International Journal on Interactive Design and Manufacturing (IJIDeM)
https://doi.org/10.1007/s12008-024-02076-7

REVIEW

A comprehensive review on lower limb exoskeleton: from origin to future expectations

S. Arunkumar[1] · **Nitin Jayakumar**[1]

Received: 2 April 2024 / Accepted: 15 August 2024

Abstract

Lower limb exoskeletons (LEEs) have become an essential part of the day-to-day life of humans. These devices are worn on the human body for assisting the user in load augmentation and gait rehabilitation. The initial LLE designs aimed at assisting in simple tasks like walking, running and jumping. With rapid development in technology, LLE design has evolved into a sophisticated structure which can interact with the user and perform its intended task. While there are a number of review articles published, the scope of which is limited to selected areas viz., general aspects, compilation of available LLE designs for various applications, comparison of actuation or control methods. The aim of this review is provide the state-of-the-art of LLE right from its origin to future directions. A comprehensive, comparative and critical overview of history, classification, design considerations, materials and manufacturing methods, positive and negative effects of wearing LLE, efficacies of LLEs in rehabilitation, challenges and future directions of LLE design are presented. The review suggests that for comfortable use of LLE, anthropomorphic and ergonomic principles be incorporated during the design stage. By using soft exosuit the muscular activity is reduced by 63.97% compared to 61.63% for rigid exoskeleton. For the LLE to synergistically with wearer and minimize the metabolic penalty, appropriate control methods, materials and manufacturing methods be chosen respectively.

Keywords Lower-limb exoskeleton · Load augmentation · Gait rehabilitation · Fuzzy control · Soft exosuit · Deep learning · Machine learning

1 Introduction

The demand for the portable electronic devices is increasing constantly with the advancement of technology. The major constraints while designing such devices are focused on reducing the size and consumption of power for ensuring portability of the exoskeletons. These assistive devices are termed as "exoskeletons" [1]. Exoskeletons are wearable devices that work in parallel with the users to augment the physical performance [2]. In order to achieve such harmony between the device and the wearer, it must be designed to anthropomorphic dimensions. The exoskeletons are actuated either through external power or by mechanical means. The control system, which sends signals to these actuators, based on the communication between the exoskeleton and the wearer, further enhances the performance of exoskeleton [3].

In the light of enhancing the quality of life and developing new technologies, exoskeletons are becoming very popular in recent times. These have huge applications in the medical and non-medical fields. Right from a simple task of assisting in walking to rehabilitation of people with serious illness and enabling increased production in manufacturing industries, exoskeletons have slowly become an integral part of human life [4]. To name a few benefits of exoskeletons, it acts as a support for intermittent sitting, carries most part of the external load. Despite these potential benefits, there are some negative effects also. Excessive use of exoskeletons might lead to musculoskeletal disorder. In addition, occasional wearing leads to accidents due to increased cognitive load, which in turn affects the human postural control. Exoskeletons can load the humans unpredictably and introduce new loads to the musculoskeletal systems. Hence, future research must be focused in solving these negative effects [5].

In the past years, industries and research institutions were effectively working on developing LLEs that could ease

---

✉ S. Arunkumar
arunkumars@am.amrita.edu

[1] Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, Kollam 690525, India

physical pain and improve work culture, productivity, and efficiency. Material handling, repetitive tasks, etc. leads to fatigue and joint pains. To avoid such issues, exoskeletons were introduced where the tasks could be performed with minimum effort and improved efficiency. The flexibility and safe use of the system are very vital and there is a continued research in the selection of actuators, control methods, materials, and advanced manufacturing techniques for modular and lightweight LLEs [6]. Few surveys suggest that the use of back-supported exoskeletons is encouraged in industries to apprehend the musculoskeletal problems faced by industrial workers. The comprehensive discussion is made to address the application, challenges, pros, cons, modifications, and flexibility of the exoskeletons [7]. The automotive industries are also adopting the use of exoskeletons in the line of assembly, material handling, part repairs, etc. These tasks require extensive body movements that could lead to fatigue and joint pains. However, the initial and maintenance costs are the primary tackles for any industry and must be addressed. The training for the use and operation of LLEs must be given to the operators to avoid difficulty while handling it. It is not mandatory for industries to adopt such technology, but with the mutual collaboration of research institutes and industry experts, an optimized model could be developed considering the cost, maintenance, and adaptability of the system [8].

1.1 Motivation

The published review papers provide us a chance to recognize the design and applications of exoskeletons in the fields of military, industry, and medicine, in general. Few of the available reviews on lower limb exoskeletons (LLE) are focused on general aspects of such as history, classification, and comparison of different LLE designs [4, 9]. Some other reviews have concentrated on particular applications like in manufacturing industries and for improving walking and running [5, 10]. While few articles have discussed the various actuation types, control strategies, materials, and manufacturing methods employed in LLEs [2, 11]. A group of reviews has surveyed the application of LLEs for rehabilitation purposes, strength augmentation, locomotion assistance, clinical validation, the complexity of human–machine interaction [3, 12–16], or for a particular disease like stroke [17, 18] or spinal cord injury (SCI) [19, 20].

1.2 Contribution

With an objective of providing the readers, with a detailed knowledge of the state-of-the-art of LLE including the latest research carried out, this work presents a comprehensive overview of the lower limb exoskeleton since its origin to current status. Relative to other reviews which focuses on specific topics of the LLE, this work examines in-depth its various aspects such as design features, actuation types, control methods, materials, manufacturing methods and applications in the areas of manufacturing and rehabilitation. The main contribution of this work is focused towards addressing the following questions: (1) what are the design, actuation, and modern control strategies adopted in LLEs? (2) what are the materials and manufacturing methods used for LLEs? (3) what are the benefits and hazards for exoskeleton wearers? (4) what is the efficacy of LLEs in the area of rehabilitation? (5) what are the challenges and future research directions of LLEs?

2 Methodology

The main aim of this review is to present the state-of-the-art of the LLEs comprehensively. An extensive search of the literature related to LLE was carried out from various databases. The details of the literature review methodology are explained below.

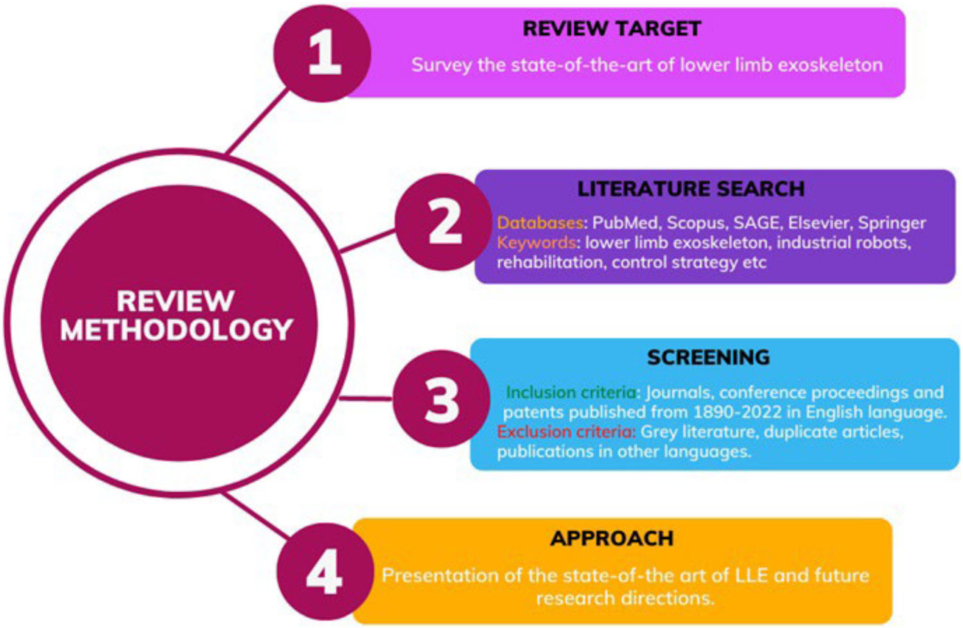
2.1 Search strategy

The articles and patents related to LLE were gathered from various databases like Scopus, Web of Science, PubMed, Springer, Elsevier, SAGE, and IEEE explore published between 1890 and 2022. The keywords related to the area of lower limb exoskeleton in combination with Boolean operators, synonyms and wildcards were typed in each database to obtain wide range of published information. The keywords such as lower limb exoskeleton, industrial robots, rehabilitation, control strategy, materials and manufacturing methods, actuation, classification, history etc. were used during the literature search process. The documents which were relevant to this work, after thorough examination were used for the review.

2.2 Inclusion and exclusion criteria

To ensure the credibility of this review, all peer-reviewed conference proceedings, journal articles and patents related to lower limb exoskeletons written in English and published until 2022 are included in the review. Grey literature (which are neither peer reviewed and nor controlled by any publisher; provide less detailed information) are excluded. If similar documents present comparable information about LLE, the articles which details the inception of the exoskeleton design or first published is selected. All the information published related to lower limb exoskeleton in languages other than English were omitted from this review.

Fig. 1 Review methodology



2.3 Approach

For understanding the depth of LLE, the information collected from the articles for this review process was categorized based on the technical and medical aspects of the exoskeleton. The technical aspects include, structural design, actuation, control strategies, materials, manufacturing methods, benefits and risks of wearing LLEs. The medical aspects such as the use of LLEs for rehabilitation, personal mobility and treatment of impairments like spinal cord injury, stroke and other diseases are included. A brief history and classification of exoskeleton is presented in the beginning section for the sake of completeness of this work. Finally, the challenges and future research directions with regard to the technical and medical aspects is discussed. The review methodology adopted in this work is shown in Fig. 1.

3 Origin and classification

3.1 Historical and modern exoskeletons

It is reported that one of the most historic exoskeletons originated in the Russian Empire in nineteenth century. It was a concept model of lower extremity exoskeleton (Fig. 2) designed by Nicholas Yagn for facilitating walking, running and jumping [21]. In order to reduce the fatigue of a person, springs were used for the redistribution of energy given by the user during motion. Despite the fact that this exoskeleton operated purely on mechanical basis, this design set the foundation for modern exoskeletons.

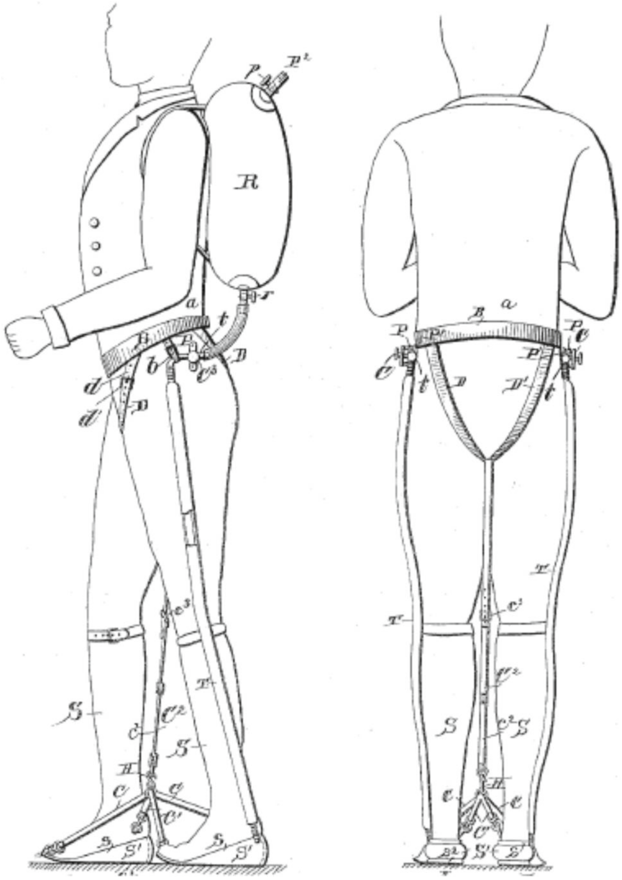


Fig. 2 Concept model of Nicholas Yagn's lower extremity exoskeleton [21]

Another exoskeleton similar to but smaller than Yagn's design was invented by Lesley C. Kelly in 1919 [22]. This was a powered device meant to facilitate running while reducing the muscle strain and fatigue. In the late 1960's, Hardiman (Human Augmentation Research and development Investigation), the first full-body powered exoskeleton was developed by General Electric Research (Schenectady, NY), along with Cornell University and monetary support from the U.S. Office of Naval Research. This was a hydraulically powered exoskeleton having a weight of 680 kg and 30 degrees of freedom meant to amplify the strength of arms (without wrists) and legs of the user in the ratio of 25:1 [23, 24]. A similar full-body powered exoskeleton was invented by Neil J. Mizen as part of Cornell Aeronautical laboratory. Unlike Hardiman I, this exoskeleton was powered by one or more servo motors. The exoskeletal structure responds to human's normal body movements and amplifies the power capabilities by several orders of magnitude [25].

With the progress in science and technology, in the subsequent decades, exoskeletons were developed for specific use. For realizing steady state running using Yagn's [22] bow spring design, the user must hop as it short of a degree of freedom (DOF) at the knee. Excessive amount of energy must be stored in the bow spring for accomplishing knee bending, normal walking and running. A "sliding foot type" kinematic walker was developed in 1969 having 2 DOF with a passive joint at the ankle and active joint (pneumatic actuation) at the hip. The knee joint was locked straight. Later in 1970, a 'partial exoskeleton' with single DOF at the knee and 3 DOF at the hip and ankle was developed. The exoskeleton was actuated using 7 pneumatic actuators and 14 electromagnetic solenoids. These features enabled the paraplegic to walk but lacked dynamic stability. In 1978, the first active exoskeleton using electromechanical drives was developed mainly for the patients with muscular dystrophy. This was controlled by a microprocessor mounted on the chest of the user. Two servoelectric drives, a 50W drive at the knee joint and 100W drive at the hip joint were installed. As a result, the patients were able to adapt and use quickly [26].

In 1980, a mobile arm support was designed for people whose arms were afflicted. The design consisted of a pneumatic system to bear the weight of the arm and a splint on which the arm was fixed. The clinical results indicated that the active range of shoulder and elbow movements was enhanced [27]. In 1989, another leg propulsion assistive device similar to Yagn's design was patented. This device worked solely using mechanical systems to enhance the locomotive capabilities of the user. Hence, it can be categorized as a passive type assistive device [28]. Another human bipedal locomotion device actuated by springs mounted on the torso of a user was patented in 1991. The user's feet were secured to the frames while the bottom of the frames contacted the ground. Basically propelled by mechanical devices, this bipedal device enables the user to take large steps while walking or running and to make trampoline-like jumps [29]. A full body exoskeleton actuated by hydraulic power and controlled by a microprocessor was designed in the mid-90 s. Device of this type could be used for rehabilitation and enhancing the performance of healthy persons [30]. The timeline of development of exoskeletons are shown in Fig. 3.

The exoskeleton design and control was much improved with the advancement of computer and software technology in the twenty-first century. For example, in the design of the Berkeley Lower Extremity Exoskeleton (BLEEX), computer aided design software was used for developing three dimensional model. This helped in visualization and correction of the design in the early phases before proceeding to manufacture. In addition, BLEEX incorporated a control scheme to mimic the wearer's movements without much delay. The exoskeleton was also designed from anthropomorphic consideration. This was accomplished by matching the DOF of human joints to that of the exoskeleton. BLEEX is capable of supporting 75 kg load including exoskeleton weight and walk up to a speed of 1.3 m/s [47]. With the further development of modern technology, exoskeletons were designed for specific purpose like for a particular human movement or pathologies. For example, in one of the design [48], the exoskeleton was mounted on the hip and thigh for achieving the human movement. For people suffering from brain injury, SCI, stroke and other walking impairments, the ReWalk, LLE can be used to carry out ambulatory functions [49, 50]. The ReWalk comprises of a DC motors at the hip and knee joints, computerized control and rechargeable batteries on the backpack. Few other exoskeletons namely eLEGS (Exoskeleton Lower Extremity Gait System), a hydraulically powered one to facilitate standing and walking for paraplegics [51]; HAL facilitating only leg movements (HAL 3) and full body movements (HAL) for people with physical disabilities [52, 53]; and MindWalker, where the brain signals are directly communicated to this exoskeleton bypassing the spinal cord using Brain-Neural-Computer Interface [54]; are developed for rehabilitation purposes. The conventional exoskeletons are rigid in terms of its structure and movements. This rigidity reduces the free movement and comfort to the wearer. With a view to alleviate this problem, flexible exoskeletons were conceived and designed [55]. The flexibility exoskeletons are one whose structure, drive and motion are flexible. However, the system stiffness is low and sometimes cannot carry self-weight of human without additional support. The force transfer efficiency and control accuracy are also with flexible exoskeletons.

