor, a frame made of hollow carbon fiber tubing and 3D printed plastic components were integrated to the front of the knee.

Furthermore, Bartenbach et al. [99] developed the concept for a multi-articular exosuit that could be applied in rehabilitation. The objective of the design was to support the maximum number of joints in the sagittal plane with only one actuator per leg. It resulted in a multi-articular structure that coupled hip and knee extension. The resulting exosuit is depicted in Fig. 6(d). This device was useful in assisting people with gait impairments in sit-to-stand movements or stair ascending. Schmidt et al. [100] introduced Myosuit, a biarticular exosuit design that provided continuous assisting force at the hip and knee joints in activities of daily life. It is illustrated in Fig. 6(e). The biarticular approach in the design of Myosuit meant that it could use one actuator per leg, which resulted in the development of one of the lightest untethered devices with a total weight of 4.1 kg. The preliminary tests on one subject performing sit-to-stand motions showed the effectiveness of Myosuit in providing adequate assistance to the hip and the knee extension; however, a knee brace with a hinge joint was added to the later designs of Myosuit [111,112]. Moreover, the XoSoft EU project aimed to develop a modular soft lower-limb exoskeleton to assist people with mobility impairments. The XoSoft Beta-1 prototype, utilizes quasi-passive actuators (QPAs) that provide assistance to the wearer with the help of the elastic energy stored in passive elastic elements in specific phases of the user's gait via engaging active electromagnetic clutches. This prototype was designed based on an energy efficiency analysis optimization presented in [113], and the preliminary tests of a single-joint hip prototype on a post-stroke patient indicated an energy reduction of 7.8%. Furthermore, in [114], this light,

Fig. 6. Exosuits used for rehabilitation (a) multi-articular (ankle plantarflexion and dorsiflexion and hip flexion) exosuit [89], (b) ReWalk, ReStore [97], (c) mono-articular (knee extension) exosuit [98], (d) multi-articular (hip and knee extension) exosuit of Bartenbach et al. [99], (e) Myosuit [100], (f) XoSoft EU Project [101], (g) WeARS [102], (h) mono-articular (ankle dorsiflexion) exosuit of Yeung et al. [103], (i) multi-articular (hip and knee) exosuit of Chen et al. [104], (j) multi-articular (hip and knee) exosuit of Park et al. [105], (k) mono-articular (hip flexion) exosuit of Jin et al. [106], (l) HIMICO [107], (m) Hitexosuit [108], (n) Knee-tendon suit [109], (o) Cross-wire assist suit [110].

energy efficient, modular, and comfortable exosuit was successfully validated on a post-stroke patient by decreasing the risk of tripping due to foot-drop. Finally, the hip–knee unilateral prototype, which is presented in [101] and shown in Fig. 6(f), and different control strategies based on gait segmentation and actuation elements were evaluated on a 68-year-old post-stroke participant with unilateral gait impairment on his right side in over-ground straight walking experiments. The hip–knee unilateral prototype's assistance, in terms of power, to the hip and the knee joints was 10.9 $\pm$ 2.2% and 9.3 $\pm$ 3.5%, respectively. The use of this device resulted in an increase in joint angles and foot clearance at specific phases of the gait cycle. In addition to these devices, Srikesh Iyer et al. [102] developed the Wearable Adaptive Rehabilitation Suit (WeARS), which is shown in Fig. 6(g). This soft multi-articular exosuit used externally actuated cables to resemble the role of agonist and antagonist muscles for the rehabilitation of patients with gait impairments. WeARS actuated the hip and the ankle joints using an adaptive, subject-specific control strategy. Preliminary experiments on this device were conducted on two healthy participants in [102] to validate the presented control strategy. A further study was conducted on 16 healthy subjects divided into two groups using WeARS exosuit to evaluate the effects of negative force interventions applied during the push-off phase of walking [115]. The results of this study indicated that subjects in both groups adopted a compensatory response to the applied intervention and demonstrated intralimb and interlimb adaptations. Yeung et al. [103] also developed an active mono-articular exosuit to assist with foot drop condition in patients with neuromuscular disorders by helping the ankle dorsiflexion, which is illustrated in Fig. 6(h). In this device, a compact servo motor was placed next to the knee that could actuate the ankle joint via Bowden cables and worn beneath the clothing.

