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REVIEW ARTICLE

Recent developments and challenges of lower extremity exoskeletons

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Summary The number of people with a mobility disorder caused by stroke, spinal cord injury, or other related diseases is increasing rapidly. To improve the quality of life of these people, devices that can assist them to regain the ability to walk are of great demand. Robotic devices that can release the burden of therapists and provide effective and repetitive gait training have been widely studied recently. By contrast, devices that can augment the physical abilities of able-bodied humans to enhance their performances in industrial and military work are needed as well. In the past decade, robotic assistive devices such as exoskeletons have undergone enormous progress, and some products have recently been commercialized. Exoskeletons are wearable robotic systems that integrate human intelligence and robot power. This paper first introduces the general concept of exoskeletons and reviews several typical lower extremity exoskeletons (LEEs) in three main applications (i.e. gait rehabilitation, human locomotion assistance, and human strength augmentation), and provides a systemic review on the acquisition of a wearer's motion intention and control strategies for LEEs. The limitations of the currently developed LEEs and future research and development directions of LEEs for wider applications are discussed.

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Introduction

The ageing population is a global issue, and physical deterioration and frailty in elderly people has become a socioeconomic problem in many countries. A survey from the United Nations reveals that people older than 60 years represented ~11.5% of the global population in 2012, and this percentage will be nearly doubled by 2050 [1]. By the year 2050, the ageing problem will be even worse in China and European countries where >30% of the population will consist of elderly people. The frailty of elderly people is reflected by reduced daily physical activities such as walking less frequently because of significantly reduced muscle mass and strength. In the worse instances, their muscles could further deteriorate and they may become bedridden or immobilized, which may accelerate the deterioration of the neuromusculoskeletal systems and their interactions [2—4]. Stroke is a major disease that may lead to a mobility disorder, and nearly three-quarters of all strokes occur in people older than the age of 65 years. The increased number of stroke patients in an ageing society will also result in many health care issues [5,6].

In addition to age-related pathologies, the number of patients experiencing mobility impairment caused by spinal cord injury (SCI) is also increasing because of accidents and diseases [7,8]. Spinal cord injury predominantly occurs in people under the age of 30 years [9]; therefore, the financial burden imposed on family and society is long-term and high. Patients who have a complete SCI lose motor and sensory functions in their lower limbs. In addition, they are at increased risk for several secondary medical consequences of paralysis such as osteoporosis, muscle atrophy, obesity, coronary heart disease, diabetes, insulin resistance, impaired bowel and/or bladder function, and pressure ulcers [10,11]. In addition, patients who have various diseases and injuries such as cerebral paralysis and orthopaedic injuries have a dysfunction in the lower extremities. Impaired mobility would significantly reduce life expectancy, and thus rehabilitation training is needed to help these patients recover and regain mobility. Therefore, it is necessary and impactful to develop assistive devices that utilize state-of-the-art technologies to help disabled people regain the ability to stand and walk, and release therapists from the heavy work of rehabilitation training [12].

Apart from the demands in health care, the applications of robotic assistive devices for human strength augmentation are also in great need. Heavy objects are usually transported by wheeled vehicles. However, many environments such as rocky slopes and staircases cause significant challenges to wheeled vehicles. Legs can adapt to a wide range of extreme terrains, and therefore legged locomotion is a desired method of transportation in these circumstances. Therefore, a leg exoskeleton can free people from much of the labour and burden of many types of manual work, lessen the likelihood of injury, and improve the efficiency of work.

An exoskeleton is a wearable bionic device that is equipped with powerful actuators at human joints, and integrates human intelligence and robot power [13—17]. With a built-in multisensor system, an exoskeleton can acquire wearer's motion intensions and accordingly assist the wearer's motion. It can apply external force/torque to the wearer's limbs under control, and hence provide user-initiated mobility. The exoskeleton enhances the strength of the wearer's joints. For example, an exoskeleton allows people with mobility disorders to regain the ability to stand and to walk over the ground, upstairs, and downstairs. Compared to traditional physical therapy, exoskeleton assistive rehabilitation has the advantages of reducing the work of therapists, allowing intensive and repetitive training, and it is more convenient to use for quantitatively assessing the recovery level by measuring force and movement patterns. In other applications, it can also help an able-bodied person carry heavy loads. Therefore, with the help of an exoskeleton, wearers can achieve a high level of performance.

In the past several decades, the progress in the development of exoskeletons has been remarkable. Universities, research institutes, and industrial companies have been actively performing research in this field, especially in recent years. Several exoskeleton systems have been developed and tested. Based on the part of the human body the exoskeleton supports, exoskeletons can be classified as upper extremity exoskeletons, lower extremity exoskeletons (LEEs), full body exoskeletons, and specific joint support exoskeletons [18—24].

