Chapter 8
Exoskeletons for Lower Limb Applications: A Review

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8.1 Introduction

Exoskeletons can be defined as wearable or robotic devices that assist people in performing their daily life movements, thus boosting the user's performance. They are used for regaining mobility, thereby allowing people to walk, stand and sit [13]. Exoskeletons, consisting of sensors, actuators and control elements, are utilised in various applications requiring carrying heavy loads or for rehabilitation and assistance of paralysed patients [32, 34].

Different classifications of exoskeletons have been proposed as shown in Fig. 8.1 [1, 12, 30, 34]. One classification is based on the part of the body the exoskeleton supports. This classifies exoskeletons as an upper limb, lower limb or full body. Exoskeletons can also be classified as active, passive or quasi-passive. Active exoskeletons require an energy source to actuate sensors and actuators, whereas passive devices do not require any energy source as they are only formed by mechanical elements such as linkage, springs and dampers. The quasi-passive devices lie between these two types [53]. Depending on the application, exoskeletons can be classified as devices for gait rehabilitation, human locomotion assistance and human strength augmentation. Finally, depending on the type of actuators, exoskeletons can be classified as electric, pneumatic or hydraulic actuators.

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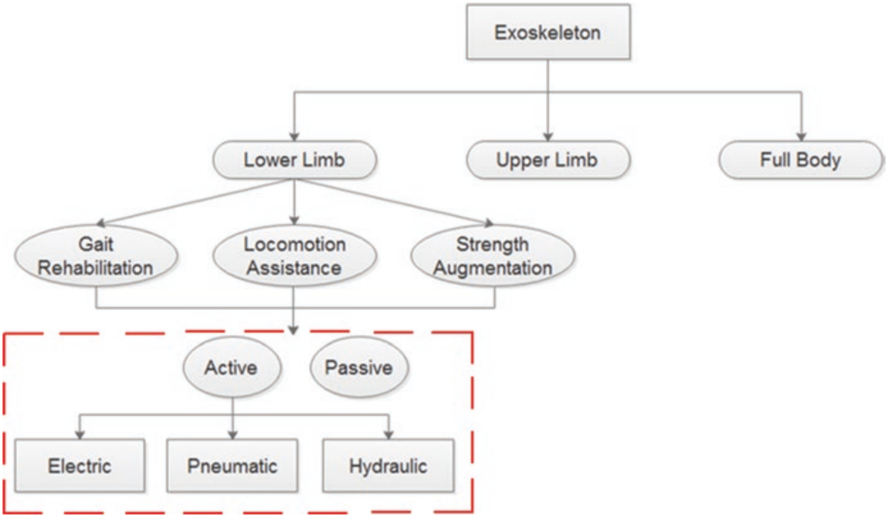


Fig. 8.1 Classification of exoskeletons with particular emphasis on lower limb systems

This is a very active research domain. According to a research through PubMed (July 2018), 140 papers were published under the topic lower limb exoskeleton design since 2003 (44% published in the last 2 years). The majority of the papers published (32 papers) focuses on control aspects including safety control, with particular emphasis on mechanical design aspects (12% of the papers). Human interface aspects are covered by 5% of the papers, around 7% covered biomechanical considerations (e.g. kinematic, compatibility, the range of motion) and 14% covered topics such as customisation, low-weight aspects, pressure reduction, actuators and energy expenditure.

This chapter focuses on the current state of the art of lower limb exoskeletons. It starts by presenting a few biomechanics concepts regarding the lower limb part of the human body, which allows understanding of the complex nature of the movements and forces that must be considered to design a proper exoskeleton. Then, the different classes of exoskeleton are described in a detailed way. Research challenges and future perspectives are also presented.

8.2 Lower Limb Biomechanics and Locomotion

Understanding human locomotion and the anatomy of the lower limb are essential in the design of exoskeletons [22]. The human lower extremity consists of three main joints: the hip, the knee and the ankle joints [54], shown in Fig. 8.2. The human lower limb can be simplified to seven degrees of freedom (DOFs) (three at the hip, one at the knee [55] and three at the ankle [79]) in different planes of the body [22]. Degrees of freedom and planes for lower limb motion are shown in Table 8.1.

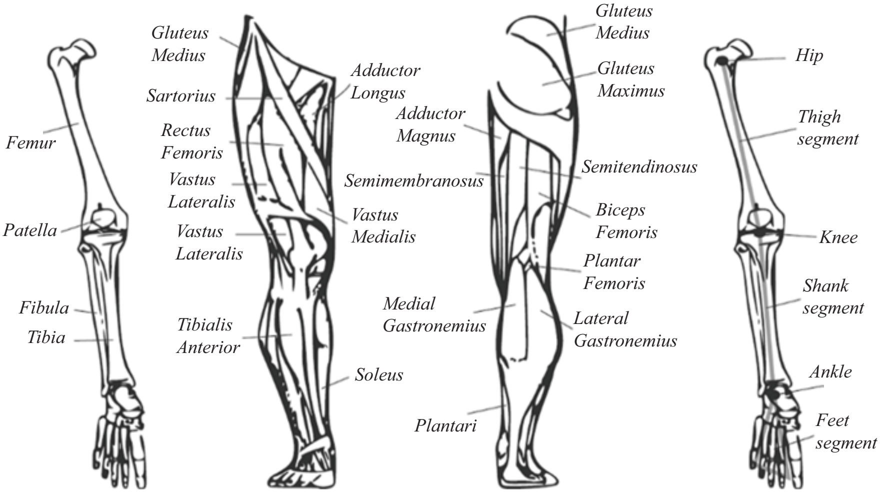


Fig. 8.2 Lower limb anatomy [56]

Table 8.1 The allowed motions at lower limb joints in different planes of the body

Joint	Plane	Motion
Hip	Sagittal	Flexion
		Extension
	Coronal	Adduction
		Abduction
	Transverse	Internal rotation
		External rotation
Knee	Sagittal	Extension
		Flexion
Ankle	Sagittal	Dorsiflexion
		Plantarflexion
	Transverse	Adduction
		Abduction
	Coronal	Inversion
		Eversion

Movement is a complex neural and biomechanical process, determined by the interaction between the central nervous system, peripheral nervous system and the musculoskeletal system [67]. Human gait is an essential part of daily living. It consists of two phases (stance phase and swing phase) and is enabled by joint movement in the lower limb. The designers of exoskeletons need to understand these joints kinematics and the gait cycle to develop effective devices. The stance phase is divided into four intervals, namely, the loading response (LRP), mid-stance (MST), terminal stance (TST) and pre-swing (PSW) [56]. The swing phase comprises three key periods, namely, initial swing (ISW), mid-swing (MSW) and terminal swing (TSW). The human gait cycle is illustrated in Fig. 8.3.

