Journal of Bionic Engineering (2023) 20:436–469
https://doi.org/10.1007/s42235-022-00289-8

REVIEW ARTICLE

Systematic Review on Wearable Lower Extremity Robotic Exoskeletons for Assisted Locomotion

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Received: 24 July 2022 / Revised: 10 October 2022 / Accepted: 16 October 2022 / Published online: 28 October 2022

Abstract
Lower extremity robotic exoskeletons (LEEX) can not only improve the ability of the human body but also provide healing treatment for people with lower extremity dysfunction. There are a wide range of application needs and development prospects in the military, industry, medical treatment, consumption and other fields, which has aroused widespread concern in society. This paper attempts to review LEEX technical development. First, the history of LEEX is briefly traced. Second, based on existing research, LEEX is classified according to auxiliary body parts, structural forms, functions and fields, and typical LEEX prototypes and products are introduced. Then, the latest key technologies are analyzed and summarized, and the research contents, such as bionic structure and driving characteristics, human–robot interaction (HRI) and intent-awareness, intelligent control strategy, and evaluation method of power-assisted walking efficiency, are described in detail. Finally, existing LEEX problems and challenges are analyzed, a future development trend is proposed, and a multidisciplinary development direction of the key technology is provided.

Keywords Lower extremity robotic exoskeletons · Bionic robot · Classification method · Human–robot interaction · Biomechatronic

1 Introduction

An exoskeleton is a rigid external covering for the body in certain animals, such as the hard chitinous cuticle of arthropods, derived from biology. An exoskeleton protects and supports the body and provides points of attachment for muscles [1], in contrast to the endoskeleton, which is completely located in the animal body. Human beings are endoskeleton animals and do not have the functions of exoskeletons. Due to the increasing demand for self-protection, support, strength and rehabilitation, people have been developing exoskeletons, generally referring to wearable devices that can support, protect and enhance specific human abilities. The connotation has been rich in the development process of things, the armor of ancient soldiers and the Extra Vehicular Activity (EVA) suits of modern astronauts can be regarded as an exoskeleton, as can prosthetics, which are used to recover structural damage to the human skeletal system.

From technological advances and the quest for specific capabilities came robotic exoskeletons, a compound of the word “robot” and the word “exoskeleton” from biology. The International Organization for Standardization (ISO) defines a robot as “an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks [2]”. An exoskeleton robotics, also known as "wearable robotics" or a "powered exoskeleton", is human-oriented, meaning human-wearable, it can stick and finish the work of human limbs using the motion of a robot. It is mainly composed of a frame and power system worn outside the human body. It can be seen as a technology that extends, complements, substitutes or

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enhances human function and capability or empowers or replaces (a part of) the human limb where it is worn [3]. Research on exoskeletons can be divided into upper limbs, lower limbs, single parts (such as hands and head), whole body and so on. More extensive research has been done on lower body wearable robots, or Lower Extremity Robotic Exoskeletons (LEEX). Feet to walk upright on the one hand, are a manifestation of the distinction between humans and other animals, and the liberation of human hands to create and use tools led to the premise of brain evolution. However, disability, disease, aging, the loss of lower limb movement function or other obstacles have plagued people, leading to an obsession with LEEX development. Humans, on the other hand, wanted to break through their limits, such as lower limb strength, speed, and endurance. The desire to achieve their professional work requirements, such as improving the survival rate and task efficiency of soldiers, protecting the weight-bearing joints of support staff and factory workers, enhancing operating capacity and operating efficiency, reducing motion fatigue and improving the quality of life of ordinary people, required further LEEX expansion.

1.1 Scope

A lower limb robot exoskeleton system is reviewed. Specifically, first, its assisting human lower limbs, excluding upper limbs; second, it has at least one active joint, excluding unpowered passive exoskeletons; and third, its being dependent on the human limbs, excluding the assisting Supernumerary Robotic Limb.

The literature search for the review was carried out in March 2022. Overall, 215 references were considered for this review, from 1889 to 2022, including 144 journals, 30 conferences, 6 patents, 7 books, 1 standard, 4 dissertations, and 23 Online documents. The databases involved include Web of Science, IEEE Xplore, ASME Digital Library and PubMed. Additionally, a free search was conducted on Google Scholar. The search involved multiple keyword searches using the terms 'exoskeleton', 'robot' and 'wearable robotics' with qualifiers including 'low limb', 'active', 'assisted', 'orthotics', 'body parts', 'structure', 'function', 'field', 'driving', 'human–robot interaction (HRI)', 'control strategy' and 'efficiency evaluation' in various combinations.

1.2 Contribution

Existing reviews have analyzed and summarized the research status of lower extremity robot exoskeletons [4, 5], key technologies [6, 7] and design criteria [8] in specific fields. However, they lack broader and more detailed information on multidisciplinary cross-fertilization, such as definition and history, types and applications, structure and actuation, human–robot interaction, control strategies, planning strategies, and locomotion efficiency evaluation. A more general definition description and a more comprehensive history provide a reference for researchers, while a broader and more detailed classification makes it easier for developers to determine which designs are most important for specific needs. Our work focuses on summarizing existing key technologies, analyzing the existing problems, and looking forward to the multidisciplinary development direction of key technologies in the future.

1.3 Organization

This review is organized as follows: Sect. 1 presents the definition of LEEX. Section 2 presents the development of LEEX from the perspective of the Industrial Revolution. Section 3 presents typical prototypes and products in classification of LEEX from four special angles. Afterwards, Sects. 4 and 5 present the key technologies and existing problems involved in the practical application of LEEX. Finally, Sect. 6 submits future research hotspots.

2 History

Human LEEX exploration has nearly 200 years of history since the concept originated. According to the Industrial Revolution development order, relevant research can be divided into five stages, the embryonic stage (after the Industrial Revolution), exploration stage (after the Second Industrial Revolution), reserve stage (after the Third Industrial Revolution), development stage (enter the Fourth Industrial Revolution) and present stage (research hotspots), as shown in Fig. 1.

The origin of LEEX was influenced by the Renaissance and the Industrial Revolution (specifically, the Steam Age of Industry 1.0 [9] in the mid-nineteenth century). It can be traced back to the steam-powered "Walking By Steam" [10] drawn by Robert Seymour, a British illustrator, in 1830, which inspired and became a prototype of the modern powered exoskeleton. In 1889, Ira C.C. Rinehart conceived the "Walking Machine" [11], which transmitted power from a source power through a crankshaft and pulley. From 1889 to 1890, Nicholas Yagn of Russia invented instruments that could assist people in walking, jumping and running. With the help of springs and compressed gas bags, energy was stored and released during walking to save effort. He applied for the first powered exoskeleton patent [12, 13]. In 1917, L. C. Kelley of the United States proposed the "Pedomotor" [14], a steam-powered aid device that assisted walking by pulling steel cables tied to the legs using a small steam engine on the wearer's back. The above devices are far from practical, mainly related to the limited development level of materials, structures and power technology (the steam