This paper primarily focuses on the LEE and discusses some typical LEEs that have been developed worldwide. These exoskeleton systems are classified into three categories (discussed in the section "Classification of LEEs"), according their different applications and target users. The human—exoskeleton motion data acquisition and analysis and control strategies for LEEs are then reviewed. The limitations of current LEEs and relevant research and development directions are also discussed.

Classification of LEEs

LEEs are primarily developed for three types of applications. The first application focuses on gait rehabilitation (i.e. helping patients with mobility disorders in the rehabilitation of musculoskeletal strength, motor control, and gait). Exoskeleton-based rehabilitation also releases the heavy burden of therapists in traditional physical therapy [13]. The second application is human locomotion assistance, which is targeted at paralyzed patients who have lost motor and sensor function in their lower limbs. Assistance from exoskeletons enable these patients to regain the ability to stand up, sit down, and walk, just as an able-bodied person [14,15]. The third application of exoskeletons is aimed at enhancing the physical abilities of able-bodied humans (i.e. human strength augmentation) [20].

Lower extremity exoskeletons for gait rehabilitation

Elderly people with weakened muscle strength may not be able to walk as frequently as before, and may also lose their stability during walking. Loss of motor control can occur because of many other medical conditions.

Neurological injuries such as cerebral paralysis, stroke, infectious diseases (e.g. polio), and SCI may result in significant muscle weakness and impaired motor control. Orthopaedic rehabilitation training generally involves performing specific movements to provoke motor plasticity and ultimately improve motor recovery. It is crucial for patients to improve their musculoskeletal strength and motor control and to minimize functional deficits.

In the traditional rehabilitation therapies, intensive labour should be involved, and physical therapists have to provide the patients with highly repetitive training that is usually inefficient [25]. Lower extremity exoskeletons developed for rehabilitation can provide intensive repetitive motions for the patients, and hence therapists can be released from the heavy work in physical therapy. In this situation, therapists can concentrate more on analyzing the patient's gait performance so as to provide more effective rehabilitation [8]. In addition, with the help of exoskeletons, the level of motor recovery of the patients can be assessed quantitatively with the interaction forces or torques measured by the sensors. A new type of robot-assisted rehabilitation is also cost-effective, compared to the traditional labour-intensive rehabilitation.

The Robotic Orthosis Lokomat was developed by Hocoma (Zurich, Switzerland) for gait rehabilitation; it provides functional walking training for patients with mobility dysfunctions in their lower limbs (Figure 1A) [25,26]. The whole Lokomat system is composed of a robotic gait orthosis, a body weight support system, and a treadmill. The patient exercises in a virtual reality environment with constant audio and visual feedback. The orthosis has 4° of freedom (DOFs) in total, and the hip and knee joints are actuated by linear drives to provide assistive torque in the sagittal plane. Force sensors mounted between the actuators and orthosis measure the hip and knee joint torques. The effectiveness of Lokomat as an intervention in gait rehabilitation to improve overground walking function in neurological patients has been verified through worldwide clinical studies [26].

Banala et al [27—29] from the University of Delaware (Newark, DE, USA) developed the Active Leg Exoskeleton (ALEX) for the gait rehabilitation of patients with mobility disabilities. The ALEX has seven DOFs: three at the waist joint, two DOFs at the hip joint (i.e. flexion/extension and abduction/adduction), one DOF at the knee joint (i.e. flexion/extension), and one DOF at the ankle joint (i.e. plantar/dorsiflexion). The hip and knee joints in the sagittal plane are actuated by linear actuators, whereas the other DOFs are passively held by springs. The effectiveness of ALEX has been demonstrated through clinical trials with stroke survivors [28,29]. After training with ALEX, the patients' gait pattern are closer to a healthy gait pattern with increased gait size and walking speeds.

The Ekso GT exoskeleton developed by Ekso Bionics (Richmond, CA, USA) is a wearable exoskeleton suit designed for the assistance and rehabilitation of patients with various levels of lower extremity weakness [30,31] (Figure 1B). It is suitable for a wide range of patients such as paralyzed patients and other patients with lower level of mobility disorder such as stroke survivors. The Ekso GT exoskeleton has six DOFs in total (i.e. 3 DOFs per leg). Its hip and knee joints are active and can provide assistance in

Figure 1 Exoskeletons for gait rehabilitation. (A) The Robotic Orthosis Lokomat (Image credit: Hocoma, Zurich, Switzerland). (B) The Ekso Exoskeleton (Image credit: Ekso Bionics, Richmond, CA, USA).

the sagittal plane. The ankle joints are passive and sprung. For the rehabilitation application, it has the feature of "variable assist," which can adjust the assistance level provided by the exoskeleton, based on the need of an individual patient [30]. Clinical studies have verified that gait training with the Ekso GT exoskeleton supports patients in relearning a correct step pattern and allows them to take a greater number of steps at a faster speed, compared to traditional rehabilitation.