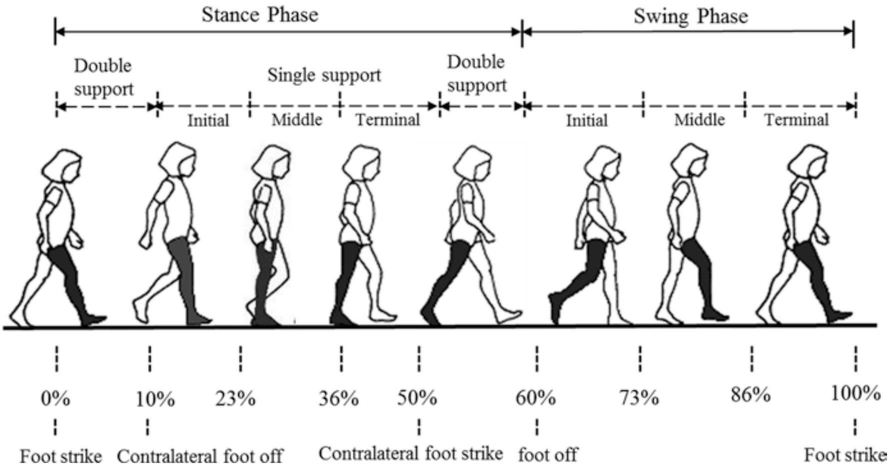


Fig. 8.3 Human gait cycle

The hip joint is located between the head of the femur and the acetabulum of the pelvis [56]. It is a ball and socket stable and strong joint, with three DOFs, surrounded by strong muscles able to perform flexion/extension, abduction/adduction, internal (medial)/external (lateral) rotations. Flexion/extension is considered to be the main DOF used in the locomotive activity [11]. The knee joint formed by the femur, tibia, fibula and patella has a number of functions during walking [56]. It comprises three articulations (tibiofemoral joint, patellofemoral joint and tibiofibular joint) and can be simplified to one DOF, allowing flexion/extension in the sagittal plane [31, 55]. The ankle joint, formed by the connection of tibia, fibula and talus, plays an important role in the equilibrium of the lower limb system [56]. This joint has three DOFs: plantarflexion/dorsiflexion, adduction/abduction and inversion/eversion [31, 79].

8.3 Classes of Lower Limb Exoskeleton

8.3.1 Gait Rehabilitation, Human Locomotion Assistance and Human Strength Augmentation

8.3.1.1 Gait Rehabilitation

Rehabilitation is an important treatment to improve the recovery of the lower limb motor functions of patients suffering from neurological disorder such as stroke, Parkinson’s disease, traumatic brain injury, spinal cord injuries, muscular dystrophy, spinal cord atrophy or cerebral palsy, enabling them to walk independently [29, 43, 60, 64]. All of these disorders result in muscular weakness which is the main reason for the development of rehabilitation exoskeletons [29]. In these cases, manual rehabilitation process is a complicated task requiring significant efforts from both the therapist and patient. Moreover, manual rehabilitation cannot provide intensive training, and the training time is limited to the therapist availability. Due to these difficulties, robotic rehabilitation devices are increasingly being used as an ideal solution for repetitive tasks, allowing the therapist to focus on other tasks such as analysing the gait performance of the patient [12, 15].

Gait rehabilitation exoskeletons can be classified into two main groups: treadmill-based exoskeletons and overground exoskeletons [43]. Treadmill-based exoskeletons are immobile robots that provide gait rehabilitation in a fixed and confined area. By contrast, overground rehabilitation robots are mobile and designed to allow patients walking over the ground in unrestricted areas. This makes the patient more independent when performing gait training. Moreover, overground exoskeletons allow patients to regain natural gait [15].

The treadmill is a rehabilitation technique that is used to improve mobility functions of patients and to improve their ability to walk after brain injury [21]. It is used to train patients with cardiopulmonary diseases and also for the rehabilitation of patients with orthopaedic and neurological diseases [10]. This exoskeleton consists of two-powered leg orthoses, body weight support system and treadmill [15]. They are stationary exoskeletons that have a fixed structure and a mobile ground platform [9]. Examples of commercially available systems include the Lokomat (Hocoma, Inc., Switzerland), LokoHelp (LokoHelp Group, Germany) and ReoAmbulator (Motorika Ltd., USA) [21, 23, 27, 71]. Among them, the Lokomat is the most commonly used device (Fig. 8.4a, b). On the one hand, it combines a physical exoskeleton with a virtual reality environment of audio and visual biofeedback and uses a DC motor with helical gears to precisely control the trajectory of the hip and knee joints [15, 23]. On the other hand, the overground exoskeleton is a mobile robotic base, consisting of robots that follow the motions of the patient's walking on overground. Rather than making the patient follow predetermined movements, this system allows patients to move under their control [21]. A number of overground gait trainers have already been commercialised such as WalkTrainer (Swortec SA, Switzerland) ReWalk (ARGO Medical), eLEGS and Indego [15, 21, 60].

The WalkTrainer (Fig. 8.4c, d), which provides overground walking with control of the pelvic motion, is composed of five main components: frame, body weight support, two leg orthoses, pelvic orthosis and electro-stimulator [6]. The main function of the frame is to follow the patient during the walking exercise. The body weight support system is used to prevent the patient from falling, the leg orthosis measures the positions of the hip, knee and ankle joints, monitoring the interaction forces between the leg orthosis and the patient, and the pelvic orthosis assists the patient during walking. Finally, the primary function of the electro-stimulator is to stimulate some muscles (e.g. gluteus maximus, biceps femoris, rectus femoris, vastus lateralis and medialis, tibialis anterior and gastrocnemius) in the patient [6, 15].

The Active Knee Rehabilitation Orthotic System (ANdROS) developed by Unluhisarcikli et al. [63] is another example of a portable gait rehabilitation. This exoskeleton (Fig. 8.5) allows for motor control by applying a corrective torque around the knee joint using an impedance controller. The device also contains two ankle-foot orthoses rigidly attached to the main frame.

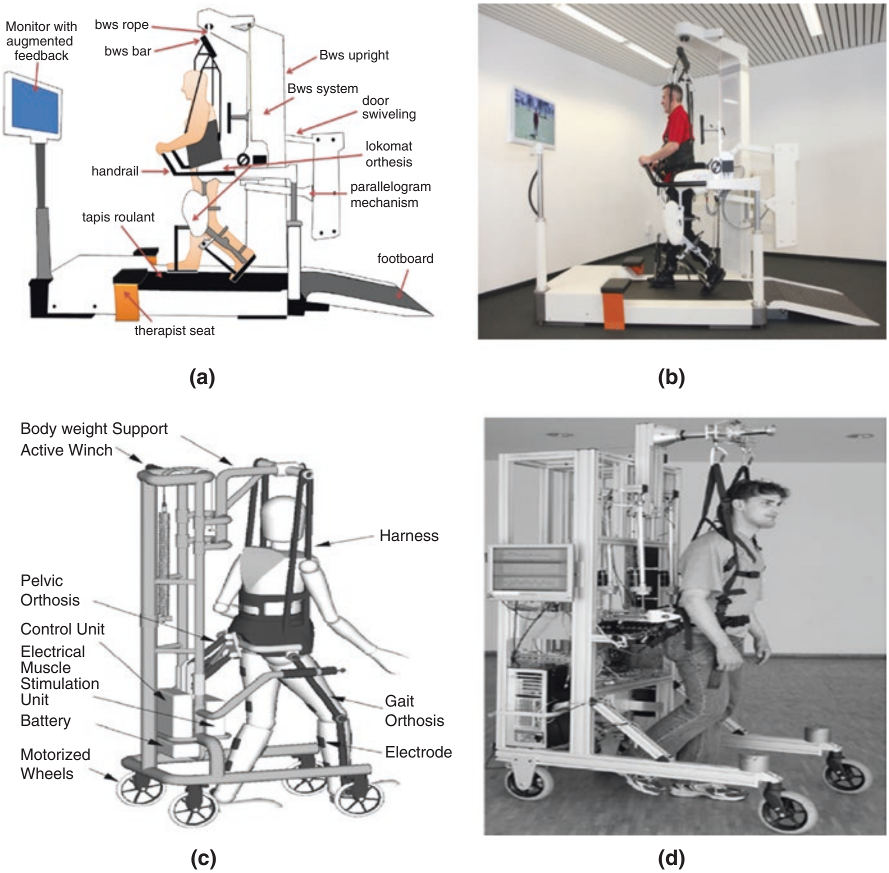
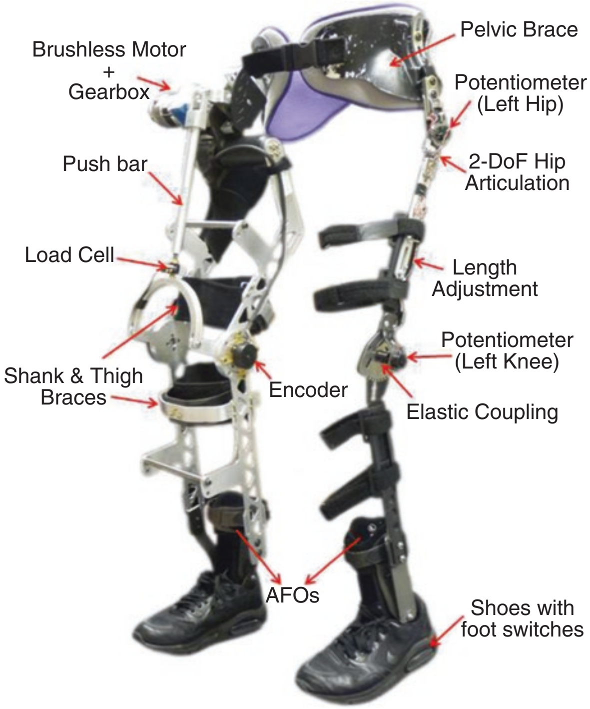