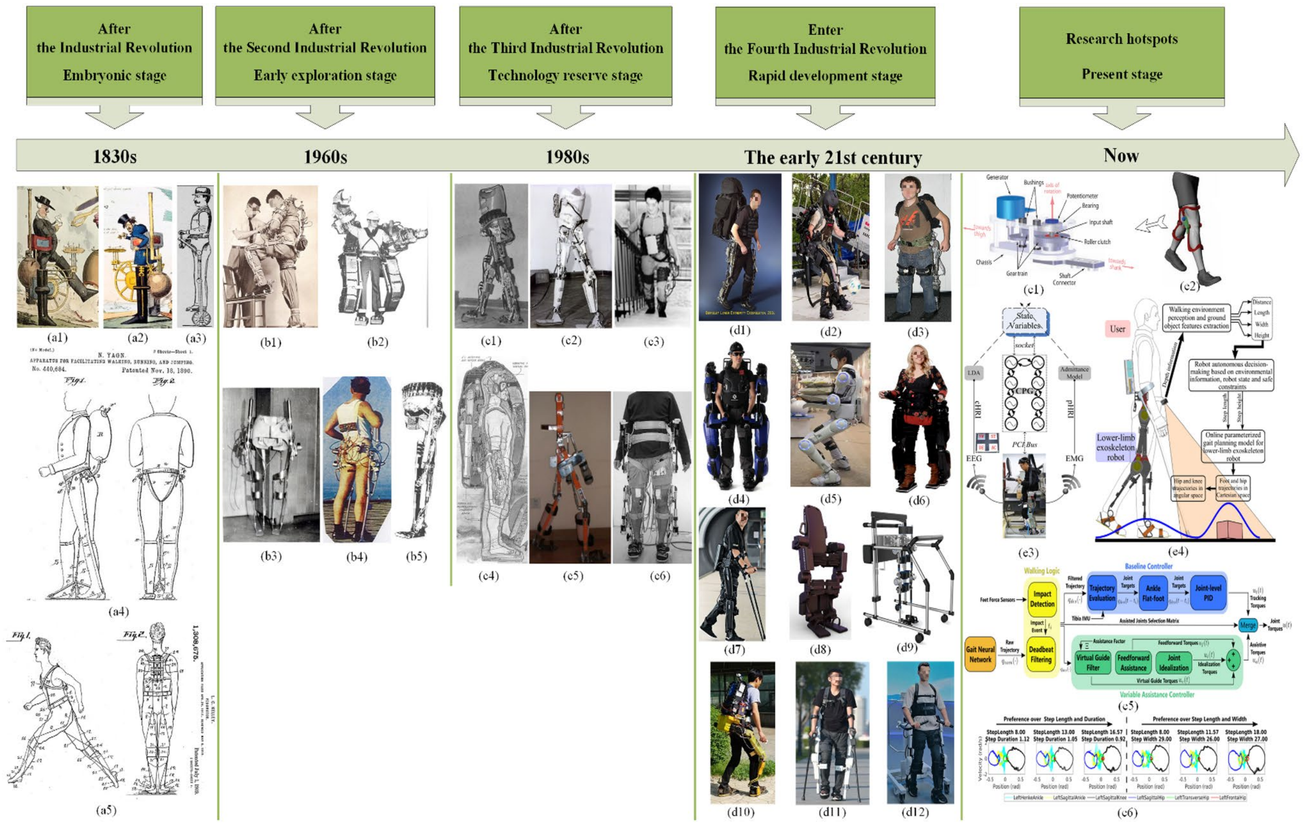


Fig. 1 A brief history of lower extremity robotic exoskeletons. (Embryonic stage: (a1) and (a2) Walking By Steam [10], (a3) Walking Machine [11], (a4) Nicholas Yagn [12, 13], (a5) Pedomotor [14]; Exploration stage: (b1) MAN-Amplifier [15], (b2) Hardiman [16], (b3) and (b4) Kinematic Walker [18], (b5) Powered Leg [19]; Reserve stage: (c1) Complete Exoskeleton [18], (c2) and (c3) Active Exoskeleton [19], (c4) Pitman [20, 21], (c5) Tsinghua University [22–24], (c6) HAL-1 [25, 26]; Development stage: (d1) BLEEX [27], (d2) XOS [30], (d3) MIT Exoskeleton [30], (d4) Guardian XO [35], (d5) HAL-5 [36], (d6) REX [37], (d7) ReWalk [38], (d8) Atalante [40], (d9) AiWalk [41], (d10) HIT-LEX [42], (d11) UGO [43], (d12) Exo-Motus [44]; Current stage: (e1) and (e2) Biomechanical energy harvester [45], (e3) Framework of a gait rehabilitation system [46], (e4) Framework for VALOR [47], (e5) Architecture of a variable assistance framework [48], (e6) Phase diagrams of gaits with COSPAR [49].)

engine) at that time. Even so, the visionary ideas of these artists and inventors have left valuable lessons for future generations.

Early LEEX exploration took place in the United States in the twentieth century, following the end of the Second Industrial Revolution (namely, the Electrical Age of Industry 2.0 in the early twentieth century) and the world wars. Cornell Aeronautical Labs began to develop the “MAN-Amplifier” exoskeleton system [15] in 1961, which was driven by a servo motor and was the first exoskeleton with force amplification. In 1965, the United States military and General Electric jointly developed a powered exoskeleton called the “Hardiman” [16]. Hardiman's hydraulic and motor drive structure overcame the power shortage of the “MAN-Amplifier”. Combined with a synergy feedback sensor system, Hardiman could not only sense the intention of the wearer's movement but also amplify the user's force by 25 times. However, it could not make the wearer walk freely as it weighed 680 kg. In 1969, Vukobratovic et al. [17] of the Mihailo Pupin Institute in Belgrade developed the “Powered Leg” and put forward the concept of rehabilitated gait systems, which can help people with severe disabilities of the lower limbs achieve partial motor function. However, the proposed gait type is fixed and single, mathematical model of gait is simplified, and feedback is introduced only at the level of maintaining the achieved "mathematical" gait. It cannot reach the practical function. In general, during the Second Industrial Revolution, LEEX technology was still groping its way forward, and found a new use besides human body enhancement, that is, limb locomotion rehabilitation.

As the third Industrial Revolution (namely, the Information Age of Industry 3.0 in the 1970s) came to a climax, Vukobratovic et al. [18, 19] improved the anthropomorphic gait of an exoskeleton used for paraplegia and rehabilitation of the disabled by using pneumatic drive and kinematic programming in 1972 and successfully tested it in the orthopedic clinic in Belgrade. In 1978, they proposed the “Complete Exoskeleton” based on Zero Moment

Point (ZMP) control and the “Active Exoskeleton” driven by motors, marking the development of exoskeletons from the early exploration stage to the technical reserve stage. Later, “Pitman” from the United States [20, 21] in the 1980s, a paraplegic walking machine from Tsinghua University in China [22–24], and the first-generation HAL exoskeleton from Japan [25, 26] in the 1990s represent typical exoskeletons in the technical reserve stage. Generally, thanks to the advent of information technology, especially computer programming, the technical of kinematic tracking of LEEX has developed rapidly. And it started to move towards bio-signal control studies, such as HAL (focus on the study of muscle electrical signals). However, due to the limitations of materials, sensor technology and equipment computing capacity, LEEX at this time has poor reliability, single function and high cost.

With the germination of the Fourth Industrial Revolution (the Era of Industry 4.0 Intelligence in the early twenty-first century), UC Berkeley accepted an investment of $50 million from the Defense Advanced Research Projects Agency (DARPA) in 2000 and developed the "Berkeley lower extreme exoskeleton", BLEEX (2004) [27–32]. It focused on improving the wearer's load, shifting the design focus to the support structure between the waist and legs, allowing the US army to easily carry a load of 90 kg. When the BLEEX is underpowered, the wearer can remove it from the leg and fold it into a normalized backpack for easy storage and transportation. HULC (2009) was applied in military layout in the United States, marking the rapid development and application of LEEX technology [33]. The Guardian XO exoskeleton, which takes only one minute to put on and take off, released by Sarcos Robotics in 2020 can allow the wearer to carry 90 kg of weight for a long time [34], and the muscle activity curve is highly similar to that of normal walking [35], indicating good following performance. Meanwhile, advanced countries around the world are developing exoskeletons for a variety of applications. Examples include HAL-5 from Japan (2005) [36], REX from New Zealand (2008) [37], ReWalk from Israel (2010) [38], ExoAtlet from Russia (2016) [39], and Atalante from France (2018) [40]. In addition, China's AiWalk from Ai-robotics Technology [41] (2016), HIT-LEX from Harbin Institute of Technology (HIT) (2016) [42], UGO from Hangzhou RoboCT Technology (2018) [43], and ExoMotus from Fourier Intelligence (2019) [44] are also developing rapidly. Overall, the accumulation of information technology has contributed to the development of robot intelligence. New breakthroughs in LEEX control strategies continue to emerge, such as Sensitivity Amplification Control (SAC) used in BLEEX, force control method based on myoelectric signals used in HAL-5, and position control method based on interactive force detection used in HIT-LEX. Compared to the twentieth century, LEEX is vastly more reliable, more versatile and less costly.

In recent years, some new concepts looking forward to the future have also been put forward. For example, in the concept of human energy harvesting [45], researchers have developed a biomechanical energy harvester that generates electricity during human walking with little extra effort. Their technology assists muscles in performing negative work, analogous to regenerative braking in hybrid cars, where energy normally dissipated during braking drives a generator, specifically, it engages power generation selectively at the end of the swing phase of walking, thus assisting deceleration of the joint. In addition, with the development of the HRI and artificial intelligence (AI), many new technologies have appeared. For example, in the study of a multimode human–robot interaction system [46], a brain-computer interface (BCI), electroencephalogram (EEG) and electromyography (EMG) were used to establish interaction between cognitive and physical levels of a human–robot system. Realizing the control of a rehabilitation exoskeleton to change the auxiliary gait mode according to the user's subjective motor intention. Another example is the vision-assisted autonomous gait planning method [47], which uses a depth camera to obtain environmental information and apply it to the autonomous decision-making of robots, thus improving robot adaptability to complex walking environments. In terms of advanced control algorithms, researchers have presented a method that leverages control barrier functions to force certain joints to remain inside predefined trajectory tubes in a minimally invasive way. It can accurately control the degree of the subject's deviation from a given gait, ensure robustness to patient disturbances, and provide variable assistance while maintaining safety [48]. The recent exploration of AI algorithms in personalized gait optimization has made it possible to adapt to individual preferences [49]. As robotic exoskeletons are required by human beings to compensate for their own defects, recover their motor ability or enhance their existing abilities. And some new requirements such as advanced HRI and personality customization emerge. LEEX will remain a research hotspot in science, technology and industrial applications in the future.

3 Classification

3.1 Classification by Auxiliary Body Parts

Human lower limbs are composed of many joints, and not all joints need assistance. Sometimes only one or several joints need to be assisted, such as to enhance human walking endurance or assist patients with hemiplegia or knee joint damage. Sometimes complete assistance is needed, such as patients with complete paralysis of the lower limbs. Therefore, LEEX can be divided into a single-joint type and a multi-joint type for different parts.