Lower extremity exoskeletons for human locomotion assistance

Lower extremity exoskeletons developed for human locomotion assistance are primarily used to help paralyzed patients who have completely lost mobility in the lower limbs. Exoskeletons can provide external torque at the positions of human joints to replace the patients' deficient motor function, and thereby give these patients greater strength to regain the ability to perform essential daily life motions such as standing up, sitting down, and walking [14,15].

The ReWalk exoskeleton developed by ReWalk Robotics (Marlborough, MA, USA; Figure 2A) is a LEEs that provides powered hip and knee motion to enable individuals with SCI to stand upright and walk [32,33]. It is the first exoskeleton suit cleared by the U.S. Food and Drug Administration in 2014 to be used as a personal device at home and in the community. The exoskeleton is controlled by on-board computers with motion sensors, restores self-initiated walking by sensing the forward tilt of the upper body, and mimics the natural gait pattern of an able-bodied person. Based on clinical study results of the ReWalk exoskeleton [15,34], paralyzed patients can practically stand upright and walk with increased independence and their life quality is greatly improved. These results also indicate that the patients experienced a reduction in secondary complications resulting from life in a wheelchair such as depression and neuropathic pain.

The Vanderbilt exoskeleton developed by Goldfarb et al [17,35] is another LEE that enables paralyzed patients to perform basic motions such as walking, sitting, standing, and walking up and down stairs. It adopts a modular-based design that paralyzed patients themselves can quickly assemble and put on or disassemble. Each thigh segment is designed with two brushless direct current (DC) motors, which are used to actuate the hip and knee joints. Its total weight is only 12 kg, which is relatively light, compared to other similar exoskeletons. This exoskeleton has been implemented in a patient with a T10 motor and sensory complete injury and the exoskeleton can provide a repeatable gait with knee and hip joint

A B

Figure 2 Exoskeletons for locomotion assistance. (A) The ReWalk Wearable System (Image credit: ReWalk Robotics, Inc., Marlborough, MA, USA). (B) The lower extremity exoskeleton developed at the Chinese University of Hong Kong (Hong Kong, China).

amplitudes that are similar to those observed during non-SCI walking [35]. With the help of the exoskeleton, the patient is able to stand up and sit down, walk, turn, and go up and down stairs.

The LEEs developed at the Chinese University of Hong Kong (CUHK-EXO) in Hong Kong, China also targets locomotion assistance of paralyzed patients (Figure 2B). The exoskeleton has six DOFs in total, among which hip and knee flexion/extension are actuated by DC motors and ankle joints are passive. A pair of smart crutches equipped with force and attitude sensors were designed for the exoskeleton system for comfortable and stable assistance. Smart phone application was also developed to make the exoskeleton system easier for patients and therapists to learn and use. The developers have recruited four paralyzed patients for relevant clinical trials.

Lower extremity exoskeletons for human strength augmentation

Lower extremity exoskeletons developed for human strength augmentation can enhance human strength and endurance during locomotion, and enable individuals to perform tasks that they cannot easily perform by themselves. They can provide soldiers, disaster relief workers, wildfire fighters, and other emergency personnel the ability to carry heavy loads such as food, rescue equipment, first-aid supplies, communications gear, and weaponry.

Approximately two decades ago, a research group at the University of California Berkeley (Berkeley, CA, USA) began working in the field of exoskeletons. The Berkeley Lower Extremity Exoskeleton (BLEEX), shown in Figure 3A, was developed to help soldiers to carry heavy loads [20,36]. It has seven DOFs per leg: three DOFs at the hip joint, one DOF at the knee joint, and three DOFs at the ankle joint. Among these DOFs, hip flexion/extension, hip abduction/adduction, knee flexion/extension, and ankle dorsiflexion/plantarflexion are actuated by linear hydraulic actuators. The remaining DOFs are passively actuated by steel springs and elastomers. It has been reported that BLEEX wearers can walk at an average speed of 1.3 m/s while carrying a 34 kg payload. Several other exoskeletons have also been developed by this group: ExoHiker, ExoClimber, and Human Universal Load Carrier [31].

The Hybrid Assistive Limb (HAL) was developed by the University of Tsukuba in Tsukuba, Japan for several applications such as helping healthy people to enhance their strength and assisting people with mobility disorders to perform essential daily life motions [37–39]. The HAL systems have different configurations such as a full body version, a two-leg version, and a single leg version. The fifth version of HAL (HAL-5) is a full body exoskeleton designed for augmenting the strength of able-bodied persons and for rehabilitation [38]. The HAL-5 weighs ∼23 kg


[redacted]
[redacted]

Figure 3 Exoskeletons to augment human strength. (A) The Berkeley Lower Extremity Exoskeleton (BLEEX) (Image credit: Professor Kazerooni of the University of California, Berkeley, CA, USA). (B) The HEXAR-HL35 Exoskeleton (Image credit: Seungnam Yu of the Korea Atomic Energy Research Institute, Daejeon, Korea).

with 15 kg worn on the lower body. The HAL-5 has eight controllable joints, which include the lower limb joints and upper limb joints, and is actuated by electric motors. It allows workers to carry heavier loads and function as an aid in emergency rescue. The HAL-5 can help a person to hold and lift heavy objects weighing up to 70 kg.