Another use for exosuits, other than rehabilitation of patients with gait impairments, is assisting the elderly and people with muscle weaknesses in their activities of daily life. An exosuit that assisted the hip and the knee joints by directly assisting hip flexion and knee extension and indirectly assisting hip extension was introduced in [104] for assisting the elderly. It is depicted in Fig. 6(i). This device was evaluated in treadmill walking experiments on 3 healthy subjects in two conditions, namely wearing and not wearing the proposed exosuit. The results of this experiment showed a metabolic rate reduction with the increasing slope of the terrain with respective reductions of 9.86%, 12.48%, and 22.08% for downhill, flat ground, and uphill conditions. Similarly, a soft wearable device using a tendon and pulley system to assist hip and knee extension of the elderly with one actuator per leg in activities such as stair ascent was developed in [105]. It is shown in Fig. 6(j). Preliminary experiments on a healthy subject verified the force transmission of this exosuit in real conditions. Moreover, Jin et al. [116] have developed a multi-articular exosuit design for the ankle and the hip assistance, which has shown a reduction in metabolic cost of walking in preliminary experiments on two healthy subjects of up to 10.2%. However, other devices used mono-articular architectures to assist a specific joint, such as a device to assist hip flexion that was developed by the same research group with the aim to minimize the metabolic cost of walking for the elderly [106]. It is illustrated in Fig. 6(k). A 2-day trial on 1 healthy male elderly subject in inclined (2% slope) and level treadmill walking showed a significant reduction in metabolic cost by an average of 7.7%. Furthermore, another study was conducted with the same device to validate the effects of repeated use of the device for 6 weeks on gait characteristics of the elderly [117]. The results of this long-term experiments on 4 healthy elderly participants showed an improvement in gait characteristics after repeated use of the exosuit. Another device, named HIMICO, was designed to increase the activity levels of the elderly by assisting the hip joint [107]. It is shown in Fig. 6 (l). Kinematic analysis of 11 middle-aged and elderly subjects who participated in the evaluation experiments of this exosuit indicated that the movements of the hip joints were significantly increased in 8 of them which could result in improved gait and reduction of fatigue. Zhao et al. [108] developed a soft knee suit (Hitexosuit) to assist the knee joint of people with muscle weaknesses in climbing the stairs. It is illustrated in Fig. 6 (m). A novel artificial muscle was used in Hitexosuit that utilized a lightweight and portable twisted string actuator. Evaluation experiments of this exosuit on three healthy subjects in stair climbing experiments showed a mean assistance efficiency of 29.8%. Another soft wearable knee extensor to assist stair climbing was introduced in [109], named knee-tendon suit, which is shown in Fig. 6(n). Feasibility of this exosuit design was evaluated on a healthy subject in knee flexion/extension experiments.

Besides mono-articular and multi-articular architectures, a new concept for assisting a single joint in multiple degrees of freedom was introduced by John et al. [110] in the design of an exosuit, named the cross-wire assist suit. It is illustrated in Fig. 6(o). This fully wearable prototype used four motor-driven Bowden cable actuators per leg with wires crossed over each other in front and back of the leg to generate torques in six directions in the hip joint.

An overview of the design aspects of all of the exosuits reviewed in Section 5 is presented in Table 3.

6. Discussion

The designs reviewed in this paper have all aimed at solving the problems of traditional rigid wearable robots. In this section, after a brief discussion about this issue and a presentation of the trends to address it, the benefits and drawbacks of each category of the robots discussed in this paper are presented, and possible future research directions in this field are investigated.