Industries are using robotic gadgets extensively to increase working efficiency and production. Exoskeletons are given to industrial workers to perform basic tasks like squats, package movement, overhead tasks, etc. because smart devices are meant to complete the repetitive working scenarios, but

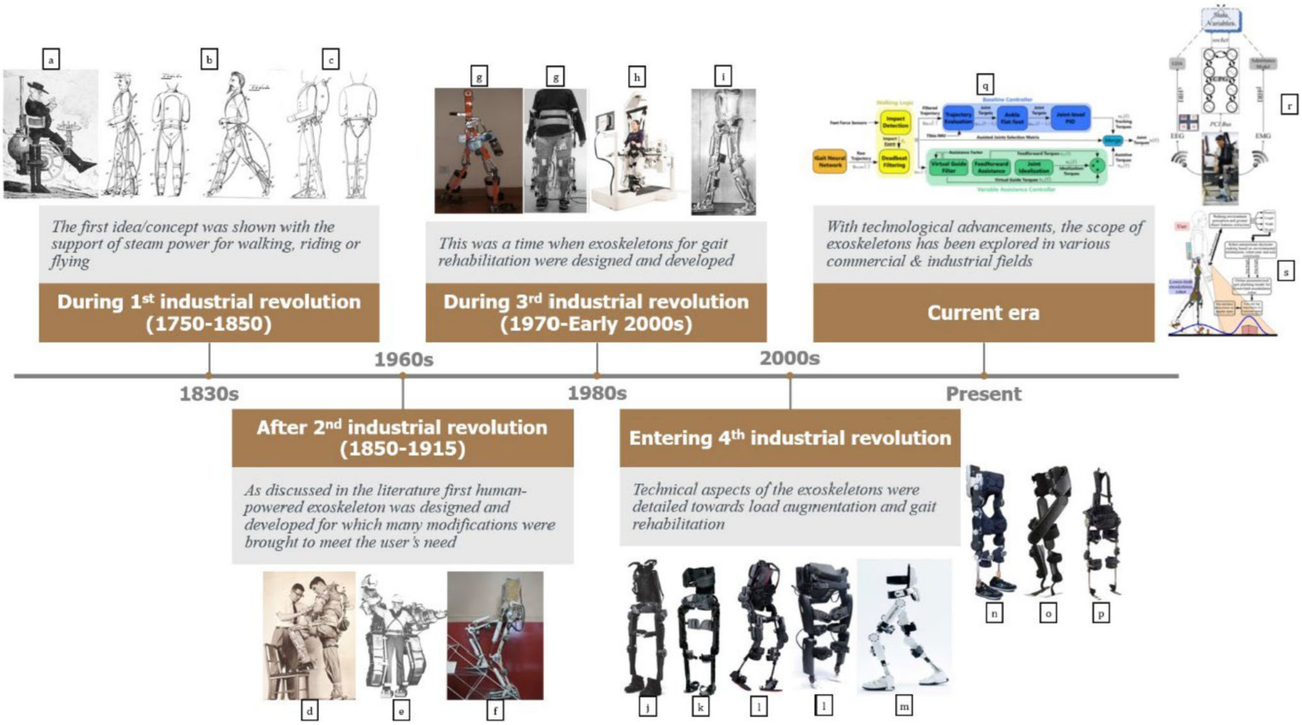


Fig. 3 Timeline of development of exoskeletons: 1st industrial revolution: **a** first concept of powered exoskeleton [31] **b** concept model of passive exoskeleton [21] **c** concept of powered exoskeleton [32]; 2nd industrial revolution: **d** hydraulic powered exoskeleton [25] **e** Hardiman with human–machine interface [24] **f** exoskeleton with electromechanical drives [33]; 3rd industrial revolution: **g** exoskeleton for rehabilitation [34] **h** Lokomat for gait training [35] **i** Humanoid robot [36]; 4th industrial revolution: **j** HEXAR [37] **k** TWIICE [38] **l** exoskeleton for SCI patients [39] **m** HAL [40] **n** TWIN [41] **o** Indego powered orthosis [42] **p** SuitX for SCI patients [43]; Current era: **q** Variable assistance LLE [44] **r** Multimodal humanoid robot interaction [45] **s** Vision assisted LLE [46]

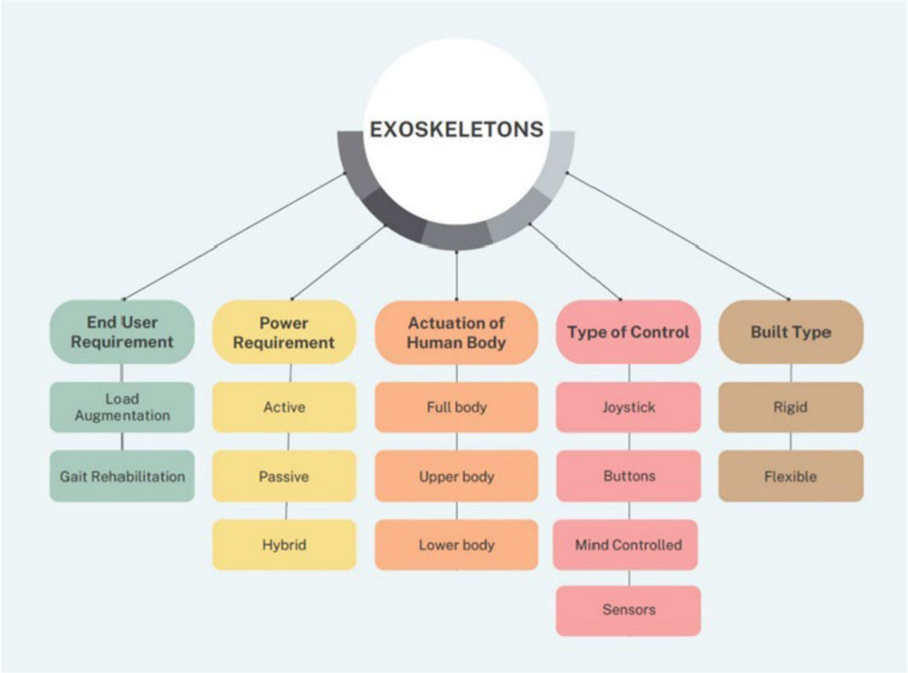
their implementation could be costly. One such lightweight LLE was proposed to reduce the fatigue in knee and thigh muscles. The system was designed and developed so that the results showed that productivity and efficiency can be improved without giving much body strain to the operator [56, 57]. The use of machine learning tool is seen in exoskeletons to predict the movement and position of the system. The tools like, deep neural networks and long-short term memory are used for the same. These strategies could be used to predict the next step of the LLE based on EMG signals. Experiments are conducted on the healthy users to procure the data, and later machine learning strategies are applied to predict the position, trajectory, and different gait phases of the LLE which could integrate with human movements [58, 59].

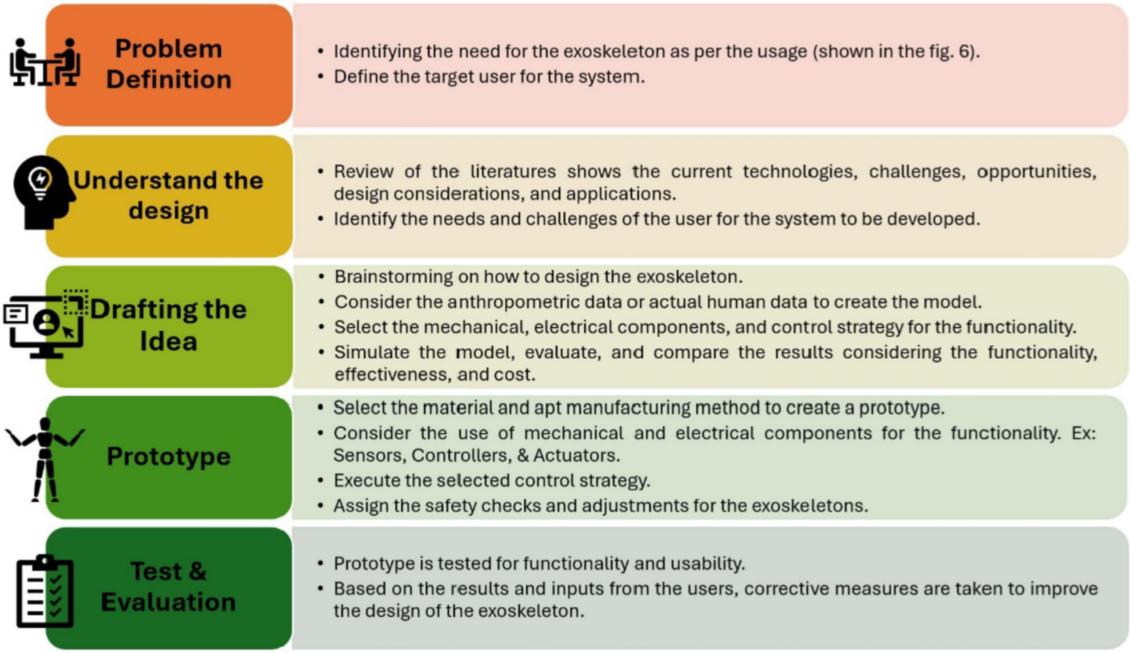
Safety is a major concern for industrial exoskeletons. To address this, the professional and regulatory have come up with safety guidelines for the use and operation of industrial exoskeletons, that comprises of adaptability, easiness, structural strength, ergonomics, comfort, performance, etc. Initially, the discussion panel is formed to discuss the possible safety concerns for the use of LLEs. Then, based on the brainstorming, the discussion points are categorized into different levels complexity. The devices are tested then to check whether the user experiences insecure or relaxed feeling while operating the LLE [60]. J-Exo was proposed for elderly patients to assist in climbing stairs and performing squats independently with less physical burden on the users. The experimental use by the subjects showed promising results with improved endurance with the use of a crotch strap as support [61]. To assist stroke patient's pelvis movement PeXo was designed for walking and balance training. This could serve as a rehabilitation tool for all possible movements of the user's pelvis. The PeXo is integrated with the self-pacing treadmill as the user can control the walking speed [62].

3.2 Classification of exoskeletons

For an all-inclusive analysis of the exoskeletons, these are classified as follows (Fig. 4). Based on the end user requirement, these are categorized for intending to *load augmentation* (to facilitate able-bodied people to carry heavy load for long duration both in smooth or rough terrain) and *gait rehabilitation* (for performing various mobility functions to restore normal functioning of body) exoskeletons.

Fig. 4 Classification of exoskeletons





Problem Definition

- Identifying the need for the exoskeleton as per the usage (shown in the fig. 6).
- Define the target user for the system.

Understand the design

- Review of the literatures shows the current technologies, challenges, opportunities, design considerations, and applications.
- Identify the needs and challenges of the user for the system to be developed.

Drafting the Idea

- Brainstorming on how to design the exoskeleton.
- Consider the anthropometric data or actual human data to create the model.
- Select the mechanical, electrical components, and control strategy for the functionality.
- Simulate the model, evaluate, and compare the results considering the functionality, effectiveness, and cost.

Prototype

- Select the material and apt manufacturing method to create a prototype.
- Consider the use of mechanical and electrical components for the functionality. Ex: Sensors, Controllers, & Actuators.
- Execute the selected control strategy.
- Assign the safety checks and adjustments for the exoskeletons.

Test & Evaluation

- Prototype is tested for functionality and usability.
- Based on the results and inputs from the users, corrective measures are taken to improve the design of the exoskeleton.

Fig. 5 Steps for development of exoskeletons

With regard to the power requirement, *active* (makes use of a power source to operate and control the actuators), *passive* (actuated by mechanical means and no external power source is used), and *hybrid* (have both electrical controllers and functional electrical stimulation) exoskeletons are available. In connection to the placement of the actuator on the joints of human, these are classified as *one joint exoskeleton* (actuator placed at hip, knee or ankle), *two joint exoskeleton* (actuator placed at hip and knee or knee and ankle) and *multiple joint exoskeleton* (actuator placed at all the three joints). Based on the part of the human body the exoskeleton supports, *full body*, *upper body* (torso and arms), and *lower body* (hip, knee, ankle and combination of these joints) exoskeletons are used. With respect to the type of control employed, *joystick*, *buttons*, *mind-controlled* (using an electrode skull cap), and *sensor* (to sense force, torque, rotation, inclination,

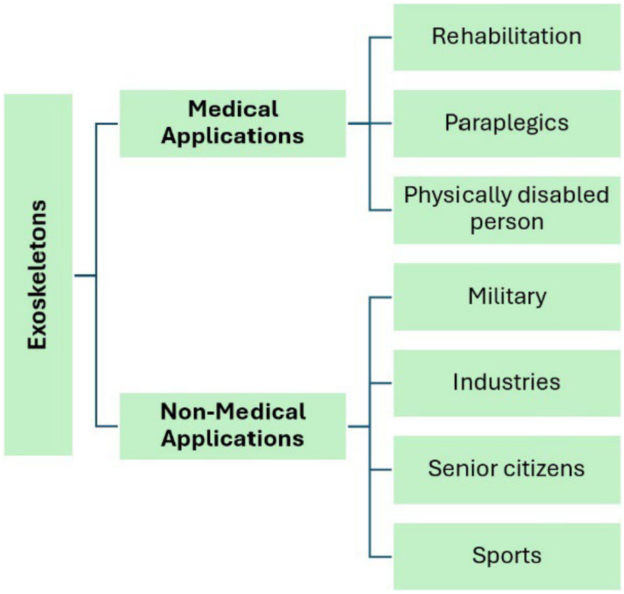


Fig. 6 Types of exoskeletons

pressure etc.) *controlled* exoskeletons are available. Based on the type of built, exoskeletons are classified as *rigid* (made of metals or carbon fibres) and *flexible* (flexibility in terms of materials and motion) exoskeletons (Figs. 5, 6).

4 Development and quality-improvement strategies of LLEs

From the point of requirement to the point of system implementation, a great deal of research is conducted to determine which solutions are best for developing the LLE. The steps involved in developing a model or system are defining the problem, comprehending the design, drafting the concept, prototyping the concept, testing the system, and assessing the system. Prioritizing the goal is a must for each phase. The flowchart shows the steps involved in the development of the exoskeletons.

The user's needs that must be met are the basis for the LLEs' quality enhancement. Although the LLEs' original use was primarily in medical applications, their current use is not restricted. Important research revealed that the number of elderly people is steadily rising worldwide and that they are not prepared to rely on others. Therefore, it is obvious that LLE quality improvement techniques should be implemented. Since the beginning, rehabilitation equipment has helped patients with paraplegics, physical impairments from accidents or aging, etc. accomplish fundamental objectives like standing, walking, and squatting. Being independent of others enhanced the user's quality of life. However, the LLEs must be simple to use, modular, and straightforward to comprehend. This involves taking into account the choice of actuators, control strategies, kinds of power supplies, materials, production processes, assembly methods, expenses, and functionality. The application of biomechanics to gait performance involves kinematic and dynamic analysis, degree of freedom, and range of motion selection. Prototypes are created with the intention of analyzing gait performance while taking the aforementioned aspects into account. To ensure that the movements are fluid and free from injuries, the LLEs must perfectly align with the user's body. Repeated industrial and clinical trials guarantee the dependability of the LLEs [13].

5 Design considerations

In the design of lower extremity exoskeleton, various criteria need to be considered to ensure safe and reliable use by the user. The important criteria to be paid attention are presented below.