The Hanyang Exoskeleton Assistive Robot (HEXAR) is a lower limb exoskeleton developed by Hanyang University in Seoul, South Korea [40,41] (Figure 3B). It is an under-actuated wearable exoskeleton system developed to help individuals carry heavy loads. The exoskeleton has 15 DOFs in total: seven DOFs for each leg and one DOF at the waist joint. Only the hip and knee flexion/extension DOFs are actuated by electrical motors. This exoskeleton is composed of a central torso harness module, a hip joint module, a knee joint module, and an ankle joint module. The torso harness module connects the exoskeleton and the wearer. With a constant force mechanism, the hip joint module bears the weight of the upper exoskeleton system and its loading. The ankle joint module bears the total weight of the exoskeleton system and provides a propulsion force for walking with its own elastic deformation via the potential energy. The wearer can walk at a speed of 1.5 km/h with a loaded 40 kg weight.

A summary of currently available LEEs mentioned previously is in Table 1. The most widely used actuators are electric motors owing to their high efficiency, control precision, and power-to-weight ratio. For gait rehabilitation and human locomotion assistance, the exoskeleton hip joints (i.e., flexion/extension) and knee joints (i.e., flexion/extension) are usually active, whereas the ankle joints are passive. This is because the main functions of human ankle joints during walking are body weight support and propulsion [42]. In gait rehabilitation with the exoskeleton, the body weight support system and treadmill are normally used so as to realize similar functions of human ankle joints. In human locomotion assistance, a pair of crutches are usually used to achieve the same function. Weight, space limitation, and cost-effectiveness should also be considered in the design of an exoskeleton. Therefore, the ankle joints of the exoskeletons with gait rehabilitation and human locomotion assistance application are usually passive.

Besides the exoskeletons mentioned previously, many other exoskeletons have been developed all over the world. To help patients with mobility disorders, the LOPES exoskeleton was developed by the University of Twente (Enschede, The Netherlands) as a gait training device [43], the ANdROS exoskeleton was developed by Harvard Medical School (Cambridge, MA, USA) and Spaulding Rehabilitation Hospital (Charlestown, MA, USA) as a wearable and portable gait rehabilitation tool [44], and a human–machine interface between a paralyzed individual and rehabilitation exoskeleton was developed by Shanghai Jiao Tong University (Shanghai, China) to help patients with lower limb paralysis [45]. To augment the physical abilities of healthy people, the HERCULE exoskeleton, which was developed by RB3D in Auxerre, France, is used to improve the wearer' strength [46]; a nurse-assisting exoskeleton was developed by the Kanagawa Institute of Technology in Atsugi, Japan to

Table 1 Overview of currently available lower extremity exoskeletons.

Exoskeleton name	Application	Actuated DOF	Actuator
Lokomat [25]	Gait rehabilitation	Hip flexion/extension & knee flexion/extension (double legs)	Electric motor
ALEX [29]	Gait rehabilitation	Hip flexion/extension & knee flexion/extension (single leg)	Linear motor
Ekso [31]	Gait rehabilitation & human locomotion assistance	Hip flexion/extension & knee flexion/extension (double legs)	Electric motor
ReWalk [33]	Human locomotion assistance	Hip flexion/extension & knee flexion/extension (double legs)	Electric motor
Vanderbilt exoskeleton [35]	Human locomotion assistance	Hip flexion/extension & knee flexion/extension (double legs)	Electric motor
CUHK-EXO	Human locomotion assistance	Hip flexion/extension & knee flexion/extension (double legs)	Electric motor
BLEEX [20]	Human strength augmentation	Hip flexion/extension, hip abduction/adduction, knee flexion/extension & ankle dorsiflexion/plantarflexion (double legs)	Linear hydraulic actuator
HAL-5 [38]	Human strength augmentation & gait rehabilitation	Hip flexion/extension, knee flexion/extension, shoulder flexion/extension & elbow flexion/extension (full body)	Electric motor
HEXAR [41]	Human strength augmentation	Hip flexion/extension & knee flexion/extension (double legs)	Electric motor

ALEX = Active Leg Exoskeleton (University of Delaware, Newark, DE, USA); BLEEX = Berkeley Lower Extremity Exoskeleton (University of Berkeley, Berkeley, CA, USA); CUHK-EXO = lower extremity exoskeleton developed at the Chinese University of Hong Kong (Hong Kong, China); DOF = degrees of freedom; HAL-5 = Hybrid Assistive Limb (5th version; University of Tsukuba, Tsukuba, Japan); HEXAR = Hanyang Exoskeleton Assistive Robot.

help nurses transfer patients [47]; a soft lower extremity robotic exosuit was developed by Wehner et al [48] at Harvard University (Cambridge, MA, USA) to augment normal muscle function in healthy individuals; and an under-actuated leg exoskeleton for load-carrying augmentation was developed by the Massachusetts Institute of Technology Media Laboratory (Cambridge, MA, USA) [49,50].