Fig. 8.4 (**a**) Schematic of Lokomat robotic system with its components [9]. (**b**) Lokomat system with the patient [21]. (**c**) The WalkTrainer robotic device with its components. (**d**) A patient testing the WalkTrainer device [6]

The ReWalk exoskeleton (Fig. 8.6) consists of a brace support suit, battery, sensors to measure the tilt angle of the upper body, joint angles and the contact with the ground and a computerised system located in the backpack. It is powered by a DC motor at the hip joint and the knee joint, while the ankle joint is un-actuated. The controller and the battery are attached to the back of the exoskeleton [43]. In addition to the system, patients should use crutches to maintain balance control [15, 60].

The eLEGS exoskeleton built in 2010 and renamed as Ekso in 2011 is commercialised by Ekso Bionics (USA). It is an exoskeleton designed for patients with hemiplegia due to stroke or spinal cord injury, presenting a total of six DOFs (3 DOFs per leg) [28] (Fig. 8.7a). The hip and the knee joints are driven by electric actuators, while the ankle joints are passive [12, 59]. The device also has three straps on each leg to support legs and a backpack that contains the battery and the controller. Crutches should also be used to support the user and to control the exoskeleton.

Fig. 8.5 The ANdROS lower limb exoskeleton [64]



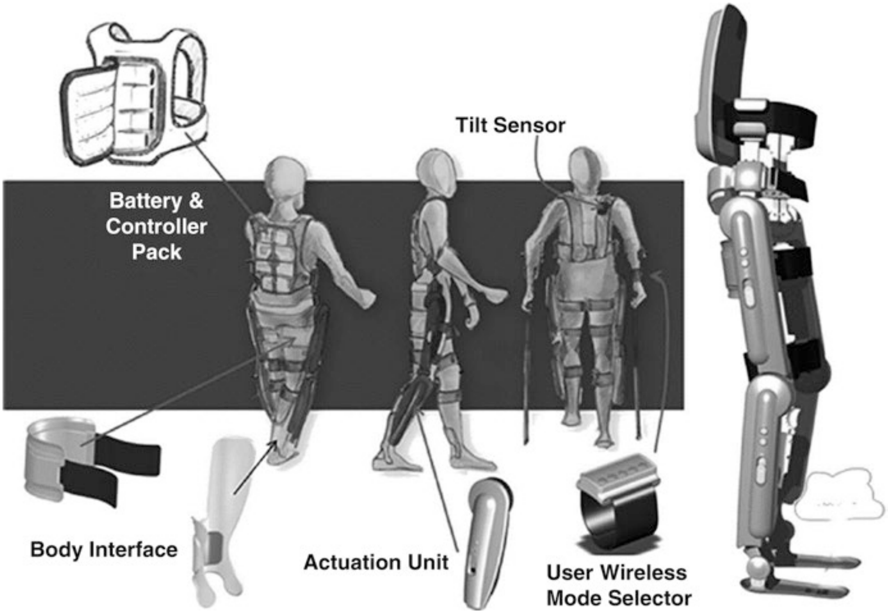


Fig. 8.6 The configuration of the ReWalk exoskeleton [25]

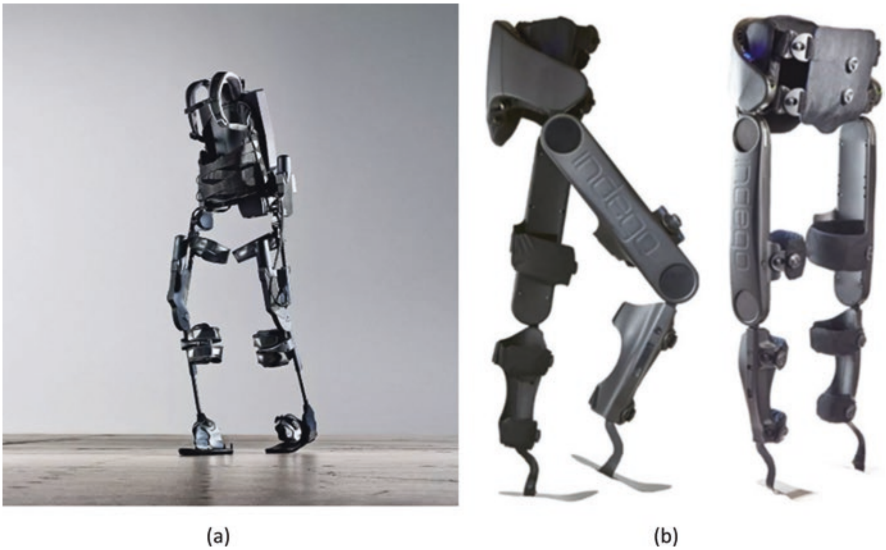


Fig. 8.7 (**a**) The Ekso exoskeleton [59]. (**b**) The Indego exoskeleton [46]

The Indego system (Fig. 8.7b) consists of three main components: the hip brace which contains the battery and the controller, two thigh frames and two shank frames. These parts can be easily split and then assembled again [59]. The hip and knee joints are electronically actuated by DC brushless motor, with passive ankle joints [28]. The Indego system allows a number of actions including sitting, standing, walking, sit to stand, stand to sit, walk to stand and stand to walk. It also has brakes at the knee joints to prevent knee buckling in the case of power failure [18].

8.3.1.2 Human Locomotion Assistance

This type of exoskeletons enables to restore mobility in patients with paraplegia as a result of spinal cord injuries [53]. These exoskeletons provide a wide range of movements that allow users to perform daily life motions such as walking, standing and sitting [70]. Human locomotion assistance exoskeletons can help paralysed patients regain their mobility, thus improving their mental and physical health [13]. An example is the walking power assist leg (WPAL) (Fig. 8.8a), designed to help people who suffer from muscle weakness in their lower limbs and for human power augmentation [2, 14]. The design consists of 12 DOFs in total, 3 DOFs at each hip joint (flexion/extension, abduction/adduction and internal/external rotations), 1 DOF at each knee joint (flexion/extension), 1 DOF at each ankle joint (dorsiflexion/plantarflexion) and 1 DOF at each metatarsophalangeal joint. The hip joints (flexion/extension) and knees (flexion/extension) are actuated by using a DC servomotor coupled with a harmonic reducer gear, whereas the other joints are free [2].