Yan et al. [50] mentioned that a single-joint type can be divided into three groups, namely, hip, knee and ankle, which are used for specific individual parts. The functions of these joints are completely different [51]. During steady state walking, the knee joint is almost undamped in the swing stage but almost locked in the standing support stage [52]. The hip and ankle joints are related to the dynamic process of the swinging leg in the swinging stage, the propulsion of the supporting leg in the stepping off stage, and the braking of the body during landing, but research in recent years also shows that they are interdependent [53–57]. Some examples of single-joint exoskeletons are shown in Fig. 2. The Honda Walking Assist is a hip robotic exoskeleton [58] designed by Honda for gait training after a stroke. It consists of two motors located at the hip and transmits torque to the user's thigh through two strap frames. Angle and current sensors are used for gait stage detection, through which an application parameterizes the inspection results and provides the corresponding torque [59]. The MAK (Marsi Active Knee) is a knee robot exoskeleton developed by Marsi Bionics [60]. It is not only suitable for hemiplegia patients with the knee joint as the main pathogenesis site but also for rehabilitation after total knee replacement. Active auxiliary control and zero-force control are carried out through a human motion force sensor, pressure detection sensing insole and knee angle sensor, and monitoring data are uploaded to an application for analysis [61]. The Autonomous Leg is an ankle-assisted exoskeleton designed by the Herr team [62] of the MIT media lab that is used to enhance human walking ability. The system fixes a glass fiberglass rod with the front of the shoe and pulls a rope through an actuator on the lower leg to provide plantar flexion assistance to the ankle, reducing the metabolic cost of walking on horizontal ground [63].

According to the joints involved, a multi-joint exoskeleton can be distinguished among trunk–hip (TH), hip–knee (HK), knee–ankle (KA), trunk–hip–knee (THK), hip–knee–ankle (HKA) or trunk–hip–knee–ankle (THKA) types, as shown in Fig. 3. The TH type is commonly used in handling scenes, such as the Active Diagnosis Orthesis (APO) of the BioRobotics Institute of the Sant'Anna School of Advanced Studies [64]. The HK type is often used to assist hip and knee motion correction, such as the Vanderbilt Powered Orthosis of Vanderbilt University [65]. The KA type is often used for knee and ankle motion correction, such as the Series Elastic Actuator (SEA) knee–ankle–foot exoskeleton from the

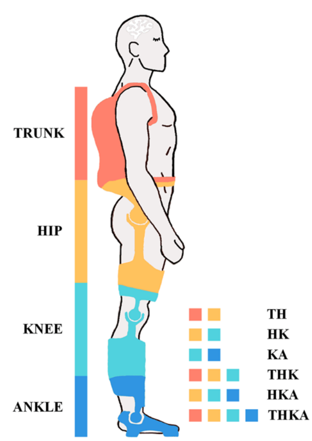


Fig. 3 Classification of multi-joint lower extremity exoskeletons *TH* trunk–hip, *hk* hip–knee, *KA* knee–ankle, *THK* trunk–hip–knee, *HKA* hip–knee–ankle, *THKA* trunk–hip–knee–ankle

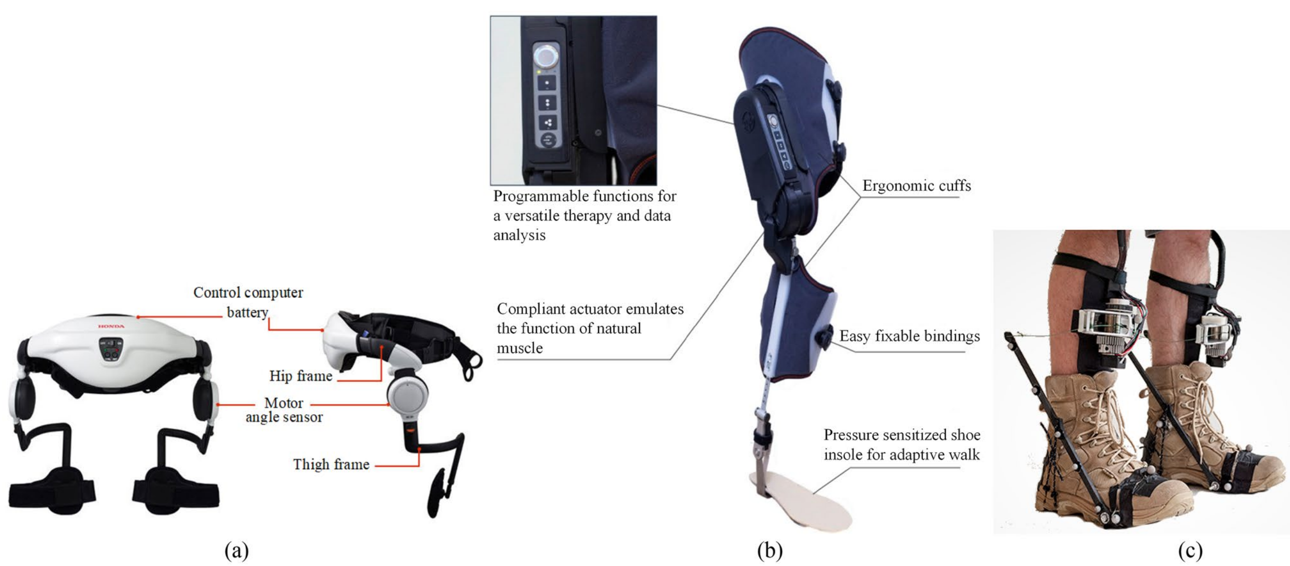


Fig. 2 Single joint lower extremity exoskeleton systems. **a** Walking Assist [58] **b** MAK [60] **c** Autonomous leg [62]

National University of Singapore [66]. The THK type consists of spinal orthosis and an HK exoskeleton to correct the direction of the spine and help paralyzed individuals walk upright, such as the Israel ReWalk Robotics [67] exoskeleton. The HKA type is commonly used for gait rehabilitation of the hip, knee, and ankle, such as the AGoRA Exoskeleton of the Columbia College of Engineering [68]. The THKA type is often used for soldiers who need to enhance strength or paraplegic patients, such as the BLEEX [27–32] of the Berkeley lower limb exoskeleton in the United States and the Atalante [40] of Wandercraft in France. A detailed comparison of single-articular and multiarticular lower extremity exoskeletons can be found in article [69], which will not be described here due to length reasons.

3.2 Classification by Structural Form

According to the structural form, lower extremity robotic exoskeletons can be classified into Rigid Lower Extremity Robotic Exoskeletons (RLEEX) and Compliant Lower Extremity Robotic Exoskeletons (CLEEX).

3.2.1 Rigid Lower Extremity Robotic Exoskeletons

An RLEEX structure is composed of many rigid connecting rods, and the drive has a large servo stiffness, such as hydraulics or a motor. It provides the disabled with the ability to walk again. In RLEEX research, the United States has been the most active. In the twentieth century, relevant technologies have been studied in depth, and mature products have been developed in various fields. For example, the BLEEX of the UC Berkeley, the HULC of Lockheed Martin [33], the Guardian XO of Sarcos Robotics [35], and the United States have become leaders in the development of exoskeletons. Successively, Asian and European countries have carried out many studies on rigid lower limb assisted exoskeletons, such as the HAL [70] of the University of Tsukuba in Japan and the MINDWALKER [71] of the Delft University of Technology in the Netherlands.

Lockheed Martin launched the Human Universal Load Carrier (HULC) [72, 73] based on the BLEEX results and aimed at the BLEEX exoskeleton's shortcomings, such as a complex structure and short endurance, and conducted a series of wearable tests with the US Army. See Fig. 4a. The design of the HULC takes fully into account the unsymmetrical driving torque of people in the process of heavy walking, optimizes the driving mode and control method, and achieves an endurance of 20 km distance with a heavy load. Moreover, supports can be added on the back to expand the function of carrying equipment. Although the HULC was tested by the US Army, it was never fielded. In addition, the project was a failure as it hindered certain movements and actually increased strain on muscles, going directly against what a powered exoskeleton is supposed to do [74].