5.1 Anthropomorphic and ergonomic design

The principles of bionics and anthropomorphic design are used extensively in development of exoskeleton structures for the safe use and increasing the comfortable range of motion. In this context, for the lower limb exoskeleton design to be human-centric, it must be embraced by the principles like compatibility of human-exoskeleton, fully-active motion assistance, good structural integrity, high centre of gravity and safety. More precisely, the number of joints in the exoskeleton must be consistent with the human joints to ensure stability of walking, all joints must be active, the exoskeleton structure must be light weight and strong enough to support the self-weight and the payload, and the centre of gravity must be high enough to facilitate self-balanced walking. There must be redundant safety mechanisms to prevent the errant working of the exoskeleton. For example, mechanisms for setting a limit on the power output, velocity of the actuators, mechanical stoppers for joints, emergency shut-off buttons for stopping motors and a system to reduce motor inertia. To ensure kinematic compatibility (compliance of exoskeleton mechanics with human gait), the DOF of exoskeleton joints is to be determined from the anthropotomy. According anthropotomy (Fig. 7), the three basic planes and axes of the human body movements are: frontal plane, sagittal plane, and transverse plane; coronal axis, sagittal axis, and vertical axis respectively (Fig. 3a). The hip joint is a ball and socket joint with 3-DOF flexion/extension (FE) adduction/abduction (AA), and internal/external-rotation (IE). This joint supports the body's weight during standing, walking and running. The knee is a hinge joint with 1-DOF flexion/extension (FE) with slight internal and external rotation carrying

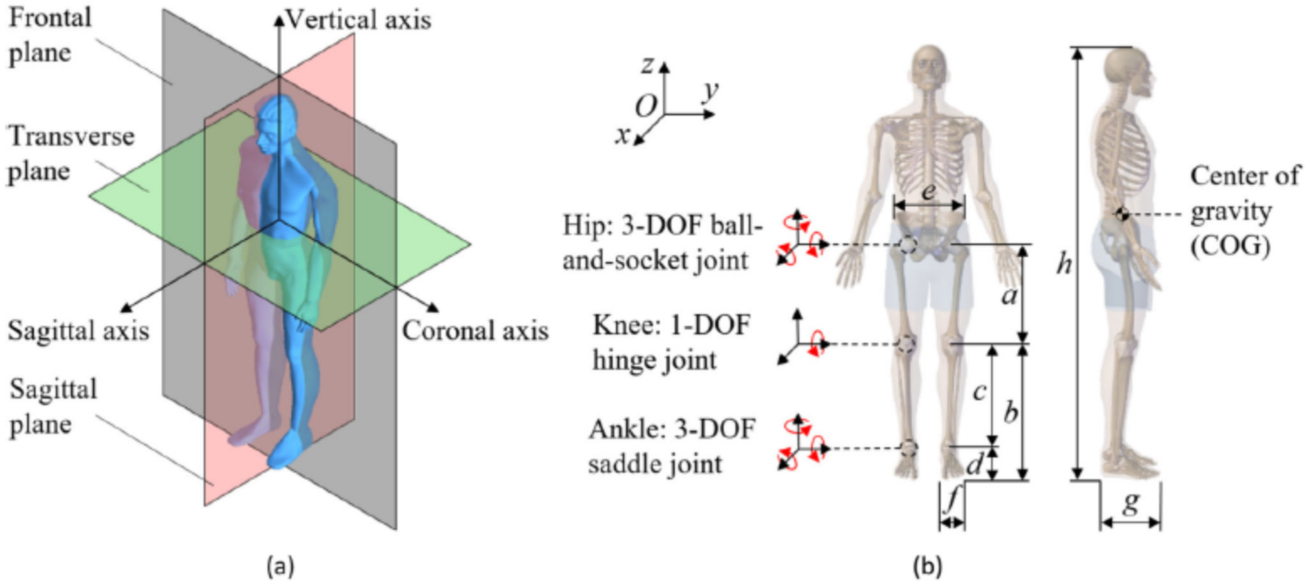


Fig. 7 Anatomy of human **a** Basic planes and axed **b** DOF, centre of gravity (COG) and dimension parameters of human [63]

body's weight. The ankle joint is a 3-DOF saddle joint with inversion/eversion (IE), dorsi/plantar-flexion (DP), and internal/external-rotation (IE) (Fig. 3b). For the LLE to work in parallel with human body movements, it must be designed by considering anthropotomy and anthropometric dimensions. This ensures adaptability of the exoskeleton for variety of users with different body shapes. The physical dimensional parameters of individuals vary from one to another. Hence, it must be chosen from a standard reference [63–65].

5.2 Actuators

The actuators used to power the lower limb exoskeleton are of three types, viz., active, passive or quasi passive and hybrid actuator. Active actuators which use power source, comprise pneumatic, hydraulic or electric actuators. The pneumatic actuators are very light in weight (can weigh below 1 kg) and highly flexible like human muscle. But these have limited power capacity, slow response, possibility of fluid leakage (leading to fluctuation in applied force) and difficult to control [66]. For example, pneumatic artificial muscles (PAM) which are called as soft actuators, resembling like human muscles, are used in applications where safety and biomimetic behaviour are of prime importance [67]. On the other hand, hydraulic actuators can deliver more power with stability, but they are bulky and costly. These actuators require regular maintenance and hydraulic oil is sensitive to load and temperature changes. Electric actuators can be controlled better relative to pneumatic and hydraulic actuators. This enables to achieve the precise movement of the exoskeleton. Hence, electric actuators are used often used in the exoskeletons. Despite this fact, they have low power density and large inertia. Passive actuators which are non-powered (exploits kinematic forces) comprise elastic components like springs and are based on gravity balance principles [68]. Quasi-passive actuators that work in conjunction with viscosity devices are dampers, clutches, or combination of these devices [69]. Passive orthoses depend only on physical effort of the wearer and can achieve slow walking speeds. Surveys have revealed that, the passive actuators reduce the metabolic energy and muscle forces needed for walking [70]. Hybrid actuators are blend of more than one type of actuator. For example, for actuating the main DOF like flexion or extension in hip joint, active actuators are used. While passive actuators are used for DOFs which are not too significant. As a consequence, this reduces the power output and maneuverability, which is more suitable for gait rehabilitation. The objective of this combination is to reduce the overall weight and cost of the exoskeleton [71, 72].

In order to enhance the human-exoskeleton interaction, compliant actuators inspired by biological muscles, are used these days. The three main types of actuators with biological properties are: series elastic actuator (SEA), pneumatic artificial muscle (PAM) and rigid-flexible combination actuator. The SEA emulates energy storage and buffering characteristics of muscle. With a view to improve the flexibility of the actuator, series of elastic components of given stiffness is introduced between the motor and the load. The idea is to circumvent the impact between motor and the load and reduce the effort of human upper limb for maintaining the balance [73, 74]. The PAM simulates the stretching and movement characteristics of muscle. This emulates the motor behaviour of the muscle, by constricting a cavity prepared using a flexible material via fluid action to produce tension [75–77]. To

Table 1 Different types of actuators used in LLEs

Sl. no	Exoskeleton name	Joint type	Actuator type	Actuator weight (kg)
1	Knee-ankle exoskeleton [83]	Knee-Ankle	DC motor (SEA)	0.8
2	Knee exoskeleton [84]	Knee	DC motor	0.76
3	Soft-inflatable exosuit [85]	Knee	Pneumatics	0.16
4	Soft ankle–foot orthotic device [86]	Ankle	Pneumatics	0.95
5	Assistive walking device [87]	Hip-Knee-Ankle	Pneumatics	12
6	BLEEX [88]	Hip-Knee-Ankle	Hydraulics	14
7	ELEBOT [89]	Hip-Knee-Ankle	Hydraulics	31
8	Lower limb exoskeleton [90]	Hip-Knee	Hydraulics	33.15

simulate the rigid-flexible combination property of muscle variety of variable stiffness structures like lever structures, cam mechanisms, and linkage mechanisms are used. This actuator uses a different motor to change the shape variable of the spring. The incorporation of addition motor increases the size and the complexity of the control algorithm. However, the variable stiffness can be realized through the admittance or impedance control algorithms [78].

Off recently, the use of variable impedance actuators (VIA) instead of stiff actuators in the rehabilitation exoskeletons is greatly increased because of its ability to make the exoskeleton more compliant [79]. The objective is to ensure a safe human–robot interaction and more fluent gait phase. This is achieved by modulating compliance of the exoskeleton joints. The compliance of the joints is mostly enhanced by adding elastic elements like springs [80]. By matching the impedance of the human joints with VIA, the user can feel more natural with the exoskeleton and can predict its behaviour easily [81, 82]. The selected LLEs using different types of actuators are presented in Table 1.

5.3 Control methods

One of the important design considerations in the design of LLEs is, to develop a control system which can perform wide-range of human-like movements. In addition, the LLE and human must work synergistically ensuring safety to the user. The different methods of generating exoskeleton movements are based on: inverse kinematics [91], motion pattern recognition [92] and user's state to forecast their anticipated movements [93, 94]. One of the vital safety issue in lower limb exoskeleton is achieving vertical balance to prevent from falling. The idea of zero-moment point (ZMP) control is usually used to maintain the vertical balance [95, 96]. The various types of control strategies used in the exoskeletal structures are presented as follows:

5.3.1 Hierarchical control system

This system consists of high-level, mid-level and low-level controllers. The wearer's motion intent based on the signals from the wearer, device and environment is perceived at the *high-level controller* (Fig. 8). The status of the current locomotive task like walking, standing, stair ascent etc. is identified by the *activity mode recognition*, while *direct volitional control* allows the user to willingly change the state of the device such as joint velocity, position and torque. The *mid-level controller* receives the information from the high-level controller for translating motion intent of the user in to a suitable output state for the device. At this level, the state of the user during motion is determined in terms of position, velocity, torque or impedance. This information is then passed on to the *low-level controller* to execute the desired motion. The error with respect to the current state is determined by this controller and attempts to minimize the same by sending commands to the actuator using feedback or feed forward system. Finally, the prosthesis or orthosis (P/O) device is actuated to perform these command [97].

5.3.2 Control system based on physical parameters

The commonly used physical parameters for controlling the exoskeleton are position, force or torque, and interaction forces. Physical based sensors can be used for detecting the motion intention of the user. For example, potentiometer, encoder, inclinometer and accelerometer are used for sensing position and motion. While force or torque sensor, strain gauge, pressure sensor, and piezoelectric sensors are used for measuring force or pressure [71]. The position control or trajectory control is mainly used to ensure that the exoskeleton joints turn in a preferred angle in synchronous with the wearer's joints. The difference between the target and feedback joint angles are regulated by the control system. Position

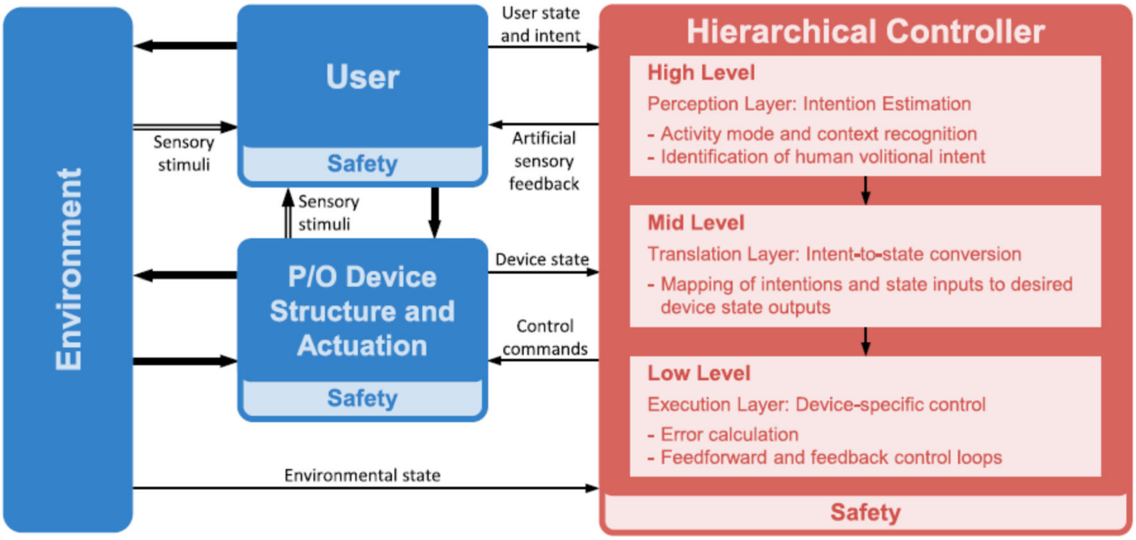


Fig. 8 General control framework for LLEs [97]

control is typically applied as a low-level controller and frequently used in gait rehabilitation and locomotion assistance. The primary issue in position based trajectory control is how to generate the requisite trajectory. In gait rehabilitation, reference positions or trajectories are obtained from healthy people and are used as target trajectories. The reference trajectory thus captured may not correspond exactly to the patient being trained. In addition, the motivation of the patients are suppressed as they are submissively trained to move along predefined trajectory paths [98]. It is suggested that extensive use of exoskeleton may reduce the patient's effort and motor learning, but leads to ineffective training [99]. Up till now, the position controlled LLEs are used in the primary stage of rehabilitation where patients do not have adequate strength [100, 101]. In case of locomotion assistance, the joint angles of the exoskeleton and user are exactly controlled to follow the pre-set trajectories. The reference trajectories of all joints are set in advance. This type of control is predominantly used in the SCI patients to enable them to walk independently [102–105]. Frequently, the Proportional-Integral-Derivative (PID) controllers are used to regulate the position, force, velocity and other variables using a feedback loop in the control system. The proportional gain regulates the ratio of system response to error signal. The integral gain is used to minimize the steady state error and the derivative term attempts to nullify the rate of change of error and decreases the overshoot.

Often, the force and position controls are used in combination in control strategies to ensure communication between the user and the device. Since in position-based trajectory control, the patients are skilled in a passive way along the fixed paths, it results in undesirable training effects. Hence, a hybrid force and position control is used, where the device is regulated to move along the specified trajectory by maintaining device-user contact force. This strengthens the patient's muscles and ensure speedy recovery [106]. This control is generally used in low-level controllers. For example, BLEEX employs hybrid force and position controller, where in the stance leg is regulated by position controller while the swing leg is regulated by force controller [47].

In addition to the position and force or torque controller, the *interaction force* between the subject and the device is also taken into account in the exoskeleton systems. The interaction force controller is used as high-level controller and is regulated by either admittance or impedance controller. The basic idea of assistive control methods is to make the device to not to interfere when the wearer is moving in the specified trajectory. But, the device must create and apply a restoring force when the wearer's movement deviates from the specified trajectory [107]. The amount of the support exerted by the device is modified commonly using impedance controllers. An impedance is any dynamic operator that receives a kinematic input like displacement or velocity and outputs a force or torque [108]. Alternatively, an admittance controller, converts the interaction force in to the expected trajectory of the exoskeleton. The performance of impedance controller is influenced by the precision of the position sensors, while for the admittance controllers, it depends on the accuracy of the force or torque sensors. The impedance or admittance parameters are usually fixed in most robot designs. However, these parameters can be manually regulated, for example, the therapists based on their experience adjust the impedance parameter [109, 110]. In the new exoskeletons, the controllers that automatically adjust the impedance parameter using adaptive control algorithms are proposed. These adaptive controllers are not widely implemented as they pose safety issues to the wearer [102, 111, 112]. The adaptive controllers, decreases the mechanical impedance (i.e. high compliance) leading to unsafe structure and may not protect the wearer. Consequently, this results in injury to the wearer. Thus, one of the challenges in incorporating adaptive control in LLEs, is to determine a suitable trade-off between compliance and safety [113].

5.3.3 Model based control system

In model based control, the control strategy can be based on *dynamic model* or *muscle model*. The dynamic model is obtained by treating the human limbs as rigid links joined together at revolving joints. This model predicts the torque produced due to gravitational, inertial, centrifugal and coriolis effects [114]. The *dynamic model* can be obtained by three methods: the *mathematical model*, *system identification* and *artificial intelligence method*. Based on the physical characteristics of the system, the *mathematical model* is derived. This type of mathematical model was implemented in BLEEX exoskeleton for supporting wearer's movement [47]. In case of *system identification*, least squares method is employed to obtain the parameters of the dynamic model using input–output data. An active impedance control method was used in an LLE to assist the patients employing recursive least squares method for determining the characteristics of the dynamic model [115]. The inputs of the recursive algorithm were angular position, angular velocity and angular acceleration, while the output was measured torque. In case of *artificial intelligence method*, the model parameters are obtained by using input and output data acquired from experiments or real world. Tools like neural network is mostly used to obtain the dynamic model parameters. For example in [116, 117] the output torque was determined using the inputs like exoskeleton joint angular position, velocity and acceleration by employing wavelet neural networks.