Human—exoskeleton motion data acquisition and analysis

To control the exoskeleton to provide intelligent, effective, and comfortable assistance to the wearer, it is essential to acquire different types of motion data of the human—exoskeleton system during movement. Measured motion data can be used to recognize the wearer's motion intention, analyze the motion status and gait pattern, and evaluate the motion performance. There are three types of biomechanical data generally associated with human motion: kinematic data such as body posture and joint angles; kinetic data such as human joint torque, ground reaction forces, and interaction force between wearer and exoskeleton; and bioelectric data such as electromyographic (EMG) signals and brain signals. Different types of sensors are usually equipped in the exoskeleton system to measure these motion data. For example, encoders, potentiometers, and an inertia measurement unit (IMU) are usually used to measure kinematic data, whereas force/torque sensors are used for kinetic data acquisition. With multiple sensor system in hardware and sensor fusion algorithms in the software, exoskeleton controllers can acquire and process motion data for motion control purpose.

On acquiring motion data, an exoskeleton's motion assistance can be initiated according to the wearer's intention. For example, in the multisensor system of the CUHK-EXO, the IMUs are mounted on the backpack to obtain the wearer's trunk posture and pressure sensors are designed in the insoles and smart crutches to detect the ground contact condition of the human—exoskeleton system. With this information, the wearer's centre of gravity can be calculated in real-time and the wearer's motion intention can be estimated by detecting the change in motion data. In controlling the ReWalk exoskeleton [33], a tilt sensor is used to estimate the wearer's walking intention. The forward tilt of the wearer's upper body initiates the patient's first step, and a functional natural gait is generated with the repeated body weight shifting.

Because bioelectric signals measured from the wearer directly indicate a human patient's motion intention, they are also frequently used in an exoskeleton system. In the sensing system of the HAL-5 exoskeleton, EMG sensors are attached on the wearer's skin to detect the extensor and flexor muscle activities of the knee and hip joints. Voltage signals associated muscle activities (i.e., myoelectric signals) are measured [37,38]. In the HEXAR exoskeleton [41], a muscle stiffness sensor was developed to obtain the signal for the degree of expansion of a muscle. The measured signals are used to detect the wearer's intention to control the exoskeleton. Bioelectric sensors [51—53] have been used in many exoskeletons. However, there are some inherent limitations to overcome. For example, the calibration of bioelectric sensors takes substantial time, and neighbouring sensor nodes and noise easily interfere with the collected bioelectric signals.

Motion data measured from the human—exoskeleton system are also important to indicate the motion status and gait patterns of the wearer, and can be further used to evaluate motion performance. In HAL-6 LB gait assistance [54], a gait cycle is divided into three phases: the swing phase, the single limb stance phase, and the double-limb stance phase. With the joint angles and floor reaction force measurements, the wearer's gait phase is detected. After the trials, motion data such as joint angles, gait speed, and cadence are saved for the assessment of the exoskeleton assistance effectiveness and the wearer's performance. In the rehabilitation of people with neurologic impairments who use gait training orthosis [55], the wearer's voluntary effort could be estimated based on the measured interaction forces between the wearer and the orthosis. Assistance from the device could then be adjusted in real-time in accordance with the wearer's effort and need.

Control strategies for LEEs

An exoskeleton is attached to the wearer, and integrates human intelligence and robotic power. From the control aspect, the wearer and exoskeleton form a closed loop as a human—exoskeleton cooperation system, as shown in Figure 4. In the exoskeleton system part, reference torque or reference joint trajectory is obtained according to specific assistive function defined. The reference inputs go through the motion controller to produce control signals that drive the actuators. The generated electromagnetic torque of the actuator is used to drive the wearer and the exoskeleton itself. As a result, the interaction torque is applied on the wearer's joints as the external assistance of the desired motion.

In the human—exoskeleton cooperation system, the function of the human body part is different among the three main applications of exoskeletons. In the application of human strength augmentation, the wearer takes charge of the motion planning, and the exoskeleton is expected to follow the wearer's trajectory. When the wearer has a desired motion, his brain will generate nerve signals according to the sensory feedback of the actual motion. The wearer will then activate his muscle to generate joint torque. The actuators are controlled to drive the exoskeleton and external loads to follow the same trajectory of human motion. By contrast, as for the exoskeletons used for the application of gait rehabilitation and human locomotion assistance, joint torque generated by the wearer's muscle is much smaller (even 0 for completely paralyzed patients). Therefore, the wearer's mobility is strongly assisted by the exoskeleton with interaction torque.