The Hybrid Assistive Limb (HAL), led by Professor Yoshiyuki Sankai at the Cybernics Laboratory at the University of Tsukuba, Japan, adopts a function-oriented design concept. The HAL can be used not only for physiotherapy nursing but also for rescue, logistics and handling, as shown in Fig. 4b. The HAL series [75–78] is the earliest commercial walking exoskeleton robot in the world. The HAL for medical rehabilitation was put into use in Japan and Europe [79–82]. The HAL's single-leg version weighs approximately 12 kg and uses an electric motor to drive the hip and knee joints of both legs. Based on human EMG signals, the soles of the feet and auxiliary crutches provide

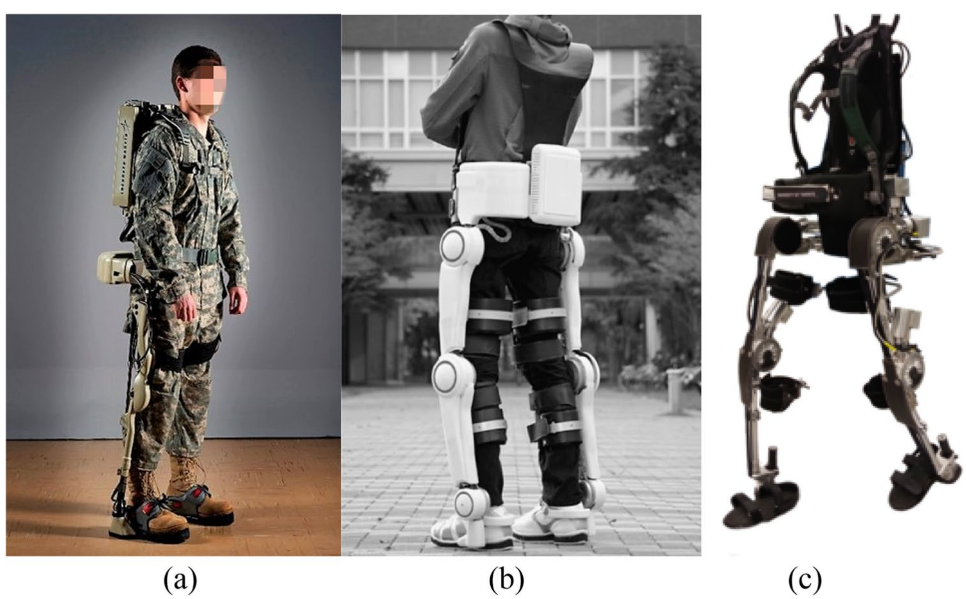


Fig. 4 Representative famous RLEEX: **a** HULC [33], **b** HAL [70], **c** MINDWALKER [71]

walking control for the exoskeletal robot. The HAL has three families: the two-leg, the left leg, and the right leg exoskeleton robot. Each series is divided into four models: S, M, L and X. These four models cover wearers between 165 and 200 cm in height, 35–48 cm in lower limb length, 28–40 cm in knee joint width, 23–30 cm in shoe size and 40–100 kg in weight. The maximum extension angle of the hip joint is 20°, the flexion angle is 120°, the maximum extension angle of the knee joint is 6°, and the flexion angle is 120°. Powered by a traditional lithium battery, the battery life can reach 180–270 min. It also has a simple operation interface that facilitates the start, stop and assist walking of the HAL to meet training needs. HAL is characterized by use of EMG sensors to measure muscle activity, and EMG signals are incorporated into an auxiliary force control algorithm. However, its control is not ideal when EMG sensors are not fit for some muscle areas, the fit to the muscle is incomplete, and there is sweat influence, especially it is worn for a long time. Moreover, its use is limited to assist in gait training, not for assistance during standing up and climbing stairs.

To realize the center of gravity transfer, the Delft University of Technology in the Netherlands added an active drive to the hip joint swing/adduction degree of freedom and developed the MINDWALKER exoskeleton robot [83], as shown in Fig. 4c. In addition, an elastic drive structure was connected in series at the end of each actuator (Series Elastic Actuator, SEA) to improve the control performance of the exoskeleton. However, the issues related to the control of stiffness in springs present a limitation. The MINDWALKER weighs 28 kg and can adapt to wearers between 153 and 188 cm in height and less than 100 kg in weight. The target maximum walking speed is 0.8 m/s. MINDWALKER is characterized by use of EEG signal sensors to measure brain activity and pioneered EEG-based position control. However, the decoding of EEG is still in its infancy. The classification accuracy of human intentions by EEG is not high. And there is a great delay, which cannot be applied in scenarios requiring high real-time performance.

Research on RLEEX in China started relatively late and can be traced back to the paraplegic walking machine of Tsinghua University [22–24]. There were sporadic achievements in the early twenty-first century, mainly concentrated in universities and research institutes.

In 2007, the University of Science and Technology of China (USTC) and the Hefei Institute of Intelligent Machines (IIM) of the Chinese Academy of Sciences (CAS) began to research technologies related to exoskeleton robots. The resulting Walking Power Assist Leg (WPAL) [84–86] is shown in Fig. 5a. According to the requirements of walking function, a total of four active degrees of freedom were set up in the hip joint and the knee joint, while only one rotational degree of freedom was set up in the ankle joint to obtain sole pressure change information in the process of gravity transfer more effectively. In terms of interaction mode, the WPAL takes the interaction force between the wearer and the exoskeleton as the basis to judge the wearer's intention and uses two-dimensional force sensors to measure it directly. An encoder at the joint measures the joint state of the exoskeleton and forms a closed-loop feedback control with the controller. In the weight-bearing walking control strategy, the WPAL estimates the load weight through a plantar pressure sensor to adjust the controller parameters to improve the assistance efficiency of the WPAL.

In 2012, Xinyu Wu's research team at the Shenzhen Institutes of Advanced Technology (SIAT) of the CAS began to study walking assisted exoskeleton robots [87–89], as shown in Fig. 5b. The robot includes a backpack, hip joint, knee joint, ankle joint and binding structure and has 14 degrees of freedom. Each leg has 7 degrees of freedom, including 3 degrees of freedom of the ankle, 1 degree of freedom of the knee and 3 degrees of freedom of the hip. Among them, the hip and knee flexion and extension are actively driven, while the ankle joint is passive. The active drive is driven by a motor. The hip joint flexion angle is 0° to 90°, and the knee joint flexion angle is 0° to 100°. The maximum angle of the joint is less than the maximum angle of the body, which meets ergonomic design and safety requirements.

In 2014, the AssItive DEvice for paRalyzed patients (AIDER) developed by Cheng Hong's team at the University of Electronic Science and Technology of China (UESTC) was officially unveiled [90–92], as shown in Fig. 5c. The robot has a total of 10 degrees of freedom, 5 degrees of freedom for each leg, including 3 degrees of freedom for the hip joint, 1 degree of freedom for the knee joint and 1 degree of freedom for the ankle joint. The hip flexion angle is − 10° to 110°, and the knee flexion angle is 5°–120°. The exoskeleton robot is suitable for wearers with legs between 40 and 51 cm and legs between 31 and 41 cm. The exoskeleton uses a four-point binding system that applies maximum force to the wearer, providing stability while standing. It has now entered the stage of clinical wearable trials.

Although these studies have yielded some results as China enters the twenty-first century, they are still in the laboratory. There is a long way to go before a mature product can be marketed.

With the deepening of RLEEX research in China, Chinese domestic companies have gradually launched some industrialized products. Such as the AiWalker and AiLegs (2016) developed by Beijing Ai-robotics Technology, in which the AiLegs participated in the torch relay of the Beijing 2022 Paralympic Winter Games, as shown in Fig. 5d. The UGO220 (2018) created by Hangzhou RoboCT Technology, as shown in Fig. 5e. And the Fourier X2 (2019) developed by Shanghai Fourier Intelligence, as shown in Fig. 5f.