Muscle model predicts the muscle movement as a function of muscle neural activities and joint kinematics [118]. This model outputs force with electromyography (EMG) as input. The other cognitive based sensors can also be employed to measure muscular activity like *muscle stiffness sensor* (MSS), *ultrasonic muscle activity sensor* and *muscle tenseness sensor* [71]. The two models used to build the muscle models are: *black box approach or non-parametric approach* and *phenomenological-based model or parametric approach*. In *black box approach*, a set of inputs and outputs are used to train neural network to predict the output for a given arbitrary input. The parameters of the neural network are accordingly adjusted while training of the network with real world data [119]. This model does not require the information of muscle and joint kinematics. The *parametric approach* uses Hill-based model derived from original model of Hill [120]. This model comprises of a contractile element, a series element, and a parallel element. The output is generated as a function of EMG signals and muscle length. There are few limitations while using EMG signals as input. These are sensitive to skin properties (blood circulation, sweat on the skin), interference from neighbouring muscle signals, electrode placement, and dependant on overall neurological condition of the participant. Hence, the EMG parameters have to be calibrated for every participant. Another demerit is that, if the participant creates uncoordinated or abnormal muscle movement, the robot moves in an undesired way [107].

A model-based control system was proposed for the exoskeletons to perform the activities of daily living like sitting, standing, walking, etc. This makes the user to take control of the system. The control scheme comprises of low, mid, high, and actuator-level controls. The series elastic actuators were used in the model to evaluate the sit-to-stand positions [121]. Model-based control with Interaction Predicting (MIP) was proposed to have less dependency on the dynamic model of the system. The interaction predictor can forecast the motion path and correct the error in the upcoming and planned trajectory [122]. The LLEs for rehabilitation use control strategies as model-based and model-free to provide better gait training and locomotion assistance. The model-free control strategy showed better responsiveness as compared to the model-based method [123]. Cerebral palsy is a paediatric disorder that happens in children and could lead to mobility loss if not solved. Hence to overcome that exoskeleton with gait training is suggested. For this, a model-based prediction strategy is assigned that could predict knee moment given the knee angle during the gait phase of walking. Two modes were taken to assess the strategy zero torque mode & assist mode [124].

5.3.4 Fuzzy logic controller (FLC)

Because of the sophisticated mechanical structure, motion trajectory and human involvement, the control architecture poses additional complexity in its design. For the LLEs to work in synergy with the wearer's joints, appropriate control schemes have to be used. Hence, a robust and effective control strategy is the most important requirement of the LLE for achieving synchronous motion [125, 126]. Several researchers have preferred the proportional-integral-derivative (PID) controller to for its simple structure. However, it is not easy to tune the PID control parameter to achieve the desired output because of the parametric ambiguities and external disturbances [127, 128]. In addition, the couplings and nonlinearities are disregarded in PID controllers [129]. To overcome the limitations of traditional control methods, several intelligent control schemes have been proposed in the literature [130–135]. The control schemes based on neural network, neuro-fuzzy compensator

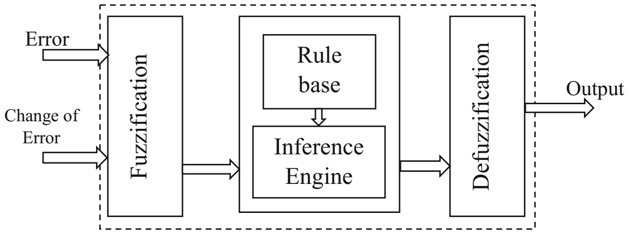


Fig. 9 Fuzzy control block diagram

for PID, time-delay-estimator aided computer torque control and linear quadratic regulator (LQR) based neural-fuzzy control are found to be more robust against payload uncertainties and external disturbances [136–140].

A fuzzy controller is one of the widely used artificial intelligence based control technique making use of the experience of an expert for controlling the system. The expert sets up decision based rules based by examining the system behaviour. The inputs given to fuzzy controller has to go through three basic stages of fuzzification, decision-making, and defuzzification (Fig. 9). The crisp input variable (state error and rate of change of state error) is transformed in to linguistic variable with predefined membership functions. In the decision-making stage, the inference engine determines the rules and fuzzy control action for the appropriate fuzzified outputs. In the defuzzification stage, the output of the inference engine is transformed in to required output for controlling the system [141]. This type of controller is implemented in EXPOS wearable robots [142, 143]

5.3.5 Hybrid controller

The advantages of different control methods are combined in to a single scheme in a hybrid controller. In HAL [52, 144] two types of control methods were used for two applications. For load augmentation, model based approach was used where in the human intention was detected through sEMG signals to estimate the output torque. For the gait rehabilitation, an autonomous control system made the wearer to trace the predefined trajectory by controlling hip and knee joint. Similarly in AIT [145] exoskeleton, the gait trajectory is predefined in offline, while the fuzzy controller is used to adjust the trajectory online.

6 Materials and manufacturing methods

The materials and manufacturing methods used in the fabrication of the lower limb exoskeleton are the most important parameters to ensure safe and reliable use. The most commonly used materials are either soft or hard and stiff materials or combination of both. The soft materials like fabric and elastomers, are used to minimize the metabolic penalty of carrying bulky exoskeleton mass. These materials conform to the existing surroundings and are inherently compliant, resembling like clothes and work in parallel with muscles to offer assistance. The drawback of these soft materials is that, it limits the magnitude of force or torque and the velocity with which the device can move. Hence, these are suitable for applications where small levels of assistance is required. In contrast, rigid exoskeletons can deliver higher forces or torque, quickly and efficiently as well. The rigid exoskeletons are made from hard and stiff materials to provide excessive power and preciseness. The goal in this case is to keep the structure light weight without compromising on the strength. Since the exoskeletons are subject to repeated loads for more than millions of times during its lifetime, fatigue behaviour of the material plays a major role. For static and small cyclic loads, the fatigue behaviour is not of serious concern and can be ignored safely (Table 2).

Table 2 Different control methods employed in LLEs

Sl. no	Selected references	Control methods
1	Hussain et al. [146], Emken et al. [147], Vallery et al. [103], Wicke et al. [148], Beyl et al. [149], Husemann et al. [150]	Trajectory tracking
2	Ju et al. [151], Simon et al. [152], Deutsch et al. [153], Bernhardt et al. [154]	Force control
3	Mayr et al. [155], Veneman et al. [156], Roy et al. [157], Emken et al. [158], Koopman et al. [159], Agrawal et al. [160]	Impedance control
4	Krebs et al. [161], Kiguchi et al. [162], Fleischer et al. [163], Yin et al. [164], Lenzi et al. [165], Fan et al. [166]	EMG based control
5	Riener et al. [167], Wolbrecht et al. [168], Colombo et al. [169], Kiguchi et al. [170], Zhang et al. [171], Riener et al. [172], Hogan et al. [173]	Adaptive control
6	Mori et al. [174], Marcheschi et al. [175], Yan et al. [176]	Mode based control
7	Kong et al. [142], Kiguchi et al. [143]	Fuzzy control
8	Sankai et al. [144], Aphiratsakun et al. [145]	Hybrid control

The commonly used materials in the manufacturing of LLEs are stainless steel, aluminium and titanium alloys, mostly employed for actuating multiple degrees of freedom. The specific strength (ratio of yield strength to density) of aluminium alloy is 9–166 Nm/kg, which is 67% less than that of titanium alloy (44–278 Nm/kg). However, titanium is expensive which limits its use. Another alternative material for rigid exoskeletons is, the polymeric or carbon fibre reinforced composites. This is commonly used in exoskeletons

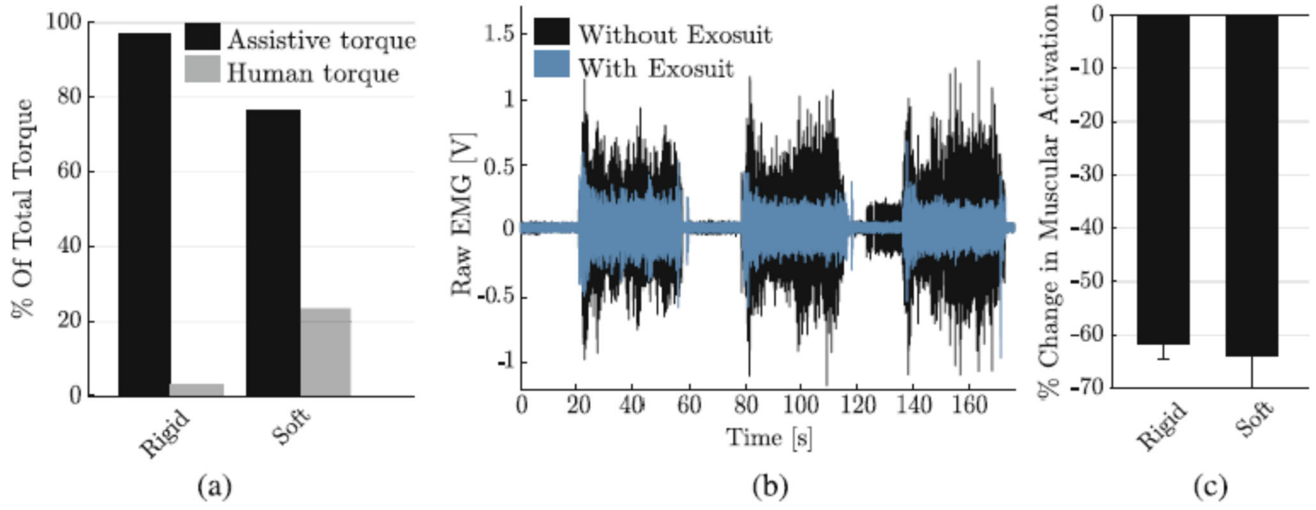


Fig. 10 Comparison of assistive torque and reduction in muscular activity **a** percent of total torque of rigid and soft exosuit **b** electromyography signals from the biceps **c** percentage reduction in muscular activity [180]

where actuation of only single degree of freedom is required [177–180]. Though polymeric composite is light in weight relative to aluminium, it is difficult to impart desired size and shape compared to metals. Carbon fibres are susceptible to wear through abrasion and care must be taken to not to use at the exoskeleton joints which are subjected to repeated motions [181]. A comparison of soft and rigid upper limb exoskeletons on the biomechanical and physiological effect on the elbow movements is shown in Fig. 10.

In case of rigid exoskeleton, shown in Fig. 10a, the percent of torque exerted by the wearer is very less in comparison to soft exosuit. This relieves the user from applying greater portion of the effort needed to flex the joint. The rigid exoskeleton delivers nearly 100% of assistive torque than the soft one (nearly 76%). As shown in Fig. 10b, the electromyography signals obtained from biceps brachii while flexing the elbow. By wearing the soft exosuit the muscular activity reduced by 63.97% in comparison to 61.63% for rigid exoskeleton [180].

The following table shows the materials and manufacturing methods adopted for the LLEs:

Exoskeleton	Manufacturing Technique	Materials
Indego [42]	3D printing and CNC machining	Carbon fiber and metals
MINDWALKER [73]	3D printing and extrusion	Carbon fiber and high-grade titanium
HAL [144]	No data	Metal frames
Lokomat [154]	3D printing and CNC machining	Metals
ReWalk [186]	3D printing	Metals
Ekso [187]	3D printing of individual parts	Carbon fiber, metal, and elastics
Rex [188]	No data	Metals

Selecting a suitable manufacturing process ensures adequate strength of links and joints, durability and comfort to wearer of the exoskeleton. Different manufacturing processes are used for metals and non-metals. Some of the conventional manufacturing processes used in the fabrication of LLEs are metal casting, extrusion and computer numerical control (CNC). Metal joining process like welding is also used in combination with CNC machining. Nevertheless, the conventional manufacturing processes have some limitations over modern manufacturing methods like 3D printing. They are, high cost of machining, lack of uniform strength and wall thickness and poor surface finish of the final parts etc. Additive manufacturing techniques like 3D printing can be used to structures of intricate geometries. This method is widely employed for polymeric materials and recently metals as well. Acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are the common polymers used for 3D printing. Other materials like polyamide, nylon, polyurethane and carbon polymers are also used for the fabrication of exoskeletons using 3D printing. Considerable reduction in the weight and fabrication time can be achieved by using 3D printing technique. The strength to weight ratio of 3D printed parts are superior to that of parts manufactured from conventional methods. It is easy to 3D print a part of complex size and shape more quickly. In order to join the 3D printed parts, thermal bonding process is used. Despite the benefits of additive manufacturing, the 3D printed components are usually susceptible for rapid wear and tear at the joints due to regular rotational motions. As a result, the joints of the exoskeleton are made from metals and rest of the portion from 3D printing. The process of manufacturing method selection in combination with optimization techniques is presented in [182]. Multi-objective optimization is used to compare different manufacturing methods, materials and thickness minimizing the cost and manufacturing time and maximizing the performance. Motivated by exoskeleton of insects, integrated manufacturing methods have been proposed to fabricate structures for attachment, protection and sensing. This method is based on infrared laser machining of laminas and bonding of layered structures [183, 184].

Compared to conventional methods, 3D printing has made it easier for producers to print complex shapes. Since there is no waiting period, the procedure is so quick that the pieces can be assembled and tested in a few days. It is possible to make the design iterations faster, cheaper, and with less work. Because only the source material is used for printing, there is minimal material waste when considering environmental sustainability. One of the main obstacles is achieving perfect dimensional accuracy because some items require fitting to subsequent parts with small dimensions. After printing, the parts must meet some basic mechanical requirements, such as tensile strength, compressive strength, stiffness, etc. The process of printing quality layers is influenced by the powder density, which makes it an important factor. Comparable to this, the powder's size and shape are also important considerations. The integration of 3D printing technology requires skilled technicians, updated software and hardware, and initial investment [185].

CAD software like SolidWorks, ANSYS, MSC Adams, etc. aids in the understanding of the model by the designers prior to the real production approach being used in subsequent phases. The goals are as follows: [186, 187]

1. To build an LLE model that resembles the actual design.
2. To create the model's shape using anthropometric data from several global locations.
3. To offer the degrees of freedom and range of motion needed for the model's kinematic analysis.
4. To apply the stresses and torques that the actual world scenario requires in order to analyze the model's structural integrity.
5. To reduce bulk and material utilization, save material and assembly costs, and improve the production process without sacrificing the LLE's objectives, structural optimization is applied to the model.
6. To design a sustainable product by selecting the apt material and manufacturing technique from the database while taking the environmental impact into account.

7 Medical aspects of LLEs

Medical exoskeletons aid the joint or limb movement of a patient in a particular way where the functionality is inadequate or lost in terms of strength or mobility. For example hip or knee exoskeletons are used for rehabilitation purposes while ankle exoskeletons are used for drop foot applications. These are used to assist patients suffering from paralysis. The conventional methods such as the use of braces and crutches, wheel chairs and orthotic devices, for assisting paraplegics have their own merits and demerits. Braces and crutches may not provide full autonomy in motion. The wheel chairs can be used only on flat surface and not on rough terrains. In addition, the patients are forced to sit in one posture for prolonged duration and eye-level interactions are also not possible with wheel chairs. Orthotic devices like functional electrical simulation (FES) can be used for short distance successfully. FES systems when used over long distances, lead to muscle fatigue and high energy consumption. Knee–ankle–foot orthoses (KAFOs) are heavy and cumbersome to wear, while reciprocal gait orthoses (RGOs) provide better ambulation over short distances [188]. A few of the exoskeletons developed for the paralysis are ReWalk [189], Ekso [190] and Rex [191], have been approved by medical regulators such as United States Food and Drug Administration thereby leading to commercialization. Due to commercialization, these products tend to be very costly and the evidence for their real usefulness is still in doubt due to technical issues. The technical issues include slow response in dynamic performance of the exoskeleton relative to humans, the weight constraint of the exoskeleton, more heavy battery pack requirement when used outdoor, comfort issues while wearing, complexities in actuation and sensing components. There are also societal issues like poor ergonomics, hesitation in use of such heavy exoskeleton for everyday use, high cost, and poor human-exoskeleton interaction which is limiting widespread clinical use of exoskeleton. For amputees, robotic prosthetics are used for improved restoration of personal mobility. These exoskeletons are sometimes termed as "Intelligent prosthetics", as they can actuate and control the exoskeleton movement based on the user-device interaction. 'C-Leg' product used for trans-femoral amputees developed by Ottobock [192] is a quite comfortable device compared to other similar ones.