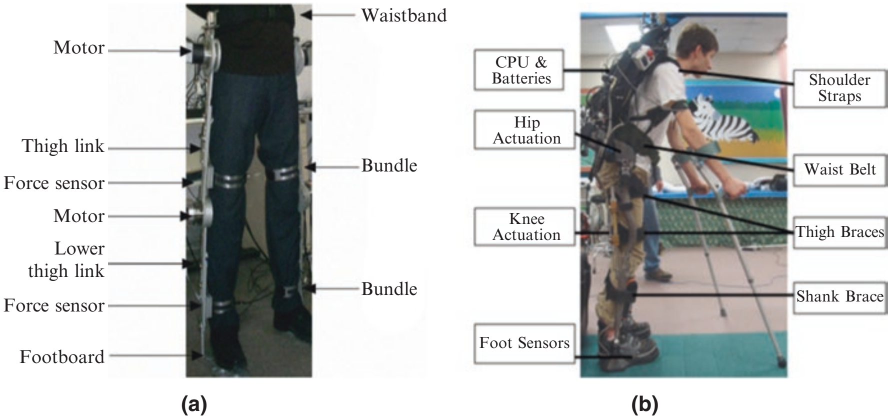


Fig. 8.8 (**a**) The WPAL exoskeleton [14]. (**b**) The medical exoskeleton with its component [62]

The Asian Institute of Technology Leg Exoskeleton-I (ALEX-I) was designed to support paraplegic persons. It consists of 12 DOFs, 3 DOFs at each hip, 1 DOF at each knee and 2 DOFs at each ankle. The exoskeleton is driven by 12 DC motors, at the hips (flexion/extension, abduction/adduction, internal/external rotations), at the knees (flexion/extension) and the ankles (dorsiflexion/plantarflexion, abduction/adduction) [3].

The lower limb orthosis proposed by Wu et al. [73] was designed to provide the wearer with full assistance when performing daily activities. The knee joint (flexion/extension) and ankle joint (dorsiflexion/plantarflexion) are driven by a pneumatic actuator, and the device aims to provide 100% torque to a person of 75 kg of weight. Strausser et al. [62] developed a medical exoskeleton which is shown in Fig. 8.8b for paraplegic mobility with 8 DOFs utilising hydraulic actuators at hip joint (flexion/extension) and knee joint (flexion/extension) to move patient's joints and utilising passive springs at the hip joint (internal/external rotations) and ankle joint (dorsiflexion/plantarflexion).

8.3.1.3 Human Strength Augmentation

Human strength augmentation exoskeletons intend to amplify the physical abilities of the users. They improve human endurance and strength during locomotion, allowing the users to carry heavy loads and walk for long distances. Moreover, they provide the wearer with strength to perform laborious tasks [12]. These exoskeletons are designed for several applications: material handling in harmful environment, assistive devices for disabled patients, industrial and military fields, disaster relief workers, carrying heavy payloads and rescuing of victims [12, 45]. Different designs have been proposed. Yamamoto et al. [74] developed the so-called power assisting suit, to support the work of a nurse in carrying a patient by his/her arm. The device consists of the shoulders, arms, waist and legs made of aluminium in order to create a lightweight structure. The arms, waist and legs are motorised using pneumatic rotary actuators.

The hydraulic lower extremity exoskeleton robot, developed by Kim et al. [39], was designed to enable soldiers to carry heavy loads on their back and to reduce muscle fatigue caused by these loads. It allows the wearer to carry a maximum load of 45 kg with a speed of 4 km/h. The design has a total of 12 DOFs. It has four active joints powered by hydraulic actuators (1 DOF at each hip (flexion/extension) and 1 DOF at each knee joint (flexion/extension)) and eight passive joints (1 DOF at each hip (internal/external rotations) and 3 DOFs for each ankle (dorsiflexion/plantarflexion, abduction/adduction, internal/external rotations)).

The Nanyang Technological University built a wearable lower extremity exoskeleton (NTU-LEE) based on an inner exoskeleton and outer exoskeleton. The inner exoskeleton uses encoders to measure the human movement [44], while the outer exoskeleton tracks the encoder signals using a proportional integral derivative (PID) controller during the load carrying process. The outer exoskeleton was designed with a total of 11 DOFs. Motors and encoders are used at hips (flexion/extension), knees (flexion/extension) and ankles (dorsiflexion/plantarflexion) with linear actuators at the trunk. Springs are also applied at the hips (abduction/adduction) and ankles (abduction/adduction) [2].

8.4 Active Versus Passive

The history of active devices dates back to the 1960s when the US military introduced several exoskeletons for military purposes. Most of these exoskeleton systems are active and use electric motors that require continuous power input [48]. As discussed by Yli-Peltola [76], most exoskeletons are powered by electricity or pressurised air, enabling movement through sensors and actuators [47].

Active exoskeletons are defined as devices that require actuators to apply forces on the legs allowing movement [5]. One of the most common is based on the muscles' electromyography (EMG) concept [1, 57]. The aim is to reduce muscle recruitment in the lower limb during locomotion which is usually measured by EMG signals [77]. The EMG signal is a biomedical signal that measures the electrical current generated during the contracting of muscles. This signal is controlled by the nervous system and is dependent on numerous anatomical and physiological properties of muscles (motor units, muscle fibres, specialised cells, extensibility, elasticity, contraction, relaxation) [57].

In order to acquire EMG data, electrodes need to be placed on the skin over the muscles [51]. EMG signals are used to evaluate the intended motion of the user. Additionally, they can be used to measure the level of interaction between the human and the exoskeleton and to control the actuators of the device [1, 49]. By analysing the muscles of a lower limb, the EMG data could be helpful for developing a lower limb exoskeleton [51]. EMG activity has been used in some devices such as the LOPES and the HAL [1, 36, 69]. The lower extremity-powered exoskeleton (LOPES) (Fig. 8.9a, b) was initially developed by Ekkelenkamp et al. [24] and further improved by Veneman et al. [69]. It has a total of 8 DOFs, two actuated pelvis segments and three actuated joints for each leg, two at the hip joint (flexion/extension, adduction/abduction) and one at the knee joint (flexion/extension). It uses EMG signals to measure muscle activity and to predict the user's motion [69]. The LOPES exoskeleton is actuated by using Bowden cable driven series elastic actuators and impedance controlled, allowing bidirectional mechanical interactions between the exoskeleton and the user [58].