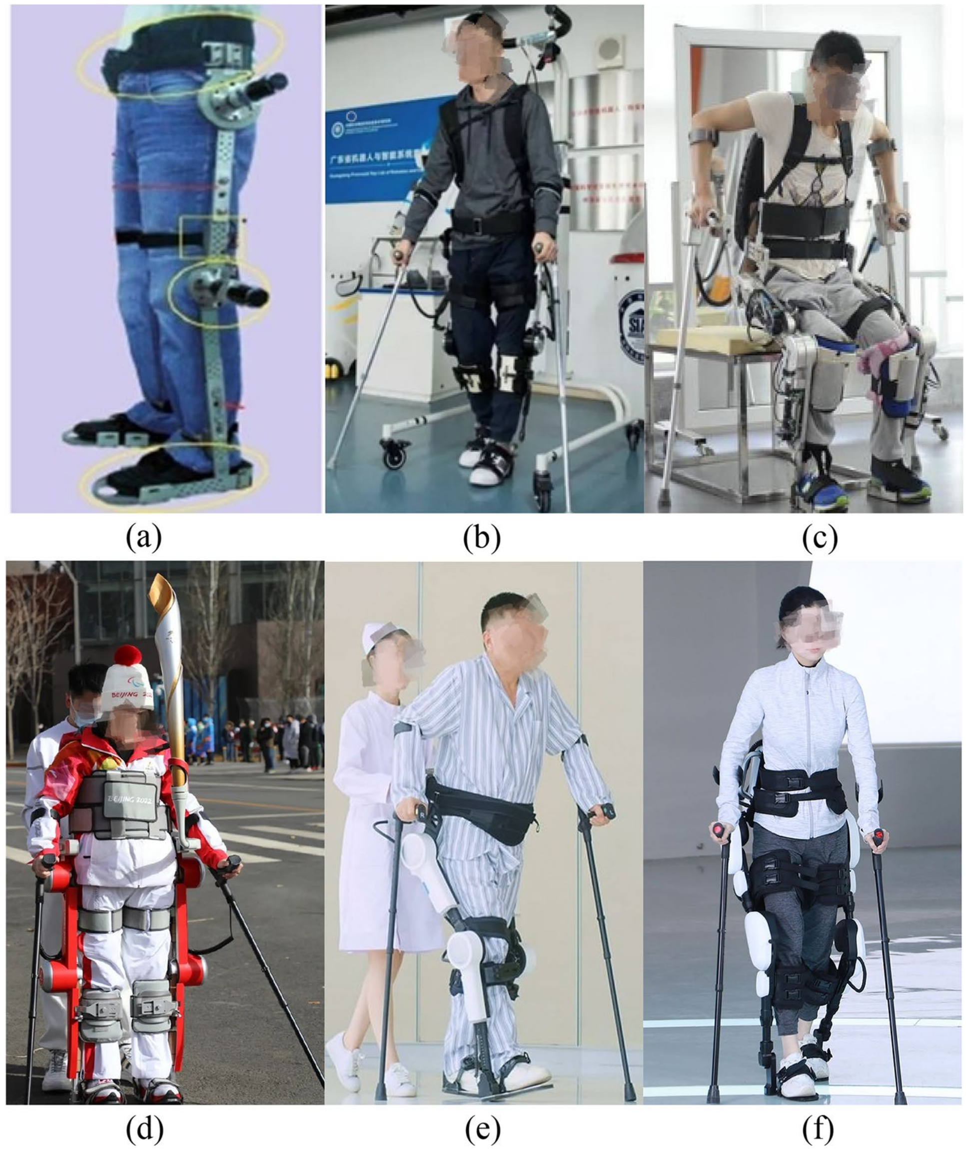


Fig. 5 Representative RLEEX development in China: **a** WPAL [84], IIM of CAS **b** Wearable exoskeleton [88], SIAT of CAS **c** AIDER [91], UESTC **d** AiLegs [41], Ai-robotics Technology **e** UGO220 [43], RoboCT Technology **f** Fourier X2 [44], Fourier Intelligence

3.2.2 Compliant Lower Extremity Robotic Exoskeletons

Sanchez-Villamañan et al. [93] defined a "compliant exoskeleton" as a system with flexible characteristics (allowing the actuator to deviate from its balance position), including flexible structures (such as textiles, belts, and sleeves) or nonrigid drives (such as elastic components, Bowden wires, and pneumatic muscles), which is lightweight, flexible, easy to wear, and flexible to walk with, also called a soft exosuit.

The Soft Exosuit of Harvard University and the ONYX of Lockheed Martin are the most typical models in the research of flexible lower limb exoskeletons. In addition, European countries have successively launched relevant research. In 2016, the European Union "Horizon 2020" robotics plan invested tens of millions of euros to support the SoftPro, SPEXOR, and XoSoft [94] projects, aiming to provide advanced, transformative and modular exoskeletons for lower limbs through the development of soft collaborative robots to assist people with mobility disabilities complete the actions needed in daily life [95].

In 2013, to cope with the problems of rigid exoskeletons such as large size, complex mechanism and poor fit, Connor Walsh's team [96] from Harvard University's Wyss Laboratory first linked soft robots [97] with the rehabilitation AIDS [98]. A lower extremity flexible exoskeleton of flexible textile material driven using a Bowden line, the Soft Exosuit was created [99, 100], as shown in Fig. 6a1. The Soft Exosuit system weighs 10.1 kg, and the flexible fabric minimizes the impact on the wearer's movement during walking. The Soft Exosuit applies auxiliary torque to human joints with the expansion function of the Bowden line, which optimizes the walking mode of the wearer by taking metabolic energy consumption as the optimization target. Ankle assistance reduces the wearer's metabolism by

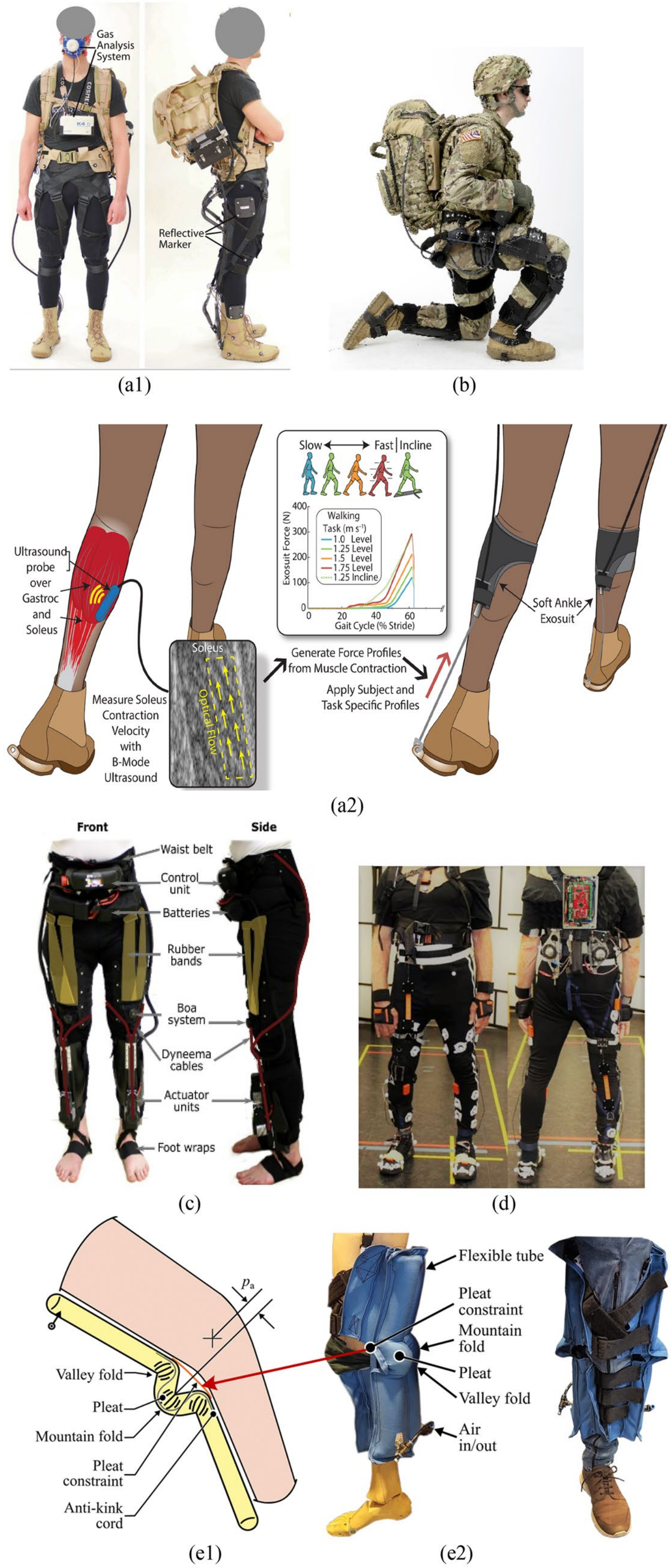


Fig. 6 Representative CLEEX exoskeletons: **a1** Soft Exosuit [93] **a2** MBA profile [98] **b** ONYX [99] **c** MyoSwiss [100] **d** XoSoft [102] **e1** PPIA and **e2** SLAK [110]

24.2 ± 7.4% during walking [101]. The metabolic cost of hip assistance was reduced by 17.4 ± 3.2%, with a more than 60% improvement in metabolic reduction compared with state-of-the-art devices that only assist hip extension [102]. In addition to studying assistance in the human walking process, Wyss laboratory also conducted related research on the human running process from 2019 to 2020, evaluating human motion intention to change the hip joint-assisted gait driving mode according to the motion state of the center of mass during human running [103]. The tethered ankle exoskeleton can make the wearer more relaxed during running and improve the energy economy by 14.6 ± 7.7% [104]. In 2021, they developed a muscle-based assistance (MBA) strategy that uses a portable ultrasound imaging system to capture continuous two-dimensional image sequences of the soleus muscle in the calf and then measures muscle dynamics through optical flow image processing to generate corresponding MBA strategies. The exosuit can generate a customized auxiliary mode online relatively fast (approximately 10 s) to achieve comfort, tailored and adaptive assistance for people and reduce walking metabolism by 15.9%, 9.7% and 8.9% at three speeds of flat walking. It may help support the adoption of wearable robotics in real-world, dynamic locomotor tasks [105], as shown in Fig. 6a2.

In 2017, the ONYX [106], a lightweight exoskeleton developed by Lockheed Martin and powered by B-Temia, was designed to enhance the wearer's strength and endurance, as shown in Fig. 6b. The ONYX, a LEEX that counteracts excessive pressure on the back and legs, is ideal for military and first responders with an electromechanical knee actuator, a full set of sensors and an AI computer that understands the user's movements and provides the right torque to assist in climbing steep slopes, lifting or dragging heavy objects. Sensors distributed on the exoskeleton feedback the measured walking speed, direction and joint angle of the wearer to a controller, which then issues instructions to control the actuator at the knee joint to output the correct torque at the ideal time to help the knee joint flex and extend. It can also better handle and support heavy weapons, enhance the ability to cross terrain under heavy loads, and even guide bone alignment and correction.

In 2017, ETH Zurich designed the flexible MyoSwiss exoskeleton [107], as shown in Fig. 6c, with a total weight of 4.56 kg and an endurance of 4 h, which provides continuous auxiliary torque for the wearer at the hip and knee joints through the synergistic enhancement effect between joints. The exoskeleton's closed-loop force controller, combined with active and passive actuators, is designed to act like external muscles and provides the user with gravity compensation, providing up to 26% torque and 35% power at the knee joint. The MyoSwiss uses a new double joint structure combined with an attitude force controller to effectively assist the wearer in daily activities.