Control strategies for gait rehabilitation

The control strategies of exoskeletons in gait rehabilitation can be generally divided into two main categories: (1) trajectory tracking and (2) assist as needed (AAN). In trajectory tracking control, the predefined trajectories of the

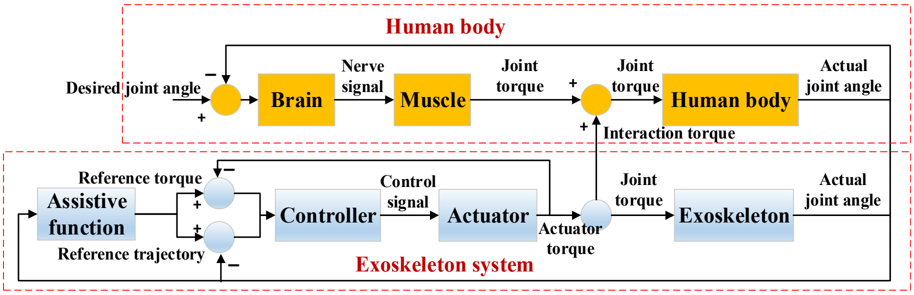

Figure 4 Schematic of the human—exoskeleton cooperation system.

lower limb joints, usually collected from healthy individuals, are used as the control targets [26]. For example, the robotic gait training orthosis developed by Hussain et al [56] is controlled to track reference trajectories. However, by using this kind of control, the wearers are normally passively trained to follow a predefined reference trajectory and their initiatives or motivations are usually not considered. Literature has suggested that physical guiding lower limb movement may decrease motor learning, and the patient's effort and participation in the training, and thus may not achieve effective training [57]. To date, trajectory tracking control is primarily used in LEEs for early stage rehabilitation when patients have very weak muscle strength [58,59].

By contrast, the AAN strategy suggests that the assistive devices only supply as much effort as a patient needs to accomplish training tasks by assessing his or her performance in real-time [8]. The assistance from assistive device is expected to be intelligently adjusted according to the patients' physical conditions and efforts in rehabilitation, so as to encourage their voluntary participation. Hybrid position and force control is one type of exoskeleton control strategy that takes into consideration the joint trajectories and interaction forces between the wearer and exoskeleton. For example, in the control of the ALEX [27,28], the interaction forces between the wearer and ALEX is measured through two force/torque sensors mounted at the thigh and shank. Suitable forces are supplied to the wearers, while considering their actual effort, to assist their leg movements to follow a desired trajectory.

Impedance control is another popular method, after the implementation of the AAN strategy in robot-assisted rehabilitation. The basic idea of impedance control is to regulate the dynamic relation between the assistive device and the wearer by relating the position error (e.g., joint angles) to the interaction force/torque through a mechanical impedance of adjustable parameters. This mechanical impedance is the output impedance of the exoskeleton, which is usually modelled as a mass-damper-spring system. High output impedance will increase the assistance from the exoskeleton to guide the patient's limb onto the reference trajectory. If the patient shows greater effort in the training, the desired output impedance of the exoskeleton will similarly be low to allow the patient to deviate more from the reference trajectory. The output impedance and level of assistance are modified, according to the patient's performance, to realize AAN gait training [55]. Based on the wearer's intention, the exoskeleton can adjust the amount of support to be assisted. Therefore, the wearer will feel more comfortable when walking with the exoskeleton. With an impedance controller, the Lokomat exoskeleton is controlled to support the wearers only as much as needed and stimulate them to produce maximal voluntary participation in gait rehabilitation [25,60]. An adaptive impedance controller was proposed by Hussain et al [55] to control the gait training orthosis that was developed for treadmill training of people with neurologic impairments. With this controller, the exoskeleton can provide interactive robotic gait training, according to the wearer's disability level and voluntary participation.

Control strategies for human locomotion assistance

Trajectory tracking control is the most widely used control strategy for exoskeletons in human locomotion assistance applications. With this control strategy, the joint angles of the exoskeleton and the wearer are precisely controlled to follow the target trajectories. The exoskeleton controller will minimize the deviation between the target and feedback joint angles.