The hybrid assistive limb (HAL) is a wearable device developed by Tsukuba University in Japan [29, 36]. The system consists of three main components, the skeleton and actuator, controller and sensors as shown in Fig. 8.9c. The frame, made of aluminium alloy and steel, is attached to the external part of the lower limb of the patient [36]. The HAL system has 4 DOFs actuated by using harmonic drive gear

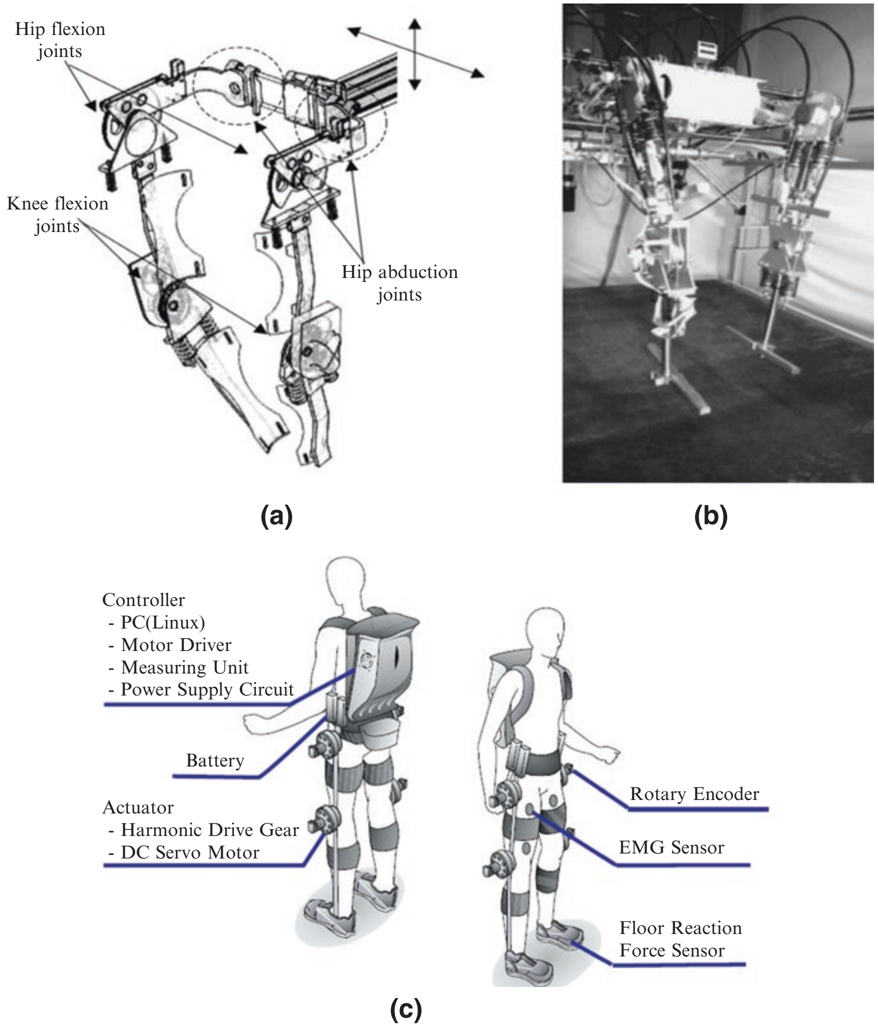


Fig. 8.9 (**a**) Design of the LOPES exoskeleton [68]. (**b**) LOPES exoskeleton prototype [15]. (**c**) The basic elements of HAL-3 exoskeleton [36]

and DC servo motor to generate torque at the hip and knee joints [2, 37]. It also uses EMG signal to predict the intended motion of the patient [36].

On the one hand, these active devices bring many merits to the user. They can offer an assistance to move the body of the patient suffering from spinal cord injuries or other diseases. Moreover, it can help the user to effectively, easily and quickly perform a certain movement [76]. As the majority of exoskeletons available in the market are active devices either electrically or pneumatically powered, this might lead to an increase in the weight of the exoskeleton resulting from the large weight of motors and power supplies. Consequently, active exoskeletons are not the better choice for training stroke patients [7].

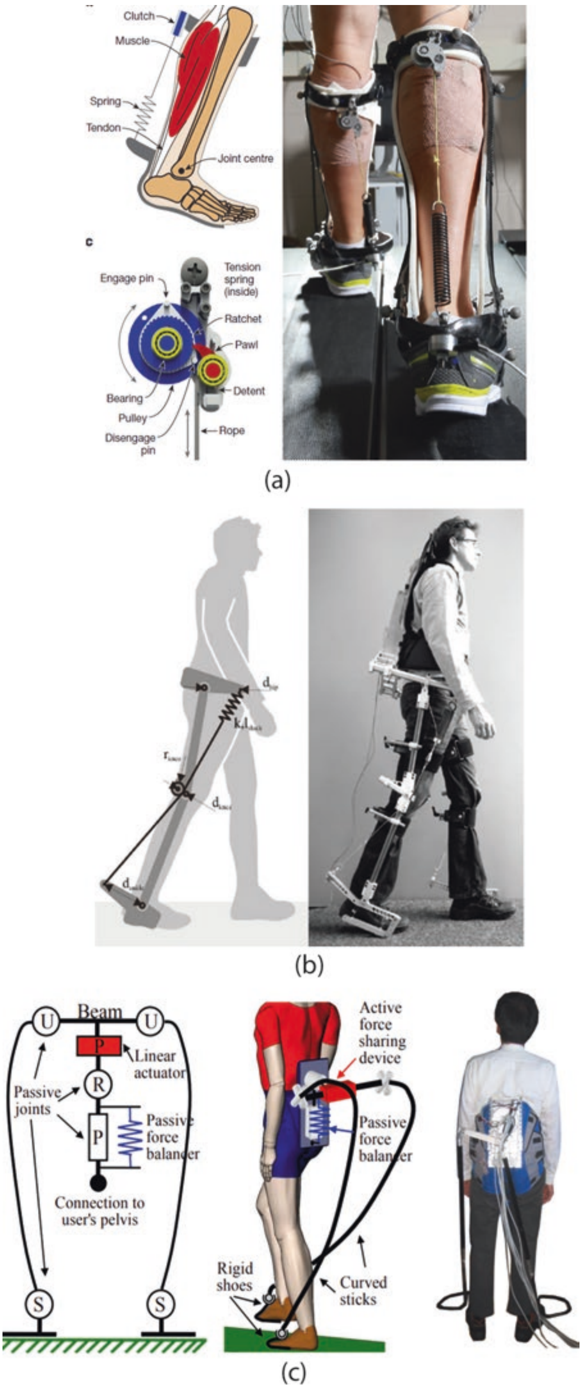
On the other hand, passive devices heavily rely on the ability of the user to apply forces to move the leg [5]. Based on the requirements from the US army to have devices without recharging, the actuators and power sources were removed, reducing the weight of the device. They operate by transferring the load from the device and the backpack to the ground by a frame [76]. Passive devices use passive springs to provide gravity compensation [48].

An example of unpowered exoskeletons is the passive ankle exoskeleton developed by Collins et al. [17]. It is a lightweight exoskeleton designed to reduce the energy cost of human walking. The device is made of a carbon fibre frame, mechanical clutch, cable and spring (Fig. 8.10a). The spring is parallel to the Achilles tendon and attached to the human leg by the frame and a lever about the ankle joint. The function of the mechanical clutch which is parallel to the calf muscles is to engage the spring during heel strike and disengage when the foot is in the air, allowing for free motion. The allowed movements at the ankle joint are plantarflexion and dorsiflexion [17].

The XPED 2 (Fig. 8.10b) is a passive exoskeleton developed by Van Dijk et al. [66] to reduce joint torques during walking. It uses elastic elements known as artificial tendons, which have the ability to store and transfer energy between joints [66]. The XPED 2 is formed by a rigid frame connected to the human body at the pelvis, shank and foot; a backpack and a cable that extends from a lever at the pelvis to a leaf spring at the foot via a pulley at the knee. The primary function of the leaf spring is to provide the elasticity to the exoskeleton [65, 66]. The device has 6 DOFs per leg (flexion/extension, abduction/adduction, internal/external rotations at the hip joint; flexion/extension at the knee joint; plantarflexion/dorsiflexion, pronation/supination at the ankle joint) [65].