In 2018, the European Union developed a research plan for the XoSoft flexible bionic exoskeleton [108, 109] and demonstrated a prototype, as shown in Fig. 6d. The exoskeleton has a modular design that can help different parts of the body by combining different joints. It uses a flexible tension sensor to measure the wearer's joint torque and an inertial sensor and a foot pressure sensor to determine walking intention. The exoskeleton has a dead weight of 2.68 kg. The XoSoft provides wearers with 10.9 ± 2.2% and 9.3 ± 3.5% of their own hip and knee power, respectively, reducing energy consumption by up to 20%.

In 2021, Veale et al. [110] from the Netherlands proposed a method to achieve a soft structure of the knee exoskeleton. A Pleated Pneumatic Interference Actuator (PPIA) structure is used to stably and comfortably apply knee extension torque to the body, as shown in Fig. 6e1. And its sufficient for Sit-To-Stand (STS). Multiple PPIAs were integrated into a soft orthosis, the Soft Lift Assister for the Knee (SLAK), as shown in Fig. 6e2. The SLAK was inflated to a pressure of 320 kPa, and it produced a maximum 324 Nm torque at a flexion angle of 82°. This exceeds the peak 180 Nm torque required for STS and torques required for other everyday tasks.

At present, the research on CLEEX in China is mostly confined to universities and research institutes, which are in the stage of experiment and verification. The outstanding researchers are Harbin Engineering University, the SIAT of the CAS, Southeast University, Shenyang Institute of Automation (SIACAS), etc. In recent years, many commercial companies have emerged, such as Shanghai Siyi Intelligent Technology, Beijing C-Exoskeleton Technology, Shenzhen Kenqing Technology and so on.

In 2011, Sui Liming's team [111] from Harbin Engineering University studied a pneumatic-assisted lower limb exoskeleton system, as shown in Fig. 7a. The system has two aluminum movable joints at the hip and knee, and each joint is driven by a pair of homemade pneumatic muscles with a 20% contraction ratio in the way of an active muscle-antagonist muscle. The team proposed a human walking posture control model with a pelvis trajectory as the representation of walking posture. Three rehabilitation strategies of passive, active and resistance were adopted for different stages of gait rehabilitation. The experimental results show that it can effectively provide some power and orthopedic functions.

In 2017, Xinyu Wu's team [112, 113] of the SIAT of the CAS developed a power-assisted exoskeleton robot based on flexible transmission, as shown in Fig. 7b. It has a weight of 20 kg, which can provide power for the wearer's hip and knee joints. Four plantar film pressure sensors on the foot (three on the sole of the foot and one on the heel) are used for gait phase division. Local motion planning based on a fuzzy algorithm is proposed in the control. By trying the k-nearest neighbor (KNN), long short-term memory (LSTM)

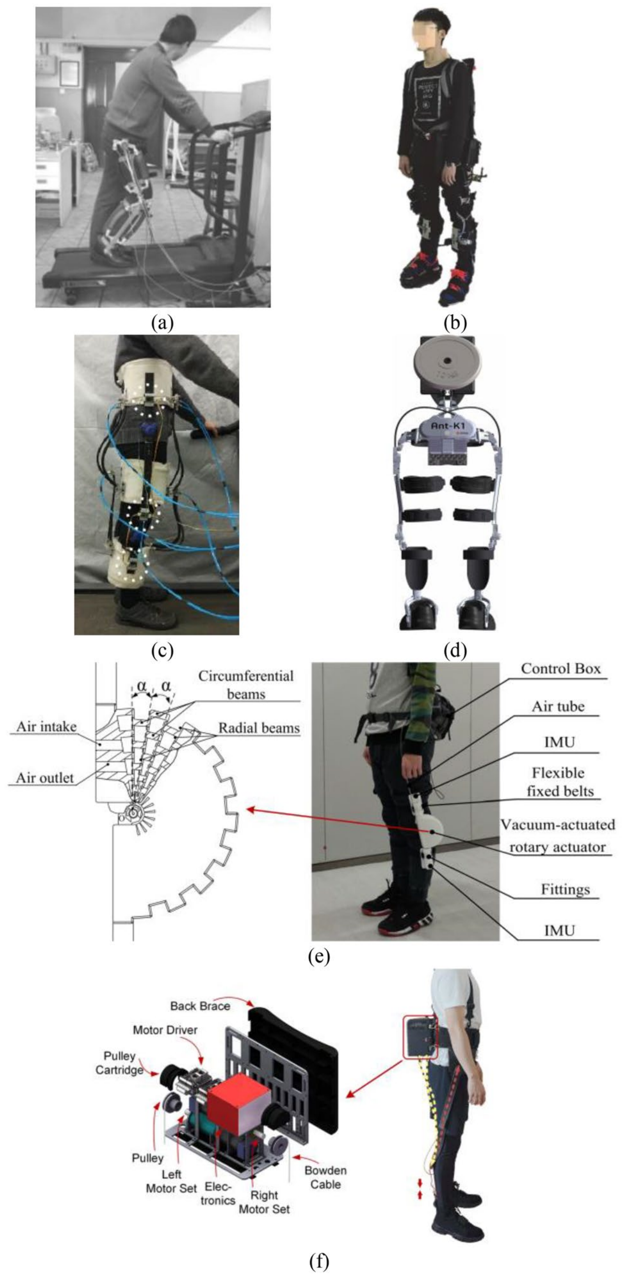


Fig. 7 Representative CLEEX in China: **a** Pneumatic muscles exoskeleton, Harbin Engineering University [111] **b** rope driven exoskeleton, the SIAT of the CAS [112] **c** flexible exoskeleton, Southeast University [114] **d** Ant-K1, Kenqing Technology [115] **e** soft knee exoskeleton, Beijing Institute of Technology [116] **f** exosuit, SIACAS [117]

and hidden Markov model (HMM), a machine learning algorithm can recognize movement patterns such as walking on flat ground, ascending and descending hills, and ascending and descending stairs, and the accuracy of most movement recognition results exceed 90%. The feasibility of the exoskeleton is verified through actual wearing movement experiments.

In 2018, Xingsong Wang and his team [114] (from the Robotics and Biomechanical Electronics Laboratory, Southeast University) studied an artificial pneumatic muscle unilateral hip-knee assisted LEEX system, as shown in Fig. 7c. Wear the system quality is 2.4 kg, two fixed airbag deployments and four groups of pneumatic artificial muscle cells, designed with one foot force measurement module, two muscle power acquisition modules, three attitude measuring pressure sensors, and four nodes that use the posture and pull data fusion of fuzzy adaptive PID algorithm control groups of artificial muscle movement. Through the analysis of joint angle, tension value and EMG value of rectus femoris muscle and biceps femoris muscle, the power assist effect of exoskeleton robot is evaluated.

In 2019, Shenzhen Kenqing Technology Co., Ltd. demonstrated a commercial dual-assisted lower limb exoskeleton system called the Ant-K1 [115], shown in Fig. 7d. The system has rigid construction, a flexible Bowden line drive to provide active power to the hip and knee joints, and a bionic spine design to support flexible upper limb movement. In addition, the weight of the system without a power supply is 9 kg, the load-bearing weight is 20 kg, the endurance is 6–8 h, supporting an 8 km/h trot forward, and the system has a powerful balance foot structure to maintain a good balance when loading.

In 2020, Zhang et al. [116], the Beijing Institute of Technology, made a soft knee exoskeleton to help walking. It is mainly driven by vacuum-actuated rotary actuators. They studied and obtained some corresponding relations among the pressure, angle and torque of the actuator. Moreover, they designed a control system including a gait estimation model and knee torque model to generate gait-consistent auxiliary torques, stretching torques and bending torques that were able to meet the needs of the knee during walking. Finally, a cardiopulmonary exercise test was used to quantitatively evaluate the exoskeleton. The results showed that the metabolic cost was reduced by an average of 6.85% when using the exoskeleton. The soft exoskeleton is shown in Fig. 7e.

In 2021, Xingang Zhao and his team at the SIACAS [117, 118] designed an exosuit. The V-shaped leg strap "attached" to the surface of human muscle and tendon is driven by Bowden wire to assist the target muscle group, as shown in Fig. 7f. The exosuit weighs 6.5 kg in total and has 92.7% of its mass close to the body's center of mass to reduce the extra inertial force exerted by the wearer during strenuous exercise. In order to adapt to the changes in human gait frequency and continuously reduce the cost of walking metabolism. Then they proposed an adaptive human motion type recognition and gait state detection method combined with the rhythmic characteristics of human gait based on the concepts of human phase plane and phase curve. The method improves rapid adaptation ability of the exosuit to changes in human step frequency, motion environment and human–machine coupling dynamics. It is verified that the designed method can effectively improve the energy economy of human walking.