As mentioned in the introduction of this paper, one of the most important drawbacks of traditional rigid exoskeletons is misalignment of the device's joints and those of the wearer. Due to the natural complexity of joint biomechanics of human lower limbs, such misalignment is almost unavoidable. For instance, the knee joint is usually approximated as a simple hinge joint in the sagittal plane. However, the natural motion of this joint in that plane is a rotation with a moving center [11]. One possible solution to this challenge, which has been extensively reviewed in this paper, is to remove the rigid linkage structure of these wearable robots altogether. Therefore, alignment of the device's joints with those of the user is no longer a requirement. As stated in Section 2, there has been a trend of growing popularity among research groups to utilize electrical cable-driven actuation systems in wearable robots; hence, the discussion of this paper was limited to these systems. Furthermore, exosuits have been the most popular design choice among researchers since they have by far made up the highest share of the devices that were reviewed in this paper. These soft wearable robots have been widely used for various purposes, from power augmentation of healthy users to rehabilitation of patients with gait impairments.

The robots reviewed under the title of exoskeleton-based cable-driven robots have the advantage of being lightweight due to the elimination of rigid structures in their design. They are also transparent to the wearer and ultimately solve the problem of joint misalignment. Exoskeleton-based cable-driven robots are able to apply continuous torques to the individual joints of the lower limbs, which makes it easier to control the motion of each joint independently. They can also be used as portable systems that makes it possible to utilize them for power augmentation of healthy users. End-effector-based cable-driven robots have a number of advantages, namely having a simple design that makes it easier to manufacture and a low manufacturing cost compared to other wearable robots. They can also remove the problem of joint misalignment, and due to their unique interface, which is through one end-effector cuff, they can effectively mimic how a therapist would assist patients during lower limb rehabilitation exercises. These robots remove the need for precise positioning of the wearable part on the wearer's leg, making them faster and easier to be donned and doffed. Moreover, exosuits have several advantages over traditional wearable devices. They are primarily made of fabrics, which in addition to making the robot significantly lighter, can eliminate the problem of needing to align a rigid frame to the biological joints of the wearer. The lower inertia of these robots can decrease the metabolic cost of transporting the mass of the suit, which makes it easier to develop fully portable exosuits. Also, Exosuits add minimal restrictions to the natural kinematics of the wearer, as their fabric structure makes them no more restrictive than regular clothing. Due to the inherent compliancy of the exosuits, their control can be less precise, too [62].

Despite all of the abovementioned benefits, there are still some drawbacks in the design of these robots. End-effector-based cable-driven robots are inherently unable to actuate lower limb joints independently. Due to their unique design, they are rarely used as untethered devices that may be the reason why they are not a favorable design choice for power augmentation purposes. Another limitation of end-effector-based cable-driven robots is the need for cables to be in constant tension, which can present some unique challenges in designing controllers for these devices. A significant drawback of exoskeleton-based cable-driven robots is the difficulty of identifying the optimal cable routing that can maximize their range of motion. Another limitation of these robots is the necessity to precisely locate the position of cuffs on the wearer's body that can present challenges in designing controllers for these robots. There are also some drawbacks to the design of exosuits. The design of exosuits cannot allow the support of compressive loads, and the loads exerted by the robot are applied mainly parallel to the wearer's body, in the form of shear forces. Exosuits also present challenging requirements for sensing and actuation [118]. Because, generally, exosuits are not able to provide continuous assistive forces, rather provide small bursts of assistive power in specific periods in the gait cycle, designing a metabolically beneficial controller is more challenging for them.

The benefits of wearable devices depend on the effectiveness of power transmission to the user's body [119]. Exoskeleton-based cable-driven robots and exosuits mainly apply assistive

Table 3
An overview of exosuits.