With regard to the structural design of LLEs, the understanding of gait neuromechanics helps in making neuromechanical modifications in response to external circumstances. Thus, application of force intervention without regard to gait neuromechanics, can adversely affect the outcome of a selected rehabilitation paradigm [193, 194]. Accordingly, the current structural design of LLEs are focused in alleviating undesired structural constraints, reducing LLE inertia, minimizing joint misalignments and incorporation of joint compliance for allowing voluntary participation during rehabilitation process [195, 196]. The control architecture is vital and is continuously evolving for applying innovative gait interventions through timely and precise actuation of motors to apply desired forces. The accurate estimation of neural activity, muscle activity and interaction forces is now possible with recent advancement in technology. This led to the development of novel control strategies for maximizing the performance restoration through user's voluntary participation [197–202].

The technical recommendation for the LLEs in medical applications comes from the statutory body that publishes the rules and guidelines for the manufacturing and marketing of the LLEs. The FDA (U. S. Food and Drug Administration) is one organization whose primary goal is ensuring that customers use systems and products safely. Developing an ecosystem for the creation of compatible, safe, and dependable exoskeletons is a key responsibility of the government, manufacturers, and clients. The FDA has only authorized three exoskeletons worldwide: ReWalk, Indego, and Ekso. The organization that oversees the production of exoskeletons establishes the precise rules and regulations. Risk management, usability, and safety have received more attention. Falls, bone fractures, skin/tissue injury, etc. are all included in risk management. Joint angles, batteries, and human-system interaction are all examples of safety [203]. The International Organization for Standardization (ISO) and the International Electro-technical Commission (IEC) have established standards for the development of systems that take functionality and safety into account. These standards are followed by exoskeletons used in medical applications. Medical exoskeletons are utilized in the rehabilitation of amputees and paraplegic patients. The ISO specifies standard codes pertaining to human-system interaction, safety, and risk management [204].

8 Challenges and future expectations

The lower limb exoskeletons have shown potential in assistance and rehabilitation applications. However, these are still quite expensive and their procurement and deployment is difficult. Therefore, it is more important to apply multidisciplinary approach to ensure its potential applicability in all domains and accessibility to general public. The potential negative effect of wearing exoskeleton for long duration may lead to musculoskeletal disorder (MSD). In contrast, occasional wearing increases the cognitive load and may cause accidents (due to misalignment between exoskeleton kinematics and human anatomy). While wearing the exoskeleton occasionally, the user simultaneously engages in conscious thought about work and the exoskeleton. This is another issue of serious concern to be investigated and thus becomes an important future research direction [5].

Safety is a foremost concern for the government and other regulatory organizations before releasing any product for the public use. Some the safety measures which can be incorporated in LLEs include, providing physical stops in the exoskeleton structure to limit the range of motion of each joint and the maximum torque that the actuators can apply. In addition, the control system should ensure user's safety and stability in emergency conditions. Safety of the battery should also be accounted while developing active exoskeletons [12]. Further research is necessary to develop or improve the safety-testing aspects to evaluate the compliance.

To make the future LLEs more comfortable for the users, from the mechanical design perspective the exoskeletons must be flexible, wearable, adaptable, modular and light-in-weight to enhance its performance. The general purpose or multifunctional LLEs must be avoided, since they turn out be bulky and less effective. Special purpose or application specific LLEs have to be developed based on the concept of modularity. In the modular approach, the exoskeleton is divided into small modules by standardizing the components. This cuts down the cost of development and maintenance. In addition, modularity increases the portability, robustness and adaptability of the exoskeleton [205, 206]. A portable LLE which significantly decreases the metabolic energy required for running or walking is yet to be developed. With regard to the materials, the use of light weight metals or alloys which are compatible with wearer's body [207, 208], 3D printed materials for links and metals for joints [209, 210] are recommended. The recent development of soft materials for transmitting force or torque led the development of soft exosuits. Soft exosuits are clothing-like devices made of fabric or elastomers that wrap around the human body and work in parallel with the muscles. These are powered by cables or wires, pneumatic actuators or electric motors embedded in the exosuit. In addition, these are lightweight, conformal and compliant to the wearer body [211–215]. Soft exosuits which can deliver high force or torque must be developed in future.

Another vital parameter that limits the performance of the exoskeleton is the weight of the actuator. Depending on the application, heavy hydraulic actuators are used for load augmentations in military and manufacturing sectors, while light weight and compact ones are preferred in medical applications. In addition, the batteries used to power the actuator have the problem of short life span, increased weight and limited number of charge/discharge cycles. This poses a challenge for the development of light weight, compact and portable powered exoskeletons. Given the limitations of the actuator technology, recent research in the artificial muscle actuator has shown significant promise in reducing the overall weight of the exoskeletons. However, there are few challenges impeding the implementation of artificial muscle actuators. The challenges include scaling up of the actuator capacity to enhance force or torque requirements, improving lifetime at high level performance and implementing compact driving electronics. The electroactive polymers have given a ray of hope, since they allow integration of force controllability and joint impedance, noise free operation and allowing anthropomorphic device morphology [216, 217]. The future actuators for the LLEs must be lightweight, noise-free, compact, reliable, and less expensive and energy efficient.

Human-exoskeleton interaction is another area which is not matured yet. The exoskeleton is expected to interact and adapt with the user and the environment by actively sensing the inputs. It is important for the exoskeleton to quickly detect the motion intention of user to provide comfort and improve the usability. The motion intention of the user can be obtained through body movement information, via video-based motion capture system, plantar pressure information, by placing 2–5 pressure sensors on the heel and sole of each foot, and bioelectrical information, using electroencephalography (EEG) and surface electromyography (sEMG) signals. The video-based motion capture equipment is very complex, expensive to operate and can be affected by various factors such as activity range and illumination [167, 168]. The bioelectrical information received via EEG which are weak electrical outputs of brain nerve cells are hard to identify, save and process in real time. The sEMG signals obtained during muscle contraction from the surface of muscles in a non-invasive way. Relative to EEG, sEMG signals directly reflect the limb movement information and has higher signal–noise ratio. These are successfully employed in detection and forecasting of user movement intention, fatigue level and joint torque as well. Currently, for the better sensing of movement intentions of LLE wearers, researchers have started to explore nerve stimulation whose basis is neuroplasticity [218–222]. A high resolution sEMG neural signal measurement system is being developed to capture real-time user sEMG signals. Thus, sufficient motion intention information, biological signals and interaction information is to be collected from the LLE system for improving the comfort of the user. Too much of information acquired from the user increases the power consumption and affects efficiency of implementation. However, with the help of various software algorithms like data mining, machine learning, deep learning and multimodal information fusion based on artificial intelligence is expected to be the future direction of LLE research [223, 224].

The research on harvesting energy from human movements is also under progress. However, the amount of energy harvested is hardly few milliwatts which is not sufficient to power the exoskeleton. Nevertheless, it can be utilized to power the sensors and other low-powered electronic devices. The efficiency of energy harvesting could be improved through further research by way of developing efficient energy conversion materials and enhancing the design of energy harvester [225, 226].

The user must adhere to fundamental human postures when using the various LLE applications, including standing, walking, and squatting. Thus, the multimodal machine learning model is implemented with the help of data from gait analysis, motion pattern recognition, EEG signals, and foot pressure in order to increase safety, accuracy, and mobility. Due to the fact that the machine learning model used EEG signals as input, the testing results demonstrated remarkable accuracy [227]. Lately, the development of LLEs has incorporated artificial intelligence or machine learning techniques to enhance rehabilitation quality, functionality, and self-sufficiency. Tools that help users use LLEs safely and effectively include support vector machines, decision trees, neural networks, reinforcement learning, and reinforcement learning [228]. The danger of harm for LLEs employed in industries is a result of their intricate jobs and constant motion. On the chosen subjects, techniques such as Support Vector Machine, Random Forest, Logistic Regression, and XGBoost were applied in order to comprehend and predict the user's fatigue during trunk flexion. The data was recorded using force plates, motion captures, and EMG sensors. The outcomes demonstrated that the devices' optimization and safety may be enhanced [229]. The battery life of wearable exoskeletons is a concern when they are utilized in harsh environments for extended periods. As a result, battery management needs to be planned without compromising the user's aid or mobility. The battery management system is optimized using the Q learning reinforcement learning method to achieve this. An exoskeleton SOC (State of Charge) value model was developed to enhance and maximize energy utilization. The model demonstrated increased prediction accuracy and a decrease in the predicted zero value. The outcomes demonstrated that battery management is amenable to optimization [230].

9 Conclusions

- A concept model of LLE which originated in the nineteenth century for facilitating walking, running, and jumping, later evolved into an intelligent device for load augmentation and gait rehabilitation. The intelligence is imparted through the use of a feedback control system (which receives inputs from various sensors and actuators) and artificial intelligence techniques.
- The use of LLEs is not limited to medical use, it is now extensively used for industrial and domestic purposes too.
- For ensuring the comfortable and safe use of LLE, the principles of anthropometry, ergonomics, different types of actuators, and safety mechanisms like limiting the position and velocity of actuators, emergency shut-off buttons and mechanical stoppers are to be incorporated during its design phase.
- For achieving synchronous motion between the LLE and wearer's joints various control schemes like hierarchical, physical parameters, model-based, fuzzy logics, and hybrid control methods must be employed.
- Depending on the magnitude of force or torque required either soft or hard materials are used in the construction of LLEs to minimize the penalty on the metabolic activity. When a small amount of force is required to be applied, soft materials like fabrics and elastomers are used. While for large forces, hard materials like aluminum and titanium alloys, and carbon fibre reinforced composites are used.
- By selecting soft exosuits, the muscular activity is reduced by 63.97% in comparison to 61.63% for rigid ones.
- The integration of machine learning tools like, deep neural networks, long-short-term memory, etc. helps in predicting the movement and position of the LLE.
- Conventional manufacturing processes like casting, welding, extrusion, and CNC are used for simple shapes. For making intricate shapes, modern manufacturing process like 3D printing is used. Multi-objective optimization methods are sometimes employed for selecting the appropriate manufacturing process.
- Though the LLEs have the potential enough to be used in the field of rehabilitation, their widespread clinical use is limited, due to their high cost and inherent technical issues.

Acknowledgements Due cognizance has been given to the various sources of data used in the study and duly cited.

Author contributions AS Conception of the study; AS Study methodology; NJ Formal investigation and analysis; NJ Writing and preparing manuscript; AS Reviewed and edited the manuscript; AS Supervision.

Funding The authors report that no financial support was received for the manuscript preparation.

Declarations

Conflict of interest The authors have no competing interests.

Human and animal rights statement This research did not involve human participants or animals.

Informed consent This research did not require informed consent

References

1. Singla, A., Dhand, S., Virk, G.S.: A brief review on human-powered lower-limb exoskeletons. In Conference: Conference on Mechanical Engineering and Technology (COMET-2016) At: Department of Mechanical Engineering, IIT (BHU), Varanasi, pp. 116–122 (2016)
2. de la Tejera, J.A., Bustamante-Bello, R., Ramirez-Mendoza, R.A., Izquierdo-Reyes, J.: Systematic review of exoskeletons towards a general categorization model proposal. Appl. Sci. **11**(1), 76 (2021). https://doi.org/10.3390/app11010076
3. Wang, T., Zhang, B., Liu, C., Liu, T., Han, Y., Wang, S., Ferreira, J.P., Dong, W., Zhang, X.: A review on the rehabilitation exoskeletons for the lower limbs of the elderly and the disabled. Electronics **11**(3), 388 (2022). https://doi.org/10.3390/electronics11030388
4. Kumar, V., Hote, Y.V., Jain, S.: Review of exoskeleton: history, design and control. In: 3rd International Conference on Recent Developments in Control, Automation and Power Engineering (RDCAPE), pp. 677–682 (2019)
5. Fox, S., Aranko, O., Heilala, J., Vahala, P.: Exoskeletons: comprehensive, comparative and critical analyses of their potential to improve manufacturing performance. J. Manuf. Technol. Manag. **31**(6), 1261–1280 (2019). https://doi.org/10.1108/JMTM-01-2019
6. Perini, M., Paolo, B.A., Riccardo, K., Riccardo, M., Alessio, M., Margherita, P., Lucia, B.: Exoskeletons in action: the impact of exoskeletons on human factors during manual material handling. Human aspects of advanced manufacturing. Prod. Manag. Process Control **11** (2024)
7. Gonsalves, N., Akanmu, A., Shojaei, A., Agee, P.: Factors influencing the adoption of passive exoskeletons in the construction industry: industry perspectives. Int. J. Ind. Ergon. **100**, 103549 (2024). https://doi.org/10.1016/j.ergon.2024.103549
8. Gan, W.Y., Ghazilla, R.A.R., Yap, H.J., Selvarajoo, S.: Industrial practitioner's perception on the application of exoskeleton system in automotive assembly industries: a Malaysian case study. Heliyon **10**(4), e26183 (2024). https://doi.org/10.1016/j.heliyon.2024.e26183
9. Nacy, S.M., Ghaeb, N.H., Abdallh, M.M.M.: A review of lower limb exoskeletons, innovative systems design and engineering www.iiste.org **7**(11) (2016)
10. Sawicki, G.S., Beck, O.N., Kang, I., et al.: The exoskeleton expansion: improving walking and running economy. J. NeuroEng. Rehabil. **17**, 25 (2020). https://doi.org/10.1186/s12984-020-00663-9
11. Hussain, F., Goecke, R., Mohammadian, M.: Exoskeleton robots for lower limb assistance: a review of materials, actuation, and manufacturing methods. Proc. Inst. Mech. Eng. [H] **235**(12), 1375–1385 (2021). https://doi.org/10.1177/09544119211032010
12. Chen, B., Ma, H., Qin, L.-Y., Gao, F., Chan, K.-M., Law, S.-W., Qin, L., Liao, W.-H.: Recent developments and challenges of lower extremity exoskeletons. J. Orthop. Trans. **5**, 26–37 (2016). https://doi.org/10.1016/j.jot.2015.09.007