Quasi-passive devices lie between active and passive exoskeletons. They require a small power supply unit to operate electronic control systems, clutches or variable dampers [53]. The concept of this light and efficient type of exoskeletons seeks to use the passive dynamics of human walking [54]. The MoonWalker (Fig. 8.10c) developed by Krut et al. [41] is a good example of quasi-passive exoskeletons. It is a lower limb exoskeleton that has the ability to partially sustain the user's weight through the use of a passive force balancer. This device is controlled by an actuator that requires very low energy to work. This is only used to shift that force the same side as the leg in stance. The exoskeleton can be used for rehabilitation and also as an assistive device.

Fig. 8.10 (**a**) The components of the passive ankle exoskeleton [17]. (**b**) The XPED 2 exoskeleton [66]. (**c**) The MoonWalker lower limb exoskeleton [41]



8.5 Actuation Systems

The actuation system consists of three different types of actuators: electric, pneumatic and hydraulic. The main function of these actuators is to provide the necessary power to the exoskeleton, enabling it to perform a certain task [30]. The majority of the exoskeletons are actuated using electric actuators (65%), and 27% uses pneumatic actuators [30, 52]. A combination of multiple actuators (hybrid system) has been also explored [2].

8.5.1 Electric Actuators

In order to address the bulkiness of hydraulic and pneumatic actuators and the difficulty to control them, electric motors are extensively used, making them the most commonly used in exoskeleton systems [15, 30]. They are easily controllable, provide a good and quick response and present the lowest power-to-weight ratio. Major drawbacks are related to backlash and friction [8, 15, 30]. A good example of an electrically actuated exoskeleton is the Hanyang Exoskeleton Assistive Robot (HEXAR)-CR50 developed by Lim et al. [42]. This exoskeleton (Fig. 8.11a) aimed to enhance muscle strength of the user while transporting a load. It has a total of 14 DOFs with 3 DOFs for the hip joints, 1 DOF for the knee joints and 3 DOFs for the ankle joints per foot. A brushless DC electric motor and harmonic gear were applied at the hip and knee joints for flexion and extension movement, while the ankle and toe joints use a quasi-passive mechanism [42].

Another example is the Vanderbilt lower limb orthosis (Fig. 8.11b) which is a powered device designed to provide gait assistance to patients with spinal cord injury. The device was designed to assist the flexion and extension of the hip and

Fig. 8.11 (**a**) Structure of HEXAR-CR50 exoskeleton and joint modules [42]. (**b**) The structure of the Vanderbilt [26]

knee joints, which are actuated by brushless DC motor [75]. The knee motors are equipped with electrically locked brakes to keep knee joint locked during a power failure. The brake is locked during the stance phase and unlocked during the swing phase also from sit to stand and stand to sit. The device includes potentiometers in the hip and knee joints, accelerometers in each thigh and some straps to protect users from skin abrasion. This device weights 12 kg and is made of a composite of thermoplastic reinforced with aluminium [26].

8.5.2 Pneumatic Actuators

Pneumatic actuators use pressurised gas to generate output forces. These actuators have a simple and light structure being also relatively cheap [8]. They have a higher power-to-weight ratio than electric motors, but less than hydraulic actuators, providing a clean and non-flammable actuation method. However, they present low stiffness and accuracy, being used in a limited number of cases [8]. A good example of a pneumatically actuated exoskeleton system was proposed by Costa and Caldwell [19] for patients suffering from paralysis (Fig. 8.12a, b). This exoskeleton is formed by an aluminium, steel and carbon-fibre composite frame and has a total of 10 DOFs, 3 DOFs at both hips, 1 DOF at each knee and 1 DOF at each ankle. A potentiometer, mounted on the joint, measures the position, while the torque is measured by using an integral strain gauge [19].

One of the existing pneumatic actuated lower limb exoskeletons is the nurse robot suit as shown in Fig. 8.12c. This device was designed to augment the strength of a nurse by providing extra forces to carry patients without any back injuries. Whenever the nurse stands up, the robot suit helps in transferring the weight to the ground. It is also supported by actuators when the nurse bends the waist or knee [75]. The nurse robot suit consists of the shoulders, arms, waist and legs made of aluminium. The arms, waist and legs are driven by pneumatic rotary actuators [74].

8.5.3 Hydraulic Actuators

These actuators are rarely used in exoskeleton systems [30]. They usually use oil as pressurised fluid to transfer power to a joint, being able to quickly and precisely generate high torques [8, 30]. In comparison with the other actuators, the hydraulic ones present not only the highest power-to-weight ratio but also a complex structure requiring additional safety mechanisms due to the high power and stiffness [8]. Examples include the rehabilitation device designed by Kobetic et al. [40]. It was designed with a total of 6 DOFs with the hip joints being driven in flexion and extension by linear hydraulic actuators. An electromechanical system was considered to lock knee flexion and extension during the stance phase and unlock during the swing phase. The ankle joints (plantarflexion/dorsiflexion) were constrained to move in a sagittal plane [2].

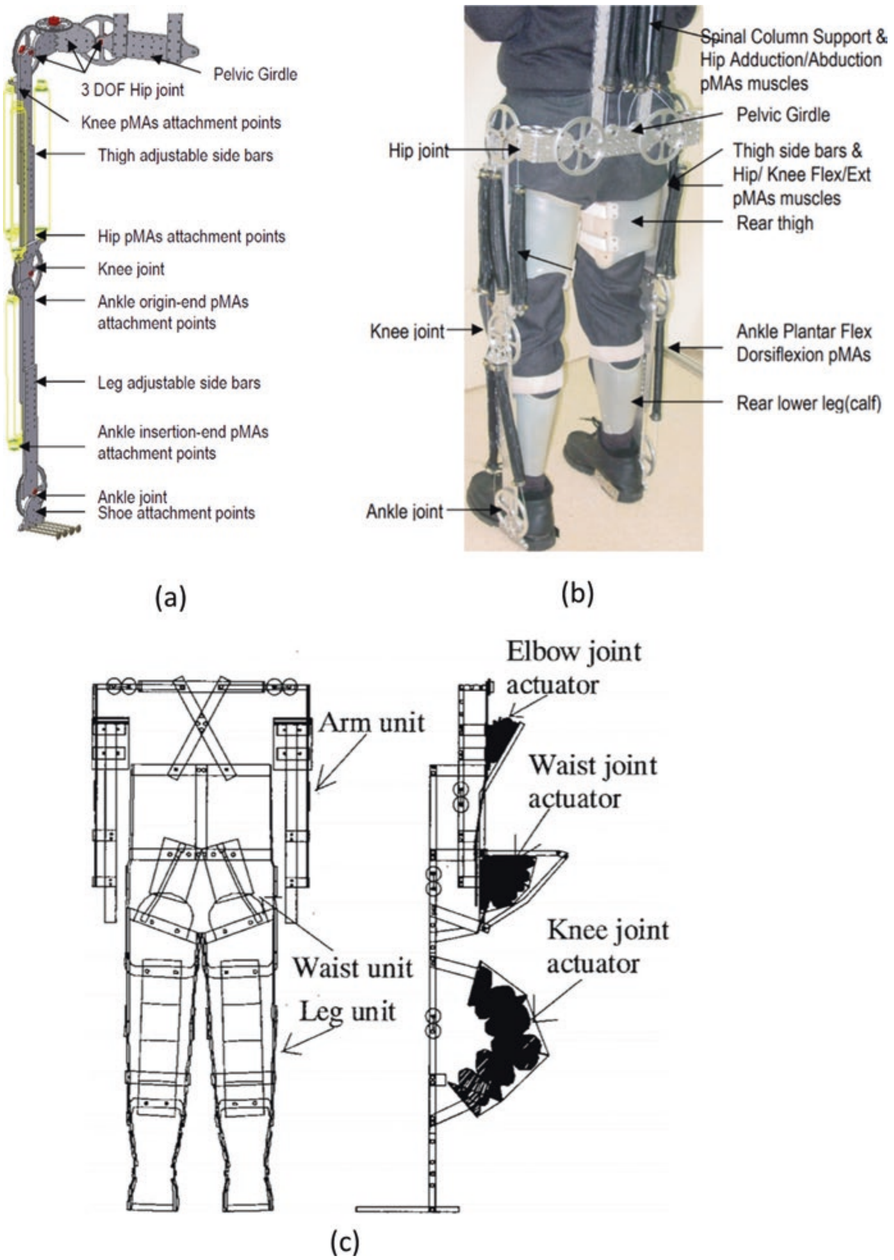


Fig. 8.12 (**a**) A representation of CAD model of the lower body exoskeleton. (**b**) The lower body exoskeleton [19]. (**c**) The nurse robot suit exoskeleton [74]