About the driven modes of CLEEX. In addition to the mainstream cable-driven (Bowden wires), pneumatic muscle and motor-driven methods [119, 120]. There are also Functional Electrical Stimulation (FES) driving methods [121, 122]. In the light of the way that the human brain controls muscles, FES elicits muscle contraction by using an external electrical stimulus, typical via wearable electrodes. It can provide not only functional movement but also therapeutic benefits to patients with neurological injuries. As well as new smart material drive methods such as ElectroActive Polymer (EAP) [123], Shape Memory Alloy (SMA) [124], and fluidic actuators [125–127]. EAPs change shape or size when stimulated by an electric field and are widely used in robotics as actuators or sensors. SMAs are materials that change shape when subjected to thermomechanical or magnetic variations and can return to their previous form at the end of the stimulus. Fluidic actuators are commonly comprised of a chamber inflated with a pressurized fluid. They are widely used in soft robotics due to their high energy density and simple manufacturing.

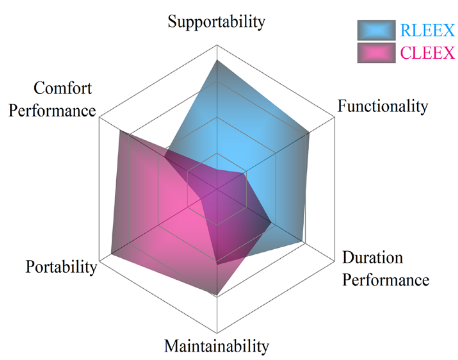


Fig. 8 Performance comparison of RLEEX and CLEEX

Compared with RLEEX, the development of CLEEX in China started late, learning from the application research of traditional RLEEX and has the advantage of being a latecomer. Zhao Xingang [128] listed the comparison between RLEEX and CLEEX systems and pointed out the advantages of CLEEX, such as considering the comfort of human–robot interaction, adapting to human anatomical differences and human compatibility, light weight, and easy to carry and wear. However, compared with RLEEX, it has a great deficiency in supporting the human body, protection and load-bearing functions. Figure 8 and Table 1 show their performance, advantages and shortcomings, implementation difficulties and applicable users in detail. A RLEEX has many supporting parts and high stiffness, leading to large mass and carrying difficulty, but its support is good. It can increase expanded parts such as sensing, auxiliary and multifunctional parts, and it can increase the amount of energy carried, such as large capacity batteries, to improve endurance. CLEEX has few mechanical parts and is easy to maintain. Its material is mostly soft woven fabric, which has

Table 1 Comparison of RLEEX and CLEEX

Comparison project	RLEEX	CLEEX
Advantages	(1) High stiffness, can enhance the support of the human body (2) Can provide large torque, improve the load-bearing capacity of human (3) Easy to analyze kinematics and dynamics model, to design a high-performance controller	(1) The system is lightweight and easy to carry and wear (2) The system has good compatibility with human movement and high comfort level (3) The weight of the system can be concentrated at the center of gravity of the human body to reduce the inertia of the limb
Shortcoming	(1) Heavy weight, high inertia, inconvenient to carry, uncomfortable to wear (2) A misalignment between the human physiological joint and the rigid linkage drive of the exoskeleton results in undesirable torques [129]	(1) Low stiffness, unable to support the body's own weight (2) Flexible materials will dissipate energy and reduce the transmission efficiency of the system
Implementation difficulties	(1) Man–machine interface comfort and optimization of volume and weight (2) Joint self-alignment and link self-adjustment design (3) Realization of low energy consumption and motion stability control of man–machine system	(1) Flexible drive is nonlinear, so it is difficult to design a high-performance controller (2) Online parameter optimization of controller for human body differences (3) Analysis of energy conversion mechanism and muscle group synergy mechanism
Applicable users	(1) Paralyzed people who cannot support their own weight (2) Armed soldiers who need protection and load (3) Logistics, porters and other manual workers (4) Elderly population with osteoporosis and joint degeneration	(1) Hemiplegic patients with walking ability (2) Field rescuers and other people who need to travel a long distance (3) Elderly population with degeneration of muscle and tendon function

a high fitting degree with the human body and is comfortable to wear. It has a lightweight and good folding ability and is easy to carry. In terms of performance, RLEEX and CLEEX are not good or bad, only requirements, and different requirements correspond to different users. In addition, according to the current development trend of exoskeletons, there will be a comprehensive RLEEX and CLEEX combined with their respective performance strengths in the future. This kind of exoskeleton emphasizes the balance of various performances to meet people's more differentiated needs and provide stable and compliant experience.

3.3 Classification by Function

According to general function, LEEX can be divided into power-assisted LEEX and medical rehabilitation LEEX, as shown in Fig. 9.

Power-assisted LEEX can be subdivided into two types:

The first is load-enhanced LEEX for lifting heavy objects, carrying heavy objects over long distances, or using heavy tools. BLEEX, HULC and Guardian XO, for example, can directly transfer various loads on the human body to the ground and walk with the guidance of limbs, with the effect of carrying little "King Kong". They are commonly used in warehouses, construction sites, emergency rescue operations, military bases and short trips. The other type is endurance-enhanced LEEX, which is used to increase the endurance of able-bodied people. HAL and Soft Exosuit, for example, take the wearer's legs as the load of the robot, optimize the output of the wearer's legs through a control algorithm, provide auxiliary torque for a human body, save energy during movement, and enhance the wearer's endurance. This kind of exoskeleton is mainly for the urgent needs of aging, aiming to improve the walking self-care ability of the elderly so that those with declining physical function can complete some daily life movements alone, such as standing up/sitting down, walking for a long time, up/downhill, and up/downstairs.

Medical rehabilitation LEEX can also be subdivided into two types:

The first is a kind of rehabilitative LEEX. These devices can help, provide resistance, or interfere with the wearer's movement to achieve therapeutic exercise and can help disabled patients gradually establish their own connection of their central nervous system, thus restoring their physical ability of independent activities and helping them overcome the limitations of disability without using the exoskeleton. For example, the LOPES-II [130] of the University of Twente in the Netherlands and the Alex-III [131] of Columbia University in the United States, are characterized by fixed structures that can support all or part of the weight of the human body and ensure patient safety with lower limb mobility difficulty during rehabilitation training. However, they are usually suspended, fixed and bulky, making them difficult to use in daily life and are commonly seen in rehabilitation centers, hospitals and other institutions. The other type is disability-assisted LEEX, which focuses on improving mobility or function in patients with musculoskeletal or neuromuscular injuries. These include robotic limbs (also known as powered prosthetics) for amputees and exoskeletons (also known as powered orthotics) for people with neuromuscular injuries (such as spinal cord injuries, stroke, multiple sclerosis or cerebral palsy). For example, the Ekso-GT [132], Indego [133] and Atlas 2030 [134] allow individuals with lower limb paralysis to walk with the help of crutches or mobile platforms. These are characterized by high stiffness to support body weight and towing human walking. This kind of exoskeleton is for paralyzed patients with stroke, spinal cord injury, muscle weakness and other nerve or muscle tissue diseases, which lead to difficulty in autonomous movement of the lower limbs. They aim to restore the original physiological function of patients and avoid muscle weakness, osteoporosis and other diseases caused by long-term sitting or lying.

Patients require a combination of systematic, scientific and targeted treatment and need exoskeletons for different stages of recovery according to different degrees of disease. For example, the rehabilitation of a patient with paralysis, gait pretraining is required first under the guidance of clinicians. While providing safety support, core muscle group strengthening, forward and backward stepping and balance training are required to establish the connection of the patient's own motor central nervous system. Second, continuous and smooth gait training with adjustable gait speed can train patients to adapt to their own center of gravity shift and gait shift, which cannot be separated from the rehabilitation exoskeleton of the lower limbs. Moreover, as treatment needs enter the second half, for patients disabled with a cane, a walker type of lower limb exoskeleton allows them to stand up and walk. Exoskeletons need to help patients reduce the

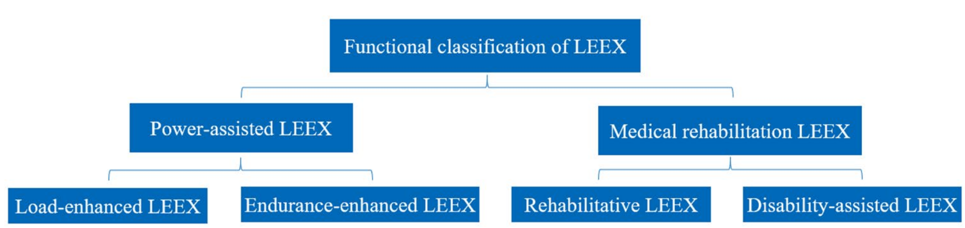


Fig. 9 Functional classification of lower extremity exoskeletons

force of their own gravity during walking for patients requiring hip, knee, or ankle joint help, such as providing security support and identifying and correcting patient gait errors. Through training, a patient's physiological function gradually recovers. Additionally, personalized support for different patient standing postures is needed. Finally, patients on the verge of recovery can use a single-jointed exoskeleton as a final aid to recovery and normal walking.

Figure 10 shows representatives of medical rehabilitation LEEX, in which (a) and (b) are rehabilitative LEEX, and (c–e) are disability-assisted LEEX.

In addition, LEEX for special functions and purposes, such as space exoskeletons and protective exoskeletons, also play an important role.