13. Kapsalyamov, A., Jamwal, P.K., Hussain, S., Ghayesh, M.H.: State of the art lower limb robotic exoskeletons for elderly assistance. IEEE Access **7**, 95075–95086 (2019). https://doi.org/10.1109/ACCESS.2019.2928010
14. Rossi, S., Chen, W., Li, J., Zhu, S., Zhang, X., Men, Y., Wu, H.: Gait recognition for lower limb exoskeletons based on interactive information fusion. Appl. Bionics Biomech. (2022). https://doi.org/10.1155/2022/9933018
15. Tao, J., Zhou, Z.: Review of key technologies for developing personalized lower limb rehabilitative exoskeleton robots. J. Shanghai Jiaotong Univ. (Sci.) (2022). https://doi.org/10.1007/s12204-022-2452-3
16. Rodríguez-Fernández, A., Lobo-Prat, J., Font-Llagunes, J.M.: Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. J. NeuroEng. Rehabil. **18**, 22 (2021). https://doi.org/10.1186/s12984-021-00815-5
17. Vaughan-Graham, J., Brooks, D., Rose, L., Nejat, G., Pons, J., Patterson, K.: Exoskeleton use in post-stroke gait rehabilitation: a qualitative study of the perspectives of persons post-stroke and physiotherapists. J. NeuroEng. Rehabil. **17**, 123 (2020). https://doi.org/10.1186/s12984-020-00750-x
18. Bruni, M.F., Melegari, C., De Cola, M.C., Bramanti, A., Bramanti, P., Calabro, R.S.: What does best evidence tell us about robotic gait rehabilitation in stroke patients: a systematic review and meta-analysis. J. Clin. Neurosci. **48**, 11–17 (2018). https://doi.org/10.1016/j.jocn.2017.10.048
19. Guanziroli, E., Cazzaniga, M., Colombo, L., Basilico, S., Legnani, G., Molteni, F.: Assistive powered exoskeleton for complete spinal cord injury: correlations between walking ability and exoskeleton control. Eur. J. Phys. Rehabil. Med. **55**(2), 209–216 (2019). https://doi.org/10.23736/S1973-9087.18.05308-X
20. Kandilakis, C., Sasso-Lance, E.: Exoskeletons for personal use after spinal cord injury. Arch. Phys. Med. Rehabil. **102**(2), 331–337 (2021). https://doi.org/10.1016/j.apmr.2019.05.028
21. Yagn, N.: Apparatus for Facilitating Walking, Running, and Jumping. U.S. Patent 420179 (1890)
22. Kelley, L.C.: Pedomotor. U.S. Patent 1,308,675 (1919)
23. Gilbert, K.E.: Exoskeleton prototype project: final report on phase I, General Electric Company, Schenectady, NY, GE Tech. Rep. S-67-1011 (1967)
24. Gilbert, K.E., Callan, P.C.: Hardiman I prototype, General Electric Company, Schenectady, NY, GE Technical Report S-68-1081 (1968)
25. Mizen, N.J.: Powered Exoskeleton Apparatus for Amplifying Human Strength in Response to Normal Body Movements. U.S. Patent 3449769 (1969)
26. Vukobratović, M., Borovac, B., Surla, D., Stokić, D.: Biped Locomotion: Dynamics, Stability, Control, and Application, pp. 321–330. Springer, Berlin (1990)
27. Radulovic, R., Piera, J.B., Cassagne, B., Grossiord, A., Boruchowitsch, G.: The mobile arm support, Prosthetics Orthotics. International **4**, 101–105 (1980)
28. Chareire, J.L.: Mechanical Leg-Propulsion Assistance Device, U.S. Patent 4872665 (1989)
29. Dick, G.J., Edwards, E.A.: Human Bipedal Locomotion Device. U.S. Patent 5016869 (1991)
30. Boldt, K.: Three Axis Mechanical Joint for a Power Assist Device, U.S. Patent 5282460 (1994)
31. http://cyberneticzoo.com/steammen/1830c-walking-by-steam-robert-seymour-british/
32. Yagn, N.: Apparatus for Facilitating Walking, Running, and Jumping. U.S. Patent 440684 (1890)
33. https://www.pupin.rs/RnDProfile/history.html
34. Guan, X.Y., Ji, L.H., Wang, R.C.: Development of exoskeletons and applications on rehabilitation. MATEC Web Conf. **40**, 2004 (2016)
35. https://www.hocoma.com/solutions/lokomat/
36. Vukobratovic, M.: When were active exoskeletons actually born? Int. J. Humanoid Robot. **4**, 459–486 (2007)
37. Kim, W., Lee, H., Kim, D., Han, J., Han, C.: Mechanical design of the hanyang exoskeleton assistive robot (HEXAR). In: 14th International Conference on Control, Automation and Systems (ICCAS 2014), pp. 479–484 (2014)
38. Vouga, T., Fasola, J., Baud, R., et al.: TWIICE one powered exoskeleton: effect of design improvements on usability in daily life as measured by the performance in the CYBATHLON race. J. NeuroEng. Rehabil. **19**, 63 (2022)
39. Hong E.K., Gorman P.H., Forrest G.F., Asselin P.K., Steven, K., William, S., Buffy, W.S., Stephen, K., Spungen, A.M.: Mobility skills with exoskeletal assisted walking in persons with SCI: results from a three center randomized clinical trial. Front. Robot. AI **7** (2020)
40. Jansen, O., Grasmuecke, D., Meindl, R.C., Tegenthoff, M., Schwenkreis, P., Sczesny-Kaiser, M., Wessling, M., Schildhauer, T.A., Fisahn, C., Aach, M.: Hybrid assistive limb exoskeleton hal in the rehabilitation of chronic spinal cord injury: proof of concept; the results in 21 patients. World Neurosurg. **110**, e73–e78 (2018)
41. Vassallo, C., et al.: Gait patterns generation based on basis functions interpolation for the TWIN lower-limb exoskeleton. In: IEEE International Conference on Robotics and Automation (ICRA), pp. 1778–1784 (2020)
42. https://www.indego.com/parkerimages/promosite/Indego/UNITED%20STATES/Downloads/Indego-Personal-Data-Sheet.pdf
43. Aarne, K.P., Sternin, V.A., Yoon, J., Michael, M., Juan, L., Amaya, C., Yong, H., Wa, W.Y., Kenneth, C., Homayoon, K.: Outcomes of a multicenter safety and efficacy study of the SuitX phoenix powered exoskeleton for ambulation by patients with spinal cord injury. Front. Neurol. **12**, (2021)
44. Gurriet, T., Tucker, M., Duburcq, A., Boeris, G., Ames, A.D.: Towards variable assistance for lower body exoskeletons. IEEE Robot. Automa. Lett. **5**(1), 266–273 (2020)
45. Gui, K., Liu, H., Zhang, D.: Toward multimodal human-robot interaction to enhance active participation of users in gait rehabilitation. IEEE Trans. Neural Syst. Rehabil. Eng. **25**(11), 2054–2066 (2017)
46. Liu, D.X., Xu, J., Chen, C., Long, X., Tao, D., Wu, X.: Vision-assisted autonomous lower-limb exoskeleton robot. IEEE Trans. Syst. Man Cybern. Syst. **51**(6), 3759–3770 (2017)
47. Zoss, A., Kazerooni, H., Chu, A.: On the mechanical design of the Berkeley lower extremity exoskeleton (BLEEX). In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, Edmonton, AB, Canada, 2–6 August, pp. 3132–3139 (2005)
48. Yasuhara, K.: Motion Assisting Device. U.S. Patent 20100049102 (2010)
49. Zeilig, G., Weingarden, H., Zwecker, M., Dudkiewicz, I., Bloch, A., Alberto, E.: Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: a pilot study. J. Spinal Cord Med. **5**(2), 96–101 (2012)
50. Esquenazi, A., Talaty, M., Packel, A., Saulino, M.: The rewalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury. Am. J. Phys. Med. Rehabil. Electron. Ed. (2012)
51. Ackerman, E.: Berkeley bionics introduces eLEGS robotic exoskeleton. IEEE Spectr. (2010)
52. Kawamoto, H., Taal, S., Niniss, H., Hayashi, T., Kamibayashi, K., Eguchi, K., Sankai, Y.: Voluntary motion support control of Robot Suit HAL triggered by bioelectrical signal for hemiplegia. In: Conference Proceedings IEEE EMBS, pp. 462–466 (2010). https://doi.org/10.1109/IEMBS.2010.5626191

53. Suzuki, K., Mito, G., Kawamoto, H., Hasegawa, Y., Sankai, Y.: Intention-based walking support for paraplegia patients with Robot Suit HAL. Adv. Robot. **21**(12), 1441–1469 (2007). https://doi.org/10.1163/156855307781746061
54. Gancet, J., et al.: MINDWALKER: going one step further with assistive lower limbs exoskeleton for SCI condition subjects. In: 2012 4th IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 1794–1800 (2012)
55. Meng, Q., Zeng, Q., Xie, Q., Fei, C., Kong, B., Lu, X., Wang, H., Yu, H.: Flexible lower limb exoskeleton systems: a review. NeuroRehabilitation **50**(4), 367–390 (2022)
56. Zheng, Yi., Wang, Y., Liu, J.: Analysis and experimental research on stability characteristics of squatting posture of wearable lower limb exoskeleton robot. Futur. Gener. Comput. Syst. **125**, 352–363 (2021). https://doi.org/10.1016/j.future.2021.06.053
57. Yan, Z., Han, B., Zihao, Du., Tiantian Huang, Ou., Bai, A.P.: Development and testing of a wearable passive lower-limb support exoskeleton to support industrial workers. Biocybern. Biomed. Eng. **41**(1), 221–238 (2021). https://doi.org/10.1016/j.bbe.2020.12.010
58. Foroutannia, A., Akbarzadeh-T, M.-R., Akbarzadeh, A.: A deep learning strategy for EMG-based joint position prediction in hip exoskeleton assistive robots. Biomed. Signal Process. Control **75**, 103557 (2022). https://doi.org/10.1016/j.bspc.2022.103557
59. Zhang, Z., Wang, Z., Lei, H., Wenquan, Gu.: Gait phase recognition of lower limb exoskeleton system based on the integrated network model. Biomed. Signal Process. Control **76**, 103693 (2022). https://doi.org/10.1016/j.bspc.2022.103693
60. Cai, M., Ji, Z., Li, Q., Luo, X.: Safety evaluation of human–robot collaboration for industrial exoskeleton. Saf. Sci. **164**, 106142 (2023). https://doi.org/10.1016/j.ssci.2023.106142
61. Haotian, Ju., Li, H., Guo, S., Yanbo, Fu., Zhang, Q., Zheng, T., Zhao, J., Zhu, Y.: J-Exo: an exoskeleton with telescoping linear actuators to help older people climb stairs and squat. Sens. Actuators A **366**, 115034 (2024). https://doi.org/10.1016/j.sna.2024.115034
62. Rodriguez-Cianca, D., Rodriguez-Guerrero, C., Grosu, V., De Keersmaecker, E., Swinnen, E., Kerckhofs, E., Vanderborght, B., Lefeber, D.: Design, control and evaluation of a treadmill-based Pelvic Exoskeleton (PeXo) with self-paced walking mode. Robot. Auton. Syst. **175**, 104610 (2024). https://doi.org/10.1016/j.robot.2023.104610
63. Liu, J., He, Y., Yang, J., Cao, W., Wu, X.: Design and analysis of a novel 12-DOF self-balancing lower extremity exoskeleton for walking assistance. Mech. Mach. Theory **167**, 104519 (2022)
64. Logan, B.M., Bowden, D., Hutchings, R.T.: McMinn's colour atlas of lower limb anatomy. Elsevier Health Sciences (2017)
65. Dellon, B., Matsuoka, Y.: Prosthetics, exoskeletons, and rehabilitation: now and for the future. IEEE Robot. Autom. Mag. **14**(1), 30–34 (2007)
66. Park, Y.L., Chen, B.R., Young, D., Stirling, L., Wood, R.J., Goldfield, E., Nagpal, R.: Bio-inspired active soft orthotic device for ankle foot pathologies. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Francisco, pp. 4488–4495 (2011)
67. Scaff, W., Horikawa, O., de Sales, M., Tsuzuki, G.: Pneumatic artificial muscle optimal control with simulated annealing. IFAC-PapersOnLine **51**(27), 333–338 (2018)
68. Banala, S.K., Agrawal, S.K., Fattah, A., Krishnamoorthy, V., Hsu, W.L., Scholz, J., Rudolph, K.: Gravity-balancing leg orthosis and its performance evaluation. IEEE Trans. Robot. **22**, 1228–1239 (2006)
69. Walsh, C.J., Endo, K., Herr, H.: A quasi-passive leg exoskeleton for load-carrying augmentation. Int. J. Humanoid Robot. **4**, 487–506 (2007)
70. van den Bogert, A.J.: Exotendons for assistance of human locomotion. Biomed. Eng. Online **2**, 17 (2003)
71. Aliman, N., Ramli, R., Haris, S.M.: Design and development of lower limb exoskeletons: a survey. Robot. Auton. Syst. **95**, 102–116 (2017)
72. Pamungkas, D.S., Caesarendra, W., Soebakti, H., Analia, R., Susanto, S.: Overview: types of lower limb exoskeletons. Electronics **8**, 1283 (2019). https://doi.org/10.3390/electronics8111283
73. Wang, S., Wang, L., Meijneke, C., Van Asseldonk, E., Hoellinger, T., Cheron, G., Ivanenko, Y., La Scaleia, V., Sylos-Labini, F., Molinari, M., Tamburella, F., Pisotta, I., Thorsteinsson, F., Ilzkovitz, M., Gancet, J., Nevatia, Y., Hauffe, R., Zanow, F., Van Der Kooij, H.: Design and control of the MINDWALKER exoskeleton. IEEE Trans. Neural Syst. Rehabil. Eng. **23**(2), 277–286 (2014)
74. Ugurlu, B., Oshima, H., Sariyildiz, E., Narikiyo, T., Babic, J.: Active compliance control reduces upper body effort in exoskeleton-supported walking. IEEE Trans. Human Mach. Syst. **50**(2), 144–153 (2020)
75. De Pascali, C., Naselli, G.A., Palagi, S., Scharff, R.B., Mazzolai, B.: 3D-printed biomimetic artificial muscles using soft actuators that contract and elongate. Sci. Robot. **7**(68), eabn4155 (2022)
76. Higueras-Ruiz, D.R., Shafer, M.W., Feigenbaum, H.P.: Cavatappi artificial muscles from drawing, twisting, and coiling polymer tubes. Sci. Robot. **6**(53), eabd5383 (2021)
77. Tawfick, S., Tang, Y.: Stronger artificial muscles, with a twist. Science **365**(6449), 125–126 (2019)
78. Torricelli, D., Gonzalez, J., Weckx, M., Jimenez-Fabian, R., Vanderborght, B., Sartori, M., Pons, J.L.: Human-like compliant locomotion: state of the art of robotic implementations. Bioinspir. Biomim. **11**(5), 051002 (2016)
79. Vanderborght, B., Albu-Schaeffer, A., Bicchi, A., Burdet, E., Caldwell, D.G., Carloni, R., Catalano, M., Eiberger, O., Friedl, W., Ganesh, G., Garabini, M., Grebenstein, M., Grioli, G., Haddadin, S., Hoppner, H., Jafari, A., Laffranchi, M., Lefeber, D., Petit, F., Stramigioli, S., Tsagarakis, N., Van Damme, M., Van Ham, R., Visser, L.C., Wolf, S.: Variable impedance actuators: a review. Robot. Auton. Syst. **61**(12), 1601–1614 (2013)
80. Baser, O., Kizilhan, H., Kilic, E.: Employing variable impedance (stiffness/damping) hybrid actuators on lower limb exoskeleton robots for stable and safe walking trajectory tracking. J. Mech. Sci. Technol. **34**, 2597–2607 (2020)
81. Sup, F., Varol, H.A., Mitchell, J., Withrow, T., Goldfarb, M.: Design and control of an active electrical knee and ankle prosthesis. In: Proceedings of the 2nd Biennial IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, BioRob 2008, pp. 523–528. Inst. of Elec. and Elec. Eng. Computer Society, New York (2008)
82. Windrich, M., Grimmer, M., Christ, O., et al.: Active lower limb prosthetics: a systematic review of design issues and solutions. BioMed Eng OnLine **15**(Suppl. 3), 140 (2016)
83. Aguirre-Ollinger, G., Yu, H.: Ower-limb exoskeleton with variable-structure series elastic actuators: phase-synchronized force control for gait asymmetry correction. IEEE Trans. Rob. **37**(3), 763–779 (2021)
84. Witte, K.A., Fatschel, A.M., Collins, S.H.: Design of a lightweight, tethered, torque-controlled knee exoskeleton. In: 2017 International Conference on Rehabilitation Robotics (ICORR), pp. 1646–1653 (2017)
85. Sridar, S., Nguyen, P.H., Zhu, M., Lam, Q.P., Polygerinos, P.: Development of a soft-inflatable exosuit for knee rehabilitation. In: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Vancouver, AB, Canada, 24–28 September, pp. 3722–3727 (2017)