Name/ Institution	Mono-articular/ Multi-articular load path	Tethered/ Untethered	Joints	Number of actuators	Application
Asbeck et al. [62]	Multi-articular	both	Ankle plantarflexion and hip flexion	1 Electrical Bowden cable-driven per leg	Power augmentation in loaded and unloaded treadmill walking
Bae et al. [89]	Combination of 1 multi-articular and 1 mono-articular	both	Ankle plantarflexion and hip flexion, Ankle dorsiflexion	2 Electrical Bowden cable-driven per leg	Rehabilitation of post-stroke patients
Asbeck et al. [68]	Combination of 1 multi-articular and 1 mono-articular	Untethered	Ankle plantarflexion and hip flexion, Hip extension	1 Electrical Bowden cable-driven for each load path on both legs (2 in total)	Power augmentation in loaded treadmill and over-ground walking
Asbeck et al. [73]	Mono-articular	both	Hip extension	1 Electrical cable-driven per leg	Power augmentation in loaded and unloaded treadmill and over-ground walking, Unloaded over-ground jogging and running
Park et al. [98]	Mono-articular	Tethered	Knee extension	1 Electrical Bowden cable-driven per leg	Rehabilitation of post-stroke or Cerebral Palsy patients
ReStore [97]	Combination of 2 mono-articular	both	Ankle plantarflexion, Ankle dorsiflexion	2 Electrical Bowden cable-driven per leg	Rehabilitation of post-stroke patients
SSEX [74]	Mono-articular	Untethered	Hip extension	1 Electrical Bowden cable-driven for both legs	Power augmentation in over-ground walking
Knee exosuit [75]	Combination of 2 mono-articular	Untethered	Knee flexion, Knee extension	1 Series Elastic Tendon Actuator (SETA) per leg	Power augmentation in stair ascent and descent
Sharbafi et al. [76]	Combination of 2 multi-articular	Untethered	Hip and knee flexion and extension	2 Electrical variable stiffness actuators per leg	Power augmentation in over-ground walking
Bartenbach et al. [99]	Multi-articular	Untethered	Hip and knee extension	1 Electrical Bowden cable-driven per leg	Rehabilitation
Myosuit [100]	Multi-articular	Tethered	Active hip and knee extension, Passive hip and knee flexion	1 Electrical Bowden cable-driven per leg, 2 Elastic passive elements per leg	Rehabilitation
XoSoft EU Projects [101]	Combination of 2 mono-articular	Untethered	Hip and knee flexion	2 Quasi-Passive Actuators (QPAs) per leg	Rehabilitation of post-stroke patients and the elderly
WeARS [102]	Multi-articular	Untethered	Hip flexion and extension, and ankle plantarflexion and dorsiflexion	2 Electrical cable-driven per leg	Rehabilitation of post-stroke patients and the elderly
Yeung et al. [103]	Mono-articular	Untethered	Ankle dorsiflexion	1 Electrical cable-driven per leg	Rehabilitation of foot-drop
Chen et al. [104]	Combination of 1 multi-articular and 1 mono-articular	Untethered	Hip and knee extension, Hip flexion	2 Electrical Bowden cable-driven per leg	Assistance in walking of different terrains
Park et al. [105]	Multi-articular	Untethered	Hip and knee extension	1 Electrical Bowden cable-driven per leg	Assistance in stair ascent and sit to stand
Jin et al. [106]	Mono-articular	Untethered	Hip flexion	1 Electrical cable-driven per leg	Assistance for the elderly in walking
HIMICO [107]	Mono-articular	Untethered	Hip flexion and extension	2 Electrical wire-driven per leg	Assistance in the activities of daily life
Hitexo-suit [108]	Mono-articular	Untethered	Knee extension	1 Twisted String Actuator (TSA) per leg	Assistance in stair ascent
Knee-tendon suit [109]	Mono-articular	Untethered	Knee extension	1 Electrical Bowden cable-driven per leg	Assistance in stair ascent and walking
Cross-wire assist suit [110]	Mono-articular	Untethered	Hip extension and flexion	4 Electrical cable-driven per leg	Rehabilitation

forces parallel to the human body. A major disadvantage of this power transmission is that the amount of applicable shear force is limited to the comfort level of the wearer. The forces exerted parallel to the skin can cause slippage, chaffing, and even pain or injury if not applied in minimal and intermittent levels [120]. There have been studies on the characterization of these comfort limits for different parts of the human body [121]. In order to avoid problems such as slippage and device deformation, higher compressive forces should be applied at connection cuffs by tightening them to the wearer's body as much as possible. However, the amount of possible circumferential compression at lower limbs is also limited. There have been studies to characterize the magnitudes of these circumferential compression forces that can cause discomfort or pain [122,123].