The Berkeley Lower Extremity Exoskeleton (BLEEX) is another example of an exoskeleton powered by hydraulic actuators [80] (Fig. 8.13). It is considered the first load bearing and energetically autonomous exoskeleton [38] and allows the

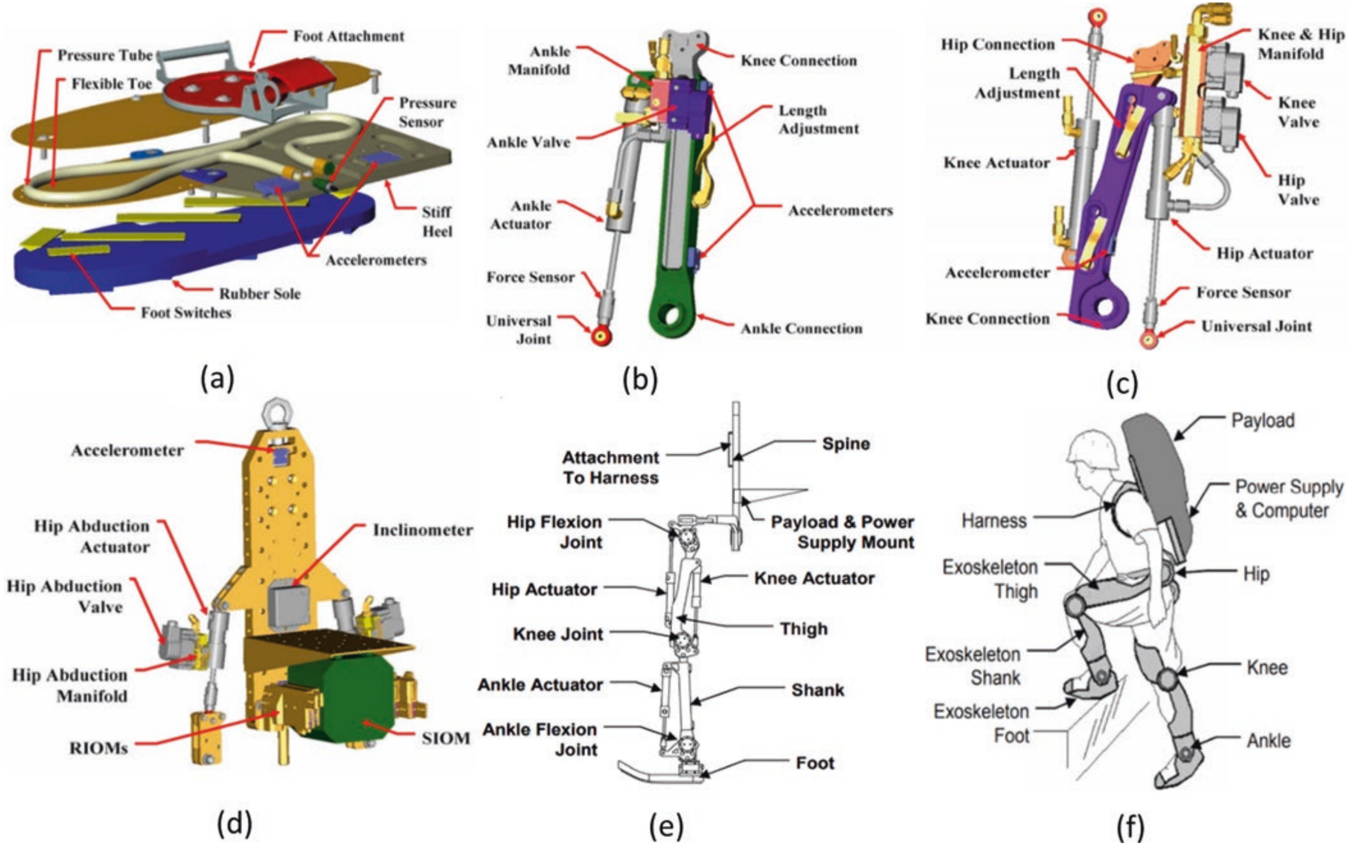


Fig. 8.13 (**a**) Foot design. (**b**) Shank design. (**c**) Thigh design. (**d**) Torso design. (**e**) Major components of BLEEX. (**f**) Final design of BLEEX [80]

user to carry a heavy load (34 kg) with minimum effort and walk with an average speed of 1.3 m/s [16, 75]. Moreover, it is also used to enhance the user's strength and endurance during locomotion [38]. The system was designed for emergency personnel such as soldiers, firefighter and disaster relief workers to carry significant payloads [16].

It consists of two powered legs, power unit and a backpack [16]. This exoskeleton has 7 DOFs per leg (3 DOFs at the hip joint, 1 DOF at the knee joint and 3 DOFs at the ankle joint). A total of 4 DOFs are active and powered by hydraulic actuators (ankle plantarflexion/ dorsiflexion, knee flexion/extension and hip adduction/abduction), while the remaining DOFs (hip internal/external rotation, ankle inversion/eversion and ankle adduction/abduction) use steel springs and elastomers [16, 75, 80].

8.6 Challenges and Opportunities

Although exoskeletons have been proven to be advantageous in many fields, there are several challenges that need to be addressed. Some of these challenges are related to the biomechanical design of the exoskeleton, safety and effective control algorithm. Additional challenges are related to the actuator selection, power supply and human/exoskeleton interface [30, 35]. According to Gopura et al. [30], the lack of the availability of proper accessory devices also constitutes a significant challenge for the exoskeleton's development. They stated that the actuation system and the technology of power transmission are not suitable enough to develop an ideal exoskeleton system.

8.6.1 Low Weight

In order to build portable exoskeletons, it is necessary to build exoskeletons as light as possible to improve their portability, making them more convenient for the user. It has been noted that materials of the frame structure and actuators are the main factors that affect the weight of these devices. Moreover, the fabrication method also has a significant impact [78]. Since these devices will become a second skin to the user, materials of these structures should be considered when developing these exoskeletons [30]. Thus, it is essential that these materials have some characteristics such as low density and toughness (e.g. the carbon fibre). Moreover, three-dimensional (3D) printing technology could be a great solution to create some components in order to obtain lightweight exoskeletons [12].

Overall, exoskeletons are heavy devices because the gearing systems and actuation units are not lightweight. However, exoskeletons should be relatively light to make the users feel comfortable when they wear the device [30]. In order to minimise the weight of the exoskeleton device, different materials and manufacturing technologies should be examined and tested for their effectiveness [61]. Lattice structures, presenting reduced weight and improved mechanical properties, will be more common. These structures could be designed and produced through a combination of topology optimisation and additive manufacturing. These lattice structures can also be used to improve the damping effects, increasing comfort.