86. Park, Y.L., Chen, B.R., Young, D., Stirling, L., Wood, R.J., Goldfield, E., Nagpal, R.: Bio-inspired active soft orthotic device for ankle foot pathologies. In: Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, Francisco, CA, USA, 25–30 September, pp. 4488–4495 (2011)
87. Costa, N., Caldwell, D.G.: Control of a biomimetic 'soft-actuated' 10DoF lower body exoskeleton. In: Proceedings of the First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, Pisa, Italy, 20–22 February 2006, pp. 495–501 (2006)
88. Kazerooni, H., Steger, R., Huang, L.: Hybrid control of the Berkeley lower extremity exoskeleton (BLEEX). Int. J. Robot. Res. **25**, 561–573 (2006)
89. Cao, H., Ling, Z., Zhu, J., Wang, Y., Wang, W.: Design frame of a leg exoskeleton for load-carrying augmentation. In: 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO), pp. 426–431 (2009)
90. Su, Q., Pei, Z., Tang, Z., Liang, Q.: Design and analysis of a lower limb loadbearing exoskeleton. Actuators **11**, 285 (2022)
91. Jatsun, S., Savin, S., Yatsun, A., Malchikov, A.: Study of controlled motion of exoskeleton moving from sitting to standing position. In: Borangiu, T. (ed) Advances in Robot Design and Intelligent Control. AISC, 371(2016), pp. 165–172. Springer, Heidelberg.
92. Jimenez-Fabian, R., Verlinden, O.: Review of control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons. Med. Eng. Phys. **34**(4), 397–408 (2012)
93. Dollar, A.M., Herr, H.: Lower extremity exoskeletons and active orthoses: challenges and state-of-the-art. IEEE Trans. Robot. **24**(1), 144–158 (2008)
94. Kawamoto, H., Lee, S., Kanbe, S., Sankai, Y.: Power assist method for HAL-3 using EMG-based feedback controller. IEEE Int. Conf. Syst. Man Cybern. **2**, 1648–1653 (2003)
95. Vukobratovic, M., Hristic, D., Stojiljkovic, Z.: Development of active anthropomorphic exoskeletons. Med. Biol. Eng. **12**(1), 66–80 (1974)
96. Aphiratsakun, N., Parnichkun, M.: Balancing control of AIT leg exoskeleton using ZMPbased FLC. Int. J. Adv. Robot. Syst. **6**(4), 319–328 (2009)
97. Tucker, M.R., Olivier, J.,Pagel, A., Bleuler, H., Bouri, M., Lambercy, O., Millán, J.R., Riener, R., Vallery, H., Gassert, R.: Control strategies for active lower extremity prosthetics and orthotics: a review. J. NeuroEng. Rehabil. **12**(1) (2015)
98. Hussain, S., Xie, S.Q., Jamwal, P.K.: Control of a robotic orthosis for gait rehabilitation. Robot. Auton. Syst. **61**, 911–919 (2013)
99. Veneman, J.F., Ekkelenkamp, R., Kruidhof, R., van der Helm, F.C., van der Kooij, H.: A series elastic- and Bowden-cable-based actuation system for use as torque actuator in exoskeleton type robots. Int. J. Robot. Res. **25**, 261–281 (2006)
100. Colombo, G., Joerg, M., Schreier, R., Dietz, V.: Treadmill training of paraplegic patients using a robotics orthosis. J. Rehabil. Res. Dev. **37**, 693–700 (2010)
101. Suzuki, K., Mito, G., Kawamoto, H., Hasegawa, Y., Sankai, Y.: Intention-based walking support for paraplegia patients with robot suit HAL. Adv. Robot. **21**, 1441–1469 (2012)
102. Emken, J.L., Harkema, S.J., Beres-Jones, J., Ferreira, C.K., Reinkensmeyer, D.J.: Feasibility of manual teach-and-replay and continuous impedance shaping for robotic locomotor training following spinal cord injury. IEEE Trans. Biomed. Eng. **55**, 322–334 (2008)
103. Vallery, H., Van Asseldonk, E.H.F., Buss, M., van der Kooij, H.: Reference trajectory generation for rehabilitation robots: complementary limb motion estimation. IEEE Trans. Neural Syst. Rehabil. Eng. **17**, 23–30 (2009)
104. Balasubramanian, S., Wei, R., He, J.: RUPERT Closed loop control design. In: 30th Annual International Conference of the IEEE, Engineering in Medicine and Biology Society. Vancouver, British Columbia, Canada, pp. 3467–3470. IEEE (2008)
105. Farris, R.J., Quintero, H.A., Withrow, T.J., Goldfarb, M.: Design of a joint-coupled orthosis for FES-aided gait. In: IEEE International Conference on Rehabilitation Robotics, Japan: IEEE, Kyoto International Conference Centre, pp. 246–52 (2009)
106. Ju, M.S., Lin, C.C., Lin, D.H., Hwang, I.S., Chen, S.M.: A rehabilitation robot with force-position hybrid fuzzy controller: hybrid fuzzy control of rehabilitation robot. IEEE Trans. Neural Syst. Rehabil. Eng. **13**(3), 349–358 (2005)
107. Marchal-Crespo, L., Reinkensmeyer, D.J.: Review of control strategies for robotic movement training after neurologic injury. J. NeuroEng. Rehabil. **6**, 20 (2009)
108. Hogan, N.: Impedance control: an approach to manipulation: part I-theory. J. Dyn. Syst. Meas. Contr. **107**, 1–7 (1985)
109. Kiguchi, K., Tanaka, T., Fukuda, T.: Neuro-fuzzy control of a robotic exoskeleton with EMG signals. IEEE Trans. Fuzzy Syst. **12**(4), 481–490 (2004)
110. Meuleman, J., van Asseldonk, E., van Oort, G., Rietman, H., van der Kooij, H.: LOPES II-design and evaluation of an admittance controlled gait raining robot with shadow-leg approach. IEEE Trans. Neural Syst. Rehabil. Eng. **24**, 352–363 (2016)
111. Nilsson, A., Vreede, K., Häglund, V., Kawamoto, H., Sankai, Y., Borg, J.: Gait training early after stroke with a new exoskeleton—the hybrid assistive limb: a study of safety and feasibility. J. Neuroeng. Rehabil. **11**, 92 (2014)
112. Maggioni, S., Lunenburger, L., Riener, R., Melendez-Calderon, A.: Robot-aided assessment of walking function based on an adaptive algorithm. In: IEEE 14th International Conference on Rehabilitation Robotics (Singapore), pp. 804–809 (2015)
113. Serena, M., Nils, R., Lars, L., Alejandro, M.-C.: An adaptive and hybrid end-point/joint impedance controller for lower limb exoskeletons. Front. Robot. AI **5**(104), 1–17 (2018)
114. Pons, J.L.: Wearable Robots: Biomechatronic Exoskeletons, Chichester. Wiley, England (2008)
115. Aguirre-Ollinger, G., Colgate, J.E., Peshkin, M.A., Goswami, A.: Active-impedance control of a lower-limb assistive exoskeleton. In: IEEE 10th International Conference on Rehabilitation Robotics (ICORR), pp. 188–195 (2007)
116. Yang, X., Lihua, G., Yang, Z., Gu, W.: Lower Extreme Carrying Exoskeleton Robot Adaptive control using wavelet neural networks. In: Fourth International Conference on Natural Computation (ICNC), pp. 399–403 (2008)
117. Chen, Z., Guo, Q., Xiong, H., et al.: Control and implementation of 2-DOF lower limb exoskeleton experiment platform. Chin. J. Mech. Eng. **34**, 22 (2021)
118. Rosen, J., Fuchs, M.B., Arcan, M.: Performances of hill-type and neural network muscle models-toward a Myosignal-based exoskeleton. Comput. Biomed. Res. **32**(5), 415–439 (1999)
119. Kiguchi, K., Hayashi, Y.: An EMG-based control for an upper-limb power-assist exoskeleton robot. IEEE Trans. Syst. Man Cybern. B Cybern. **99**, 1–8 (2012)
120. Hill, A.V.: The heat of shortening and the dynamic constants of muscle. Proc. Roy. Soc. Lond. Ser. B Biol. Sci. **126**, 136–195 (1938)
121. Vantilt, J., Tanghe, K., Afschrift, M., et al.: Model-based control for exoskeletons with series elastic actuators evaluated on sit-to-stand movements. J. NeuroEng. Rehabil. **16**, 65 (2019). https://doi.org/10.1186/s12984-019-0526-8
122. Song, G., Huang, R., Qiu, J., et al.: Model-based control with interaction predicting for human-coupled lower exoskeleton systems. J. Intell. Robot. Syst. **100**, 389–400 (2020). https://doi.org/10.1007/s10846-020-01200-5
123. Saeed, M.T., Gul, J.Z., Kausar, Z., Mughal, A.M., Din, Z.M.U., Qin, S.: Design of model-based and model-free robust control

strategies for lower limb rehabilitation exoskeletons. Appl. Sci. **12**, 3973 (2022). https://doi.org/10.3390/app12083973

124. Chen, J., Damiano, D.L., Lerner, Z.F., Bulea, T.C.: Validating model-based prediction of biological knee moment during walking with an exoskeleton in crouch gait: potential application for exoskeleton control. In: 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR), Toronto, ON, Canada, pp. 778–783 (2019). https://doi.org/10.1109/ICORR.2019.8779513
125. Esquenazi, A., Talaty, M., Packel, A., Saulino, M.: The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury. Am. J. Phys. Med. Rehabil. **91**(11), 911–921 (2012)
126. Amiri, M.S., Ramli, R., Ibrahim, M.F.: Hybrid design of PID controller for four DoF lower limb exoskeleton. Appl. Math. Model. **72**, 17–27 (2019)
127. Chen, J., Hochstein, J., Kim, C., Damiano, D., Bulea, T.: Design advancements toward a wearable pediatric robotic knee exoskeleton for overground gait rehabilitation. In: 2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob) Enschede, The Netherlands, August 26–29 (2018)
128. Luo, Y., Wang, C., Wang, Z., Ma, Y., Wang, C., Wu, X.: Design and control for a compliant knee exoskeleton. In: Proceedings of the 2017 IEEE International Conference on Information and Automation (ICIA) Macau SAR, China (2017)
129. Zhang, X., Yue, Z., Wang, J.: Robotics in lower-limb rehabilitation after stroke. Hindawi Behav. Neurol. **2017**, 13 (2017)
130. Sun, W., Lin, J., Su, S., Wang, N., Er, M.J.: Reduced adaptive fuzzy decoupling control for lower limb exoskeleton. IEEE Trans. Cybern. **51**, 1099–1109 (2020)
131. Yang, Y., Ma, L., Huang, D.Q.: Development and repetitive learning control of lower limb exoskeleton driven by electrohydraulic actuators. IEEE Trans. Ind. Electron. **64**(5), 4169–4178 (2017)
132. Ajayi, M.O., Djouani, K., Hamam, Y.: Bounded control of an actuated lower-limb exoskeleton". J. Robot. **2017**, 20 (2017)
133. Yang, P., Zhang, G., Wang, J., Wang, X., Zhang, L., Chen, L.: Command filter back stepping sliding model control for lower-limb exoskeleton. Math. Probl. Eng. **2017**, 10 (2017)
134. Long, Y., Du, Z.J., Wang, W.D., Dong, W.: Robust sliding mode control based on GA optimization and CMAC compensation for lower limb exoskeleton. Appl. Bionics Biomech. **2016**, 13 (2016)
135. Wu, J., Gao, J., Song, R., Li, R., Li, Y., Jiang, L.: The design and control of a 3DOF lower limb rehabilitation robot. Mechatronics **33**, 13–22 (2016)
136. Zhang, X., Wang, H., Tian, Y., Peyrodie, L., Wang, X.: Model-free based neural network control with time-delay estimation for lower extremity exoskeleton. Neurocomputing **272**, 178–188 (2018)
137. Narayan, J., Dwivedy, S.K.: Towards neuro-fuzzy compensated PID control of lower extremity exoskeleton system for passive gait rehabilitation. IETE J. Res. **69**, 1–18 (2020)
138. Han, S., Wang, H., Tian, Y., Christov, N.: Time-delay estimation based computed torque control with robust adaptive RBF neural network compensator for a rehabilitation exoskeleton. ISA Trans. **97**, 171–181 (2020)
139. Nataraj, R., van den Bogert, A.J.: Simulation analysis of linear quadratic regulator control of sagittal-plane human walking—implications for exoskeletons. J. Biomech. Eng. **139**(10) (2017)
140. Narayan, J., Dwivedy, S.K.: Robust LQR-Based Neural-Fuzzy Tracking Control for a Lower Limb Exoskeleton System with Parametric Uncertainties and External Disturbances, SP 5573041, pp. 1176–2322 (2021)
141. Gouda, M.M., Danaher, S., Underwood, C.P.: Fuzzy logic control versus conventional PID control for controlling indoor temperature of a building space. IFAC Proc. **33**(24), 249–254 (2000)
142. Kong, K., Jeon, D.: Design and control of an exoskeleton for the elderly and patients. Mechatron. IEEE/ASME Trans. **11**(4), 428–432 (2006)
143. Kiguchi, K., Rahman, M.H., Sasaki, M., et al.: Development of a 3DOF mobile exoskeleton robot for human upper–limb motion assist. Robot. Auton. Syst. **56**(8), 678–691 (2008)
144. Sankai, Y.: HAL: hybrid assistive limb based on cybernics. Robot. Res. 25–34 (2011)
145. Aphiratsakun, N., Parnichkun, M.: Balancing control of AIT leg exoskeleton using ZMP based FLC. Int. J. Adv. Robot. Syst. (2009)
146. Hussain, S., Xie, S.Q., Jamwal, P.K.: Robust nonlinear control of an intrinsically compliant robotic gait training orthosis. IEEE Trans. Syst. Man. Cybern. Syst. **43**, 655–665 (2013)
147. Emken, J.L., Harkema, S.J., Beres-Jones, J.A., Ferreira, C.K., Reinkensmeyer, D.J.: Feasibility of manual teach-and-replay and continuous impedance shaping for robotic locomotor training following spinal cord injury. IEEE Trans. Bio-med. Eng. **55**, 322–334 (2008)
148. Duschau-Wicke, A., von Zitzewitz, J., Caprez, A., Luenenburger, L., Riener, R.: Path control: a method for patient-cooperative robot-aided gait rehabilitation. IEEE Trans. Neural Syst. Rehabil. Eng. **18**, 38–48 (2010)
149. Beyl, P., van Damme, M., van Ham, R., Vanderborght, B., Lefeber, D.: Design and control of a lower limb exoskeleton for robot-assisted gait training. Appl. Bionics Biomech. **6**, 229–243 (2009)
150. Husemann, B., Müller, F., Krewer, C., Heller, S., Koenig, E.: Effects of locomotiontraining with assistance of a robot-driven gait orthosis in hemiparetic patientsafter stroke a randomized controlled pilot study. Stroke **38**, 349–354 (2007)
151. Ju, M.S., Lin, C.C.K., Lin, D.H., Hwang, I.S., Chen, S.M.: A rehabilitation robot with force-position hybrid fuzzy controller: hybrid fuzzy control of rehabilitation robot. IEEE Trans. Neural Syst. Rehabil. Eng. **13**, 349–358 (2005)
152. Simon, A.M., Brent Gillespie, R., Ferris, D.P.: Symmetry-based resistance as a novel means of lower limb rehabilitation. J. Biomech. **40**, 1286–1292 (2007)
153. Deutsch, J.E., Latonio, J., Burdea, G.C., Boian, R.: Post-stroke rehabilitation with the Rutgers Ankle system: a case study Presence. Teleop. Virt. **10**, 416–430 (2001)
154. Bernhardt, M., Frey, M., Colombo, G., Riener, R.: Hybrid force-position control yields cooperative behaviour of the rehabilitation robot LOKOMAT. In: Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics, pp. 536–539 (2005)
155. Mayr, A., Kofler, M., Quirbach, E., Matzak, H., Frohlich, K., Saltuari, L.: Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patientsusing the Lokomat gait orthosis. Neurorehabil. Neural Repair **21**, 307–314 (2007)
156. Veneman, J.F., Kruidhof, R., Hekman, E.E.G., Ekkelenkamp, R., Van Asseldonk, E.H.F., van der Kooij, H.: Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. IEEE Trans. Neural Syst. Rehabil. Eng. **15**, 379–386 (2007)
157. Roy, A., Krebs, H.I., Williams, D.J., Bever, C.T., Forrester, L.W., Macko, R.M., et al.: Robot-aided neurorehabilitation: a novel robot for ankle rehabilitation. IEEE Trans. Robot. **25**, 569–582 (2009)
158. Emken, J.L., Reinkensmeyer, D.J.: Robot-enhanced motor learning: accelerating internal model formation during locomotion by transient dynamic amplification. IEEE Trans. Neural Syst. Rehabil. Eng. **13**, 33–39 (2005)
159. Koopman, B., van Asseldonk, E.H.F., van der Kooij, H.: Selective control of gait subtasks in robotic gait training: foot clearance support in stroke survivors with a powered exoskeleton. J. Neuroeng. Rehabil. 10 (2013)
160. Agrawal, S.K., Banala, S.K., Fattah, A., Sangwan, V., Krishnamoorthy, V., Scholz, J.P., et al.: Assessment of motion of a swing

leg and gait rehabilitation with a gravity balancing exoskeleton. IEEE Trans. Neural Syst. Rehabil. Eng. **15**, 410–420 (2007)