To adopt trajectory tracking control in exoskeletons, reference trajectories of all the active joints of the exoskeleton should be set in advance. Emken et al [61] (Irvine, CA, USA) proposed the teach-and-replay technique to generate the reference trajectory. In their research, the developed ambulation-assisting robot ARTHuR was worn by patients with a SCI but the electrical motors function was not turned on, and the stepping kinematic data were collected with manual assistance. The reference trajectory was generated by replaying the recorded kinematic data. A similar method was used for seven SCI patients by Swift et al [62] (Berkeley, CA, USA) to generate the reference trajectory for the exoskeleton lower extremity gait system (eLEGS) with the Vicon 8 camera motion analysis system. Vallery et al [63] (Zurich, Switzerland) also proposed an online trajectory generation method, called the "complementary limb motion estimation," which is applied for hemiparetic patients. Reference trajectory for the disabled leg was generated online, based on the movements of the unimpaired leg.

Exoskeletons developed with trajectory tracking control include eLEGS, which was developed to help SCI patients to regain mobility. Its control structure is composed of three independent control levels, which includes a human—machine interface that determines the user's intention, a trajectory generation level that translates the user intention into desired joint responses, and a low level controller that computes the output required for the individual motors to produce the desired joint response [62]. The ReWalk exoskeleton, which was developed to help thoracic-level complete SCI patients to walk independently, is also controlled by a predefined trajectory. The Vanderbilt exoskeleton [17], the Robotic Upper Extremity Repetitive Trainer (RUPERT) exoskeleton [64], and a joint-coupled orthosis [65] have also adopted similar control strategies.

Control strategies for human strength augmentation

Hybrid position and force control are the most widely used control strategy for the exoskeletons in the application of human strength augmentation such as transporting or lifting heavy loads tasks. For example, BLEEX is controlled with a hybrid position and force controller, which is only based on the motion data measured from the exoskeleton [66]. In a gait cycle, the exoskeleton's stance leg is controlled with a position controller while its swing leg is controlled with a force controller. In addition, seven inclinometers are worn by wearers to measure their limb and torso angles that are used in the position control. In this way, a good model of the BLEEX torso and payload, which is difficult to obtain because it changes as a payload is added and removed, is not required for the hybrid position and force control.

In different applications, the wearers have different physical conditions, and hence different control strategies should be adopted for the exoskeletons. Even in the same application such as the exoskeletons for gait rehabilitation purpose, different control strategies may be appropriate in different phases of the rehabilitation. In the initial stage of rehabilitation, the trajectory tracking control strategy is suitable when the wearers do not have much strength in their lower limbs. However, after a period of training the patients may have an improved physical condition, and AAN control strategies should be adopted to provide more effective training with the patients' active participation.

Discussion

The exoskeleton systems integrate the advanced technologies of mechanics, materials, electronics, bionics, control technology, and artificial intelligence. In the past few years, the progress in LEE development has been remarkable. There have been great improvements in performance, wearability, and portability of the exoskeletons. In addition, some small and light actuators, comfortable human—exoskeleton interfaces, and efficient and long-lasting power supplies have been developed. Furthermore, developments in human body models and gait biomechanics provide the necessary background for the design of devices that closely mimic the dynamics of the wearer's motion. However, many challenges remain in the development and application of LEEs.

Limitations of the currently developed LEEs

Several challenging topics exist with regard to the development of functional, autonomous exoskeletons. Most currently developed LEEs are heavy with limited torque and power. This factor makes the exoskeletons less portable, especially for paralyzed patients. Some of the wearer's movements are also difficult to achieve. For example, a paralyzed patient still needs the help of crutches to support the body weight during sit-to-stand movements. Cost is also an important issue. Most current exoskeletons in the market are very expensive and only affordable to a small number of people.

Mechanical design and actuators limit the performance of current LEEs. The mechanical design of many current prototypes affects and alters the biomechanics of the normal human gait. This factor results in a big metabolic cost and discomfort to the wearer, and limits the length of usage time. The mechanical structure of an exoskeleton should be customized to an individual's own contours and anatomical needs. Lightweight actuators with high power and efficient transmissions are also very important issues, which researchers in this field will have to face. In addition, the noise of the exoskeletons that makes the wearers uncomfortable should be minimized.

Furthermore, another limitation is the information exchange between the wearer and the exoskeleton system. Some intentions of the wearer cannot be obtained accurately and quickly by the sensors used in the current exoskeletons. Thus the advancements in neural technology will be of critical importance in the field of exoskeletons. In applying human locomotion assistance, most currently developed exoskeletons could only help paraplegic patients stand up and sit down, walk on a level ground, and climb stairs. Many other functions are needed such as entering cars, side stepping, walking on uneven terrains such as trails, beach, and grass. All of these terrains currently limit the wide application of exoskeletons in patients' daily lives.

Future research and development directions of LEEs

To design an effective, stable, low-mass and economical exoskeleton, future LEE research and development should focus on the following aspects.