With regards to the application of the devices that have been introduced in this study, two main fields can be identified, namely rehabilitation of users with gait impairments and power augmentation of healthy subjects. Exoskeleton-based robots have been used for rehabilitation of post-stroke patients, and have shown promise in being able to increase step height and maximum joint angles with long-lasting impacts on gait patterns of patients in preliminary experiments. These devices have also been successful in addressing the issue of foot-drop, which is a common gait impairment among post-stroke patients. Moreover, end-effector-based robots have been exclusively used for rehabilitation purposes, such as Straight Leg Rise (SLR) trainings and treadmill walking. Experiments on patients with Cerebral Palsy, incomplete Spinal Cord Injury, or chronic stroke have shown the effectiveness of these devices in improving the over-ground walking speed and the 6-minute walking distance of patients. Long-term studies have also shown that these improvements in movement abilities of patients are long-lasting after repeated use. Furthermore, exosuits have been utilized in rehabilitation trainings of post-stroke and Cerebral Palsy patients. Increasing foot clearance in the swing phase of gait, which addresses the issue of foot-drop, and providing assistive power during the push-off phase of walking are among the most significant benefits of these devices for patients. Additionally, since exosuits have shown the ability to substantially reduce the metabolic cost of walking, they were proven to be beneficial in assisting the elderly in their activities of daily life. Apart from rehabilitation and assistive purposes, exoskeleton-based robots and especially exosuits are widely used for power augmentation of healthy users in various tasks from unloaded and loaded over-ground walking to jogging and running. Exoskeleton-based robots that are designed to assist users in loaded and unloaded gait have shown significant metabolic cost reductions of up to 11%. Similarly, exosuits have shown encouraging metabolic cost reductions in various experiments as explained in detail in Section 5. It is worth noting that exosuits are more popular among researchers for power augmentation purposes, and they have shown considerable metabolic cost reductions for walking, jogging, and running.

As established in this section, exosuits and exoskeleton-based cable-driven robots are limited in the amount assistive force they can provide. For example, exosuits cannot generally exceed 40% of joint torques necessary for normal gait, which is only limited by the maximum shear force that the wearer can support. Hence, these devices can generally only be used by healthy users or those with some level of residual movement abilities. Consequently, these devices cannot be used for patients who are in the early stages of recovery. Therefore, future designs aimed at solving the problem of joint misalignment through removing the rigid structure of the device should focus on finding viable solutions to enable their design to apply higher level of assistive forces to the wearer while maintaining the mentioned benefits of current designs.

7. Conclusion

Many researchers have tried to alleviate the most critical drawbacks of traditional wearable devices, such as the misalignment of the robot's joints and the biological joints of the wearers. One way to address the problem of joint misalignment is to design active or passive mechanisms that align the joints of the robot with those of the wearer. However, it usually leads to heavy and bulky designs that may need several additional actuators. Hence, there has been a growing interest in developing soft wearable robots with cable-driven actuators for the lower limbs in recent years.

A thorough review of the cable-driven lower limb wearable robots aimed to solve the problem of joint misalignments by removing rigid structures, was carried out in this paper. It resulted in the categorization of these robots into three main groups, namely exoskeleton-based robots, end-effector-based robots, and exosuits. Although end-effector-based robots are low-cost and easy to design, they are mainly used as tethered rehabilitation devices. On the other hand, exoskeleton-based robots are more versatile and are used for both the rehabilitation of patients and the power augmentation of healthy users in tethered and portable forms. These robots, along with exosuits, which use textile-based structures instead of rigid cuffs, have an upper limit on the amount of applicable assistive forces based on the comfort level of the wearer.

One possible solution to this major drawback of these robots may be using devices that apply perpendicular forces to the limbs of the wearer, yet not adding rigid links and joints to the device. This can be a viable research direction in the future. By considering the growing trend towards developing robots without a rigid structure and the benefits of using cable-driven actuators in soft robots for the lower limbs, it is essential to try to find possible alternatives to address the limitations of current designs. This paper aimed to provide an overview of current achievements in the field of active soft cable-driven lower limb wearable robots and their limitations for researchers in this field.

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Declaration of competing interest

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