161. Krebs, H.I., Palazzolo, J.J., Dipietro, L., Volpe, B.T., Hogan, N.: Rehabilitation robotics: performance-based progressive robot-assisted therapy. Auton. Robot. **15**, 7–20 (2003)
162. Kiguchi, K., Rahman, M.H., Sasaki, M., Teramoto, K.: Development of a 3DOF mobile exoskeleton robot for human upper-limb motion assist. Robot. Auton. Syst. **56**, 678–691 (2008)
163. Fleischer, C., Wege, A., Kondak, K., Hommel, G.: Application of EMG signals for controlling exoskeleton robots. Biomed. Tech. **51**, 314–319 (2006)
164. Yin, Y.H., Fan, Y.J., Xu, L.D.: EMG and EPP-integrated human-machine interface between the paralyzed and rehabilitation exoskeleton. IEEE Trans. Inf. Technol. Biomed. **16**, 542–549 (2012)
165. Lenzi, T., De Rossi, S.M.M., Vitiello, N., Carrozza, M.C.: Intention-based EMG control for powered exoskeletons. IEEE Trans. Bio-Med. Eng. **59**, 2180–2190 (2012)
166. Fan, Y., Yin, Y.: Active and progressive exoskeleton rehabilitation using multi-source information fusion from sEMG and force-position EPP. IEEE Trans. Biomed. Eng. **60**, 1 (2013)
167. Riener, R., Lunenburger, L., Jezernik, S., Anderschitz, M., Colombo, G., Dietz, V.: Patient-cooperative strategies for robot-aided treadmill training: first experimental results. IEEE Trans. Neural Syst. Rehabil. Eng. **13**, 380–394 (2005)
168. Wolbrecht, E.T., Chan, V., Reinkensmeyer, D.J., Bobrow, J.E.: Optimizing compliant, model-based robotic assistance to promote neurorehabilitation. IEEE Trans. Neural Syst. Rehabil. Eng. **16**, 286–297 (2008)
169. Colombo, R., Pisano, F., Mazzone, A., Delconte, C., Micera, S., Carrozza, M.C., et al.: Design strategies to improve patient motivation during robot-aided rehabilitation. J. Neuroeng. Rehabil. 4 (2007)
170. Kiguchi, K., Tanaka, T., Fukuda, T.: Neuro-fuzzy control of a robotic exoskeleton with EMG signals. IEEE Trans. Fuzzy Syst. **12**, 481–490 (2004)
171. Zhang, F., Li, P., Hou, Z.-G., Lu, Z., Chen, Y., Li, Q., et al.: SEMG-based continuous estimation of joint angles of human legs by using BP neural network. Neurocomputing **78**, 139–148 (2012)
172. Riener, R., Luenenberger, L., Colombo, G.: Human-centered robotics applied to gait training and assessment. J. Rehabil. Res. Dev. **43**, 679–693 (2006)
173. Hogan, N., Krebs, H.I.: Interactive robots for neuro-rehabilitation. Restor. Neurol. Neuros. **22**, 349–358 (2004)
174. Mori, Y., Okada, J., Takayama, K.: Development of a standing style transfer system “ABLE” for disabled lower limbs. IEEE/ASME Trans. Mechatron. **11**(4), 372–380 (2006)
175. Marcheschi, S., Salsedo, F., Fontana, M., et al.: Body extender: whole body exoskeleton for human power augmentation. Paper presented at the Robotics and Automation, IEEE International Conference (2011)
176. Yan, T., Cempini, M., Oddo, C.M., et al.: Review of assistive strategies in powered lower–limb outhouses and exoskeletons. Robot. Auton. Syst. **64**, 120–136 (2015)
177. Asbeck, A.T., De Rossi, S.M., Galiana, I., Ding, Y., Walsh, C.J.: Stronger, smarter, softer: next-generation wearable robots. IEEE Robot. Autom. Mag. **21**(4), 22–33 (2014)
178. Walsh, C.: Human-in-the-loop development of soft wearable robots. Nat. Rev. Mater. **3**, 78 (2018)
179. Young, A.J., Ferris, D.P.: State of the art and future directions for lower limb robotic exoskeletons. IEEE Trans. Neural Syst. Rehabil. Eng. **25**, 171–182 (2017)
180. Chiaradia, D., Xiloyannis, M., Solazzi, M., Masia, L., Frisoli, A.: Comparison of a soft exosuit and a rigid exoskeleton in an assistive task. In: Carrozza, M., Micera, S., Pons, J. (eds) Wearable Robotics: Challenges and Trends. WeRob 2018. Biosystems and Biorobotics, 22. Springer, Cham (2019)
181. Witte, K.A., Collins, S.H.: Chapter 13—design of lower-limb exoskeletons and emulator systems. In: Rosen, J., Ferguson, P.W., Robotics, W. (eds) Academic Press, pp. 251–274 (2020). ISBN 9780128146590
182. Totah, D., Kovalenko, I., Saez, M., Barton, K.: Manufacturing choices for ankle-foot orthoses: a multi-objective optimization. Procedia CIRP **65**, 145–150 (2017)
183. Haldane, D.W., Casarez, C.S., Karras, J.T., et al.: Integrated manufacture of exoskeletons and sensing structures for folded millirobots. J. Mech. Robot. **7**(2), 021011 (2015)
184. Hussain, F., Goecke, R., Mohammadian, M.: Exoskeleton robots for lower limb assistance: a review of materials, actuation, and manufacturing methods. Proc. Inst. Mech. Eng. [H] **235**(12), 1375–1385 (2021)
185. Shahrubudin, N., Koshy, P., Alipal, J., Kadir, M.H.A., Lee, T.C.: Challenges of 3D printing technology for manufacturing biomedical products: a case study of Malaysian manufacturing firms. Heliyon **6**(4), e03734 (2020). https://doi.org/10.1016/j.heliyon.2020.e03734
186. Hoyos Rodriguez, D.: Realistic computer aided design: model of an exoskeleton (2019)
187. Arunkumar, S., Mahesh, S., Rahul, M., et al.: Design and analysis of lower limb exoskeleton with external payload. Int. J. Interact. Des. Manuf. **17**, 2055–2072 (2023). https://doi.org/10.1007/s12008-023-01272-1
188. Rupal, B.S., Rafique, S., Singla, A., Singla, E., Isaksson, M., Virk, G.S.: Lower-limb exoskeletons: research trends and regulatory guidelines in medical and non-medical applications. Int. J. Adv. Rob. Syst. **14**(6), 1–27 (2017)
189. Zeilig, G., Weingarden, H., Zwecker, M., et al.: Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation byof the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: a pilot study. J. Spinal Cord Med. **35**(2), 96–101 (2012)
190. Kolakowsky-Hayner, S.A., Crew, J., Moran, S., et al.: Safety and feasibility of using the Ekso™ bionic exoskeleton to aid ambulation after spinal cord injury. J. Spine **4**, 003 (2013)
191. Kilicarslan, A., Prasad, S., Grossman, R.G., et al.: High accuracy decoding of user intentions using EEG to control a lowerbody exoskeleton. In: 2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), Osaka, Japan, 3 July 2013, pp. 5606–5609. IEEE (2013)
192. Dietl, H., Kaitan, R., Pawlik, R., et al.: C-leg-ein neues system zur ersorgung von oberschenkelamputationen. Orthop Technik **49**, 197–211 (1998)
193. Ting Lena, H., et al.: Neuromechanical principles underlying movement modularity and their implications for rehabilitation. Neuron **86**, 38–54 (2015)
194. Li, Z., Liu, H., Yin, Z., Chen, K.: Muscle synergy alteration of human during walking with lower limb exoskeleton. Front. Neurosci. **12**, 1050 (2019)
195. Junlin, W., et al.: Comfort-centered design of a lightweight and backdrivable knee exoskeleton. IEEE Robot. Automat. Lett. **3**, 4265–4272 (2018)
196. del Carmen, S.-V., Gonzalez-Vargas, J., Torricelli, D., Moreno, J.C., Pons, J.L.: Compliant lower limb exoskeletons: a comprehensive review on mechanical design principles. J. Neuroeng. Rehabil. **16**, 55 (2019)
197. Park, E.J., Akbas, T., Eckert-Erdheim, A., Sloot, L.H., Nuckols, R.W., Orzel, D., et al.: A hinge-free, non-restrictive, lightweight tethered exosuit for knee extension assistance during walking. IEEE Trans. Med. Robot. Bion. **2**, 165–175 (2020)
198. Baunsgaard, C.B., Nissen, U.V., Brust, A.K., Frotzler, A., Ribeill, C., Kalke, Y.B., Holmström, U.: Gait training after spinal cord

injury: safety, feasibility and gait function following 8 weeks of training with the exoskeletons from Ekso Bionics. Spinal Cord **56**, 106–116 (2018)
199. Wu, A.R., Dzeladini, F., Brug, T.J., Tamburella, F., Tagliamonte, N.L., Van Asseldonk, E.H., Ijspeert, A.J.: An adaptive neuromuscular controller for assistive lower-limb exoskeletons: a preliminary study on subjects with spinal cord injury. Front. Neurorob **11**, 30 (2017)
200. Gui, K., Tan, U.X., Liu, H., Zhang, D.: Electromyography-Driven progressive assist-as-needed control for lower limb exoskeleton. IEEE Trans. Med. Robot. Bion. **2**, 50–58 (2020)
201. Li, Z., Yuan, Y., Luo, L., Su, W., Zhao, K., Xu, C., Pi, M.: Hybrid brain/ muscle signals powered wearable walking exoskeleton enhancing motor ability in climbing stairs activity. IEEE Trans. Med. Robot. Bion. **1**, 218–227 (2019)
202. Gordleeva, S.Y., Lobov, S.A., Grigorev, N.A., Savosenkov, A.O., Shamshin, M.O., Lukoyanov, M.V., et al.: Real-time EEG–EMGhuman–machineinterface-basedcontrol systemfor a lower-limb exoskeleton. IEEE Access **8**, 84070–84081 (2020)
203. He, Y., Eguren, D., Luu, T.P., Contreras-Vidal, J.L.: Risk management and regulations for lower limb medical exoskeletons: a review. Med. Devices (Auckl) **10**, 89–107 (2017). https://doi.org/10.2147/MDER.S107134
204. Rupal, B.S., Rafique, S., Singla, A., Singla, E., Isaksson, M., Virk, G.S.: Lower-limb exoskeletons: research trends and regulatory guidelines in medical and non-medical applications. Int. J. Adv. Robot. Syst. (2017). https://doi.org/10.1177/1729881417743554
205. Vélez-Guerrero, M.A., Callejas-Cuervo, M., Mazzoleni, S.: Artificial intelligence-based wearable robotic exoskeletons for upper limb rehabilitation: a review. Sensors **21**(6), 2146 (2021)
206. Souza, R.S., Sanfilippo, F., Silva, J.R., Cordero, A.F.: Modular exoskeleton design: requirement engineering with KAOS. In: 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 978–983 (2016)
207. Sui, D., Fan, J., Jin, H., Cai, X., Zhao, J., Zhu, Y.: Design of a wearable upper-limb exoskeleton for activities assistance of daily living. In: Proceedings of the 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM), Munich, Germany, pp. 845–850 (2017)
208. Asokan, A., Vigneshwar, M.: Design and control of an EMG-based low-cost exoskeleton for stroke rehabilitation. In: Proceedings of the 2019 Fifth Indian Control Conference (ICC) 2019, Delhi, India, pp. 478–483 (2019)
209. Sangha, S., Elnady, A.M., Menon, C.: A compact robotic orthosis for wrist assistance. In: Proceedings of the 2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), Singapore, pp. 1080–1085 (2016)
210. Tageldeen, M.K., Perumal, N., Elamvazuthi, I., Ganesan, T.: Design and control of an upper arm exoskeleton using Fuzzy logic techniques. In: Proceedings of the 2016 2nd IEEE International Symposium on Robotics and Manufacturing Automation (ROMA), Ipoh, Malaysia (2016)
211. Lambelet, C., Lyu, M., Woolley, D., Gassert, R., Wenderoth, N.: The eWrist—a wearable wrist exoskeleton with sEMG-based force control for stroke rehabilitation. In: Proceedings of the 2017 International Conference on Rehabilitation Robotics, ICORR 2017, London, UK, pp. 726–733 (2017)
212. Chen, C.T., Lien, W.Y., Chen, C.T., Twu, M.J., Wu, Y.C.: Dynamic modeling and motion control of a cable-driven robotic exoskeleton with pneumatic artificial muscle actuators. IEEE Access **8**, 149796–149807 (2020)
213. Samper-Escudero, J.L., Gimenez-Fernandez, A., Sanchez-Uran, M.A., Ferre, M.: A cable-driven exosuit for upper limb flexion based on fibres compliance. IEEE Access **8**, 153297–153310 (2020)
214. Varghese, R.J., Lo, B.P.L., Yang, G.Z.: Design and prototyping of a bio-inspired kinematic sensing suit for the shoulder joint: precursor to a multi-DoF shoulder exosuit. IEEE Robot. Autom. Lett. **5**, 540–547 (2020)
215. Xiloyannis, M., Chiaradia, D., Frisoli, A., et al.: Physiological and kinematic effects of a soft exosuit on arm movements. J. NeuroEng. Rehabil. **16**, 29 (2019)
216. Herr, H., Kornbluh, R.: New horizons for orthotic and prosthetic technology: artificial muscle for ambulation. In: Smart Structures and Materials 2004: Electroactive Polymer Actuators and Devices (EAPAD):San Diego, CA, Vol. 5385, No. 1, pp. 1–9 (2004)
217. Mulgaonkar, A., Kornbluh, R., Herr, H.: A new frontier for orthotics and prosthetics: application of dielectric elastomer actuators to bionics. In: Carpi, F., De Rossi, D., Kornbluh, R., Pelrine, R., Sommer-Larsen, P. (eds.) Dielectric Elastomers as Electromechanical Transducers: Fundamentals, Materials, Devices, Models and Applications of an Emerging Electroactive Polymer Technology. Elsevier, New York (2008)
218. Prakash, C., Kumar, R., Mittal, N.: Recent developments in human gait research: parameters, approaches, applications, machine learning techniques, datasets and challenges. Artif. Intell. Rev. **49**(1), 1–40 (2018)
219. Du, F., Chen, J., Wang, X.: Human motion measurement and mechanism analysis during exoskeleton design. In: International Conference on Mechatronics and Machine Vision in Practice, Nanjing, China (2017)
220. Reza, S.T., Ahmad, N., Choudhury, I.A., Ghazilla, R.A.: A study on muscle activities through surface EMG for lower limb exoskeleton controller. In: 2013 IEEE Conference on Systems, Process & Control (ICSPC), Kuala Lumpur, Malaysia (2014)
221. Jezernik, S., Colombo, G., Keller, T., Frueh, H., Morari, M.: Robotic orthosis Lokomat: a rehabilitation and research tool. Neuromodul. Technol. Neural Interface **6**(2), 108–115 (2003)
222. Sitaram, R., Ros, T., Stoeckel, L., Haller, S., Scharnowski, F., Lewis-Peacock, J., Weiskopf, N., Blefari, M.L., Rana, M., Oblak, E., Birbaumer, N., Sulzer, J.: Closed-loop brain training: the science of neurofeedback. Nat. Rev. Neurosci. **18**(2), 86–100 (2017)
223. Crea, S., Donati, M., de Rossi, S.M., Oddo, C.M., Vitiello, N.: A wireless flexible sensorized insole for gait analysis. Sensors **14**(1), 1073–1093 (2014)
224. Rossi, S., Chen, W., Li, J., Zhu, S., Zhang, X., Men, Y., Wu, H.: Gait recognition for lower limb exoskeletons based on interactive information fusion. Appl. Bionics Biomech. 9933018 (2022)
225. Rafique, S., Bonello, P.: Experimental validation of a distributed parameter piezoelectric bimorph cantilever energy harvester. Smart Mater. Struct. **19**(9), 094008 (2010)
226. Roundy, S., Wright, P.K., Rabaey, J.M.: Energy Scavenging for Wireless Sensor Networks. Norwell, New York (2003)
227. Zheng, Y., Song, Q., Liu, J., et al.: Research on motion pattern recognition of exoskeleton robot based on multimodal machine learning model. Neural Comput. Appl. **32**, 1869–1877 (2020). https://doi.org/10.1007/s00521-019-04567-1
228. Coser, O., Tamantini, C., Soda, P., Zollo, L.: AI-based methodologies for exoskeleton-assisted rehabilitation of the lower limb: a review. Front Robot AI. **11**, 1341580 (2024). https://doi.org/10.3389/frobt.2024.1341580
229. Kuber, P.M., Godbole, H., Rashedi, E.: Detecting fatigue during exoskeleton-assisted trunk flexion tasks: a machine learning approach. Appl. Sci. **14**(9), 3563 (2024). https://doi.org/10.3390/app14093563
230. Li, J., Chen, C.: Machine learning-based energy harvesting for wearable exoskeleton robots. Sustain. Energy Technol. Assess. **57**, 103122 (2023). https://doi.org/10.1016/j.seta.2023.103122