Low weight. To make the LEEs more portable and convenient for the wearers to use, the exoskeletons should be as light as possible. The materials of the mechanical structure and actuators are the main factors that limit the weight of the exoskeletons. Therefore, the materials used to create the exoskeleton frame should have the characteristics of low density, high intensity, and toughness (e.g., the carbon fibre). Some parts of the exoskeletons could be produced by three-dimensional printing technology.

Actuators. For the active joints of LEEs, actuators with a small volume, a high power-to-weight ratio, high efficiency, and compliance are needed. Efforts are also needed to improve the actuator's durability and lifetime at high levels of performance. In the future, pneumatic muscle actuators that are easily manufactured, use a similar principle as the natural skeletal muscles, and have limited maximum contraction may be widely used in exoskeletons, especially for rehabilitation applications. Some new actuators should also be investigated for exoskeletons such as the multifunctional actuator developed by Guo and Liao [67] which integrates motor, clutch, and brake functions into a single device, and the bilateral-servo actuator [68]. Furthermore, to improve the transmission efficiency, an efficient transmission mechanism should be designed for the exoskeleton active joints such as reducing the transmission unit and adopting high precision gears.

Human—exoskeleton interface. The LEE is attached to the user at multiple points using padding and straps to help support his or her body and couple the body to the exoskeleton. Paraplegic patients are very susceptible to skin wounds and pressure sores because they cannot feel an irritation or pressure point. Therefore, the pads must be carefully designed to prevent any skin issues during use of the exoskeleton. The interface should be customized to an individual's own contours and anatomical needs. The exoskeleton dimensions should also be adjustable to fit with different wearers. Furthermore, today's exoskeletons are still not sufficiently intelligent to help the wearer move in accordance with their intention. This factor is because of the lack of information exchange between the wearer's nervous system and the exoskeleton. The control systems of the future exoskeletons may use the EMG signals from the sensors placed inside the muscle to assess an individual's motor intention. The neural implants may also be used in the future. An electroencephalogram (EEG)-based interface could even be developed to control the exoskeletons if limitations such as high sensitivity and overlapping of different electrical activities generated by different cortical areas can be solved [69]. The control systems implemented for the exoskeletons should meet requirements such as AAN, safety, and stability.

Safety. In the development of LEEs, safety remains a crucial issue because the wearer is strapped inside a powerful exoskeleton suit. The mechanical structure of an exoskeleton should be designed with physical stops, which are placed to limit the range of motion of each joint. The physical stops should withstand the maximum torque that the actuators can apply. Safety should also be incorporated in the exoskeleton control system. Additional control strategies should also be developed to guarantee the wearer's stability and safety in emergency conditions. Velocities and interaction force should be detected in real-time. Emergency shutdown systems should also be designed for the exoskeletons. Furthermore, other safety factors such as the safety of the battery should also be taken into account in the design of an exoskeleton.

Energy efficiency. To have a mobile system, most developed LEEs adopt independent power using batteries. However, limited by current battery technology, the weight of the battery pack of an exoskeleton system is usually heavy. The energy efficiency of the exoskeletons needs to be improved to prolong the operation time. Innovative structures that can store and release energy in different phases of the gait cycle should be investigated. For example, Wiggin et al [70] proposed a biologically inspired design with a novel "smart-clutch" to engage and disengage the parallel springs in the exoskeleton. The developed ankle exoskeleton with this mechanism reduced the metabolic energy expenditure of walking in patients with weak ankle plantar flexors (e.g. SCI, stroke, normal ageing). By contrast, the control algorithm and gait pattern of the exoskeletons also need to be further optimized, based on different applications, to save energy. For example, Kim et al [71] have made some attempts in this direction by proposing an energy-efficient gait pattern and swing trajectory of the exoskeleton through function distribution analysis.

Lower cost. The price of the LEEs is also a challenging issue in its development. The existing exoskeleton systems are out of financial reach for most people with mobility disorders. An exoskeleton may be as expensive as US $100,000 or US $130,000 [72], which most people cannot afford. Researchers should make efforts to develop exoskeletons that are available to most disabled people. With improvements in robotics and mechatronics technologies, the price of high performance actuators and sensors could hopefully be lowered to make the exoskeleton system more affordable.

Conclusion

With an ageing society and an increase in patients with impaired mobility, there is no doubt that LEEs will have important roles in therapy assistance and in musculoskeletal rehabilitation. In addition, the use of LEEs is also promising in the industry to assist able-bodied workers with heavy-duty tasks. In this paper, the authors introduced typical and currently available LEE systems. The sensors and methods used in exoskeletons to acquire the wearer's motion intention and analyze motion performance were then discussed. Control strategies of LEEs for each type of applications were also summarized. The limitations of the current available LEE systems were reviewed and discussed. To improve current LEEs for future wide applications, efforts should be focused on the aspects of materials, actuators, human—machine interface, safety, energy efficiency and cost-effectiveness of exoskeletons.

Conflicts of interest

The authors have no conflicts of interest to declare.

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