8.6.2 Actuators

Actuators are one of the major challenges that need to be taken into account when developing robotic exoskeleton systems. For powered exoskeletons, specific features such as small volume, high power-to-weight ratio, high efficiency and compliance are necessary to be considered. The durability and lifetime of actuators also need to be improved [12]. New multifunctional actuators that integrate motor, brake and clutch functions into one device represent a good solution for improved exoskeletons [12]. The exoskeleton must also be designed taking into consideration the actuation system and its impact on the energy required to power the exoskeleton systems [11].

8.6.3 Cost

The cost of exoskeletons is an important issue influencing the development of lower extremity exoskeletons. Most users cannot afford these devices as they cost a significant amount of money [50]. A survey conducted by Wolff et al. [72] showed that the cost of the device constitutes the main concern for patients as it limits the adoption of exoskeletons in their daily lives. Therefore, researchers and engineers are required to make significant efforts to develop affordable devices. Prices are expected to decrease due to recent advances in robotics and mechatronic and also the reduction of the price of sensors and actuators [12].

Regarding rehabilitative exoskeletons, it can be said that there are several barriers that might limit the usage of this kind of exoskeletons in homes. Portability and cost are two factors that can affect the use of rehabilitation devices in patients' homes. There is also a general consensus that the exoskeleton devices are highly overpriced. However, the introduction of new technologies creates a possibility to design lightweight, cheap and portable exoskeletons [61].

8.6.4 Mechanical Design

Another challenge is related to the structure of the exoskeleton device that should have high strength and flexibility [30]. Furthermore, they must be adjustable to suit different users with different body weight and shapes. Modularity is in this case an important issue. These devices are required to have some features that allow the user to calibrate the exoskeleton to fit the wearer's requirements [35]. The mechanical design of some exoskeletons could reduce the performance of lower extremity exoskeletons and affect the biomechanics of the normal human gait. As a result, it will cause a discomfort to the user and increase the metabolic cost. In addition to this, the usage time of the device will be reduced. Moreover, some sections of the human body are complex to design. They require special designs to simulate the natural motion of the human [30]. Additionally, the mechanical structure of the device should be personalised to suit a particular individual. Another important consideration is that the noise caused by the exoskeleton should be minimised as it makes the wearer uncomfortable [12].

8.6.5 Safety

Safety is an important aspect of any exoskeleton devices and it should be given a great attention from both designers and manufacturers. As the use of an exoskeleton presents some risks (e.g. falls, fracture), further studies and efforts should be made to address them [33]. Furthermore, the safety of the battery needs to be considered when designing an exoskeleton. Shutdown systems in emergency conditions should be considered. Exoskeletons should have physical stops to limit the range of motion at joints, which must resist the maximum torque applied by actuators [12]. Dellon and Matsuoka [20] emphasise the importance of having safety standards for human–robot interaction, outlining some safety mechanisms that must be implemented such as limiting power output and limiting velocities of actuators. Since there is an interaction between the exoskeleton and the user, the exoskeleton devices are required to be mechanically compatible with the human anatomy, allowing the wearer to perform any movement safely and without any obstructions [11]. There are many factors that are critical and must be considered for ensuring user's safety, such as number of degrees of freedom, compliance with the measurements of the human body, range of motion, motion speed and the maximum force [32].

8.6.6 Human–Exoskeleton Interface

Young and Ferris [77] emphasise that the lack of understanding of the primary mechanisms that control the user's motion and the way that those mechanisms interact with the exoskeleton in parallel with the person is one of the major challenges in the field of exoskeleton research. Exchanging the information between the user and the device is one of the limitations of current exoskeletons. The reason is that some of the user's intentions cannot be quickly and accurately obtained by the sensors used in the devices. Therefore, new technologies such as artificial intelligence (AI) and neural technology will be extremely important for the development of future exoskeletons. Neural implants might be used to provide a feedback to the brain. Future exoskeletons will include EMG signals that predict the motion of the user and the neural implants as control systems. An electroencephalogram (EEG) can also be used to control the exoskeletons. An important point related to the human–robot interface is the occurrence of skin pressure sores. It has been found that the most common way to secure the device to the leg is by using the straps [11]. Therefore, these straps should be carefully designed to avoid skin issues [12].

Exoskeleton robots should not affect the functions of other body parts. The human–robot interaction (HRI) is significant when designing exoskeleton devices and should be customised to the individual's contour and anatomical needs [12]. Two aspects of HRI, namely, the physical human–robot interaction (pHRI) and the cognitive human–robot interaction (cHRI), should be considered. pHRI is related to the physical contact between the device and the user to transfer the power from the exoskeleton to the wearer or vice versa, while cHRI is related to the transmission of information from the user to the exoskeleton or vice versa [15].

8.6.7 *Customisation and Personalisation*

Exoskeletons must be designed and fabricated for the individual user. The main problem so far is associated with production costs. However, the emergence of additive manufacturing, a group of fabrication processes that create 3D objects by adding materials layer by layer contrary to convention subtractive processes, makes mass customisation and personalisation possible. Additive manufacturing (AM) comprises seven key technologies (see Table 8.2) (Vat photo-polymerisation, powder bed fusion, direct energy deposition, material extrusion, sheet lamination, material jetting and binder jetting) that allow the production of a wide range of metals, polymers, ceramics and composite materials. Key advantages of AM are as follows:

- Freedom of design: AM can produce an object of virtually any shape.
- Complexity for free: Increasing object complexity will increase production costs only marginally.

Table 8.2 Summary of all AM technologies

Technology	Principle
Vat photo-polymerisation	It is an additive manufacturing process in which a liquid in vat is selectively cured by light-activated photo-polymerisation
Powder bed fusion	It is an additive manufacturing that fuses regions of powder bed selectively through thermal energy
Direct energy deposition	It is an additive manufacturing process in which material is deposited from the nozzle and then melted by focused thermal energy
Material extrusion	Additive manufacturing processes in which material is melted and then extruded through a nozzle
Sheet lamination	It is an additive manufacturing process in which sheets of materials are bonded to form an object
Material jetting	It is one of the additive manufacturing processes that deposits wax and/or photopolymer droplets through a nozzle to create 3D object
Binder jetting	It is an additive manufacturing process that joins powder materials through the deposition of a liquid bonding agent

- Lightweight for free: Lightweight structures can be produced with reduced costs.
- No tooling required.
- Even complex objects are manufactured in one process step.
- Part consolidation: Reducing assembly requirements by consolidating parts into a single component, even complete assemblies with moving parts.

AM is also the most suitable technology for the production of small batches. The use of AM to produce certain parts of exoskeletons is now a reality, and we expect that this trend will significantly increase in the next years [4].

8.7 Conclusion

There is no doubt that lower extremity exoskeletons have significant roles in improving the quality of life of people with mobility disorders. These devices allow them to regain the ability to perform daily life activities. Exoskeletons have been designed for several purposes including rehabilitation, augmentation and locomotion assistance. They can be powered by some sensors and actuators, or they can be passive (unpowered). There are a number of exoskeletons already been commercialised for different purposes. However, this review identified areas for potential development. In order to produce exoskeleton with reduced weight and costs, and improved performance, it is important to use low-weight actuators and design devices with improved safety characteristics, improving also the mechanical design and the interface with users. The use of additive manufacturing will also contribute to the development of more personalised devices. Finally, artificial intelligence will also contribute to the development of smarter exoskeletons.

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