Space exoskeletons can be divided into space-exercise exoskeletons and space-assisted exoskeletons. Space-exercise exoskeletons, through setting resistance in the exoskeleton joints, help astronauts exercise in microgravity or weightless environments, prevent astronaut osteoporosis and muscle atrophy, and measure and record the astronaut physiological data transmitted back to earth, allowing a doctor to better obtain feedback about the crew training plan. Space-assisted exoskeletons have been proposed in recent years. They are mainly used to eliminate the influence of the joint damping torque of an extravehicular spacesuit during an astronaut's extravehicular activity, assist the astronaut's lower limb movement and relieve the lower limb fatigue in future space operation, star walking, material handling and long-distance driving. For example, the X1 exoskeleton [135], codeveloped by the National Aeronautics and Space Administration (NASA) and the Institute of Human and Machine Cognition (IHMC) in 2012, has four motorized joints at the hip and knee, as well as six passive joints, allowing avoidance, turning, pointing and bending. Custom control enables the X1 to be used in different ways: the device can be used for space exercise, providing resistance for leg movement to exercise, and force measurement for large muscle groups of lower limbs [136]. In this case, the X1 is a space-exercise exoskeleton. In the future, the X1 can provide power for astronauts to work on the surface of distant planetary bodies to improve their walking and working ability in a microgravity environment. At this time, the X1 is a space-assisted exoskeleton, as shown in Fig. 11a. However, Porter et al. [137] designed a compliant exoskeleton with adjustable stiffness for the knee joint. Its function is to reduce metabolic costs during locomotion in reduced gravity, maximize mobility, and improve astronaut performance. In addition, the results demonstrate the ability to integrate a compliant exoskeleton into the space suits to improve space suit design to enable longer, safer, and more complex EVAs in partial gravity. Another example is the active spacesuit joint-assisted exoskeleton of the School of Aeronautics and Astronautics of the UESTC, which has carried out structural optimization research on two generations of prototypes [138]. The weight of the optimized second-generation prototype is 40.03% lighter than that of the first-generation, as shown in Fig. 11b.

Protective exoskeletons can be divided into military tactical exoskeletons and radiation protective exoskeletons. A military tactical exoskeleton kit is a versatile package that incorporates strength, protection, soldier monitoring, and weapons. For example, Revision Military's Prowler exoskeleton has lower limb enhancement and armor protection, which can play a great role in combat effectiveness in combination with the carried positioning, physiological monitoring and weapons [139], as shown in Fig. 11c. The main function of a radiation protective exoskeleton is to carry a heavy radiation protective suit, which reduces the body burden of the operator and brings more choices for the research and development of high-performance protective suits. For

(a) (b) (c) (d) (e)

Fig. 10 Representative of medical rehabilitation LEEX: **a** LOPES II [130] **b** ALEX III [131] **c** Ekso-GT [132] **d** Indego [133] **e** Atlas 2030 [134]

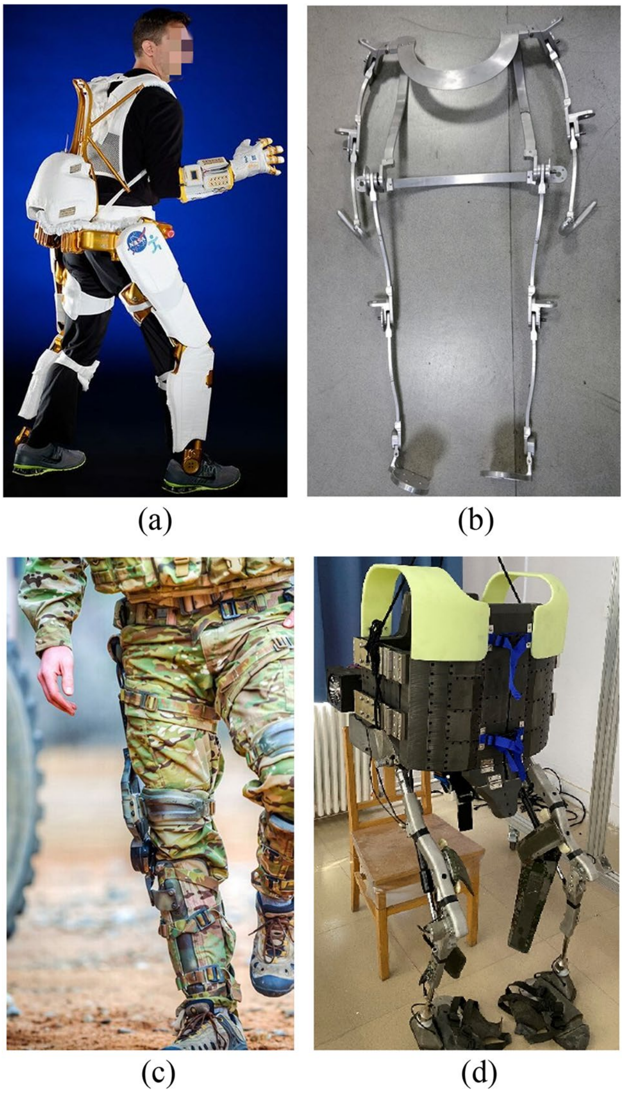


Fig. 11 Representative of special functional classification of LEEX: **a** X1, NASA [136] **b** 2nd joint-assisted exoskeleton, UESTC [138] **c** Prowler, Revision Military [139] **d** fast neutron shielding suit with human exoskeleton, LZU [140]

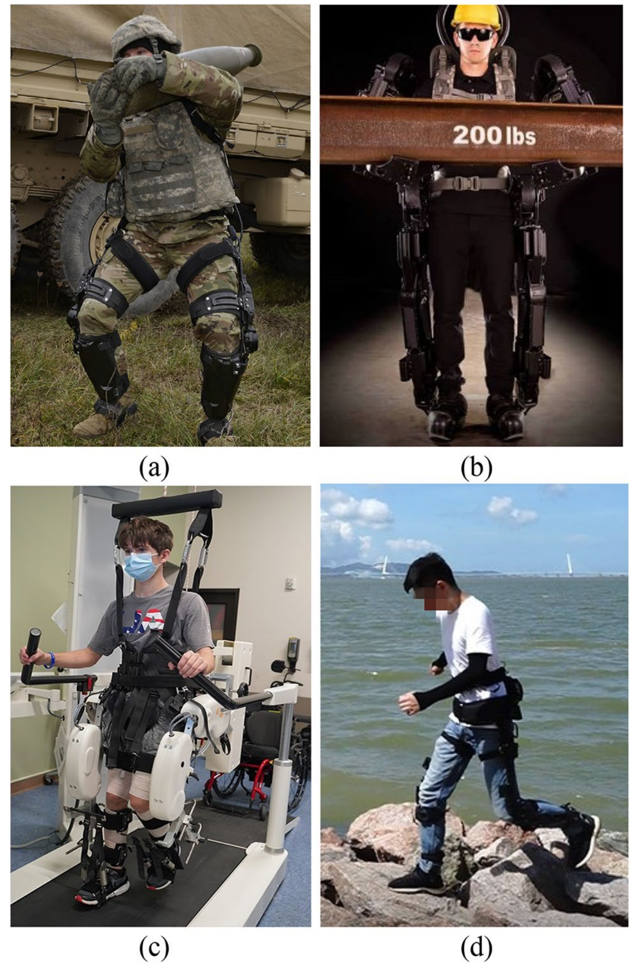


Fig. 12 LEEX in different industries: **a** military field [141], **b** industrial field [142], **c** medical field [143], and **d** consumer field [146]

example, Lanzhou University (LZU) studied a prototype of a fast neutron protective suit for a human exoskeleton [140], as shown in Fig. 11d.

3.4 Classification by Field

Just as stem cells in biology need to differentiate according to the functions of different organs to meet a specific biological function, LEEX can be further differentiated according to the application characteristics of a field to meet specific needs. As shown in Fig. 12, LEEX plays different roles in different fields.

In the field of military and disaster relief [141], LEEX can enable soldiers to carry heavier loads when running, reduce load-bearing fatigue and improve combat efficiency. It can also enhance a rescue team's protection, loading and mobility and can carry out an operation when large equipment cannot operate due to site terrain limitation, ensuring timely rescue and smooth execution of the task.

In the field of construction, logistics, manufacturing and other labor-intensive industries [142], LEEX can assist manual workers and special operators, such as construction workers, airport logistics porters and shipyard workers, so that they can operate a larger load and help them complete repetitive tasks. Improving working efficiency and reducing injury probability and chronic disease risk caused by skeletal muscle strain are widely used in firefighting and disaster relief, cargo handling, field exploration, construction inspection, patrolling and other scenarios.

In the field of medicine [143, 144], LEEX play an important role in patient self-care and allied care. It can help patients with spinal injury or stroke carry out rehabilitation exercise, assist patients in reshaping their central nervous system, prevent muscle atrophy, joint contracture, osteoporosis [145], improve the patient's internal circulation system and psychological state, relieve depression, and so on, and liberate traditional rehabilitation physiotherapists from heavy physical work. In addition, surgeons can wear lower limb exoskeletons to reduce standing fatigue and improve surgical accuracy.

In the field of consumption [146], LEEX play a very large role in assisting healthy ordinary people in hiking, traveling and climbing stairs and improving people's quality of life in protecting joints and reducing exercise fatigue. Exoskeletons for the general public are mostly inexpensive, lightweight and portable.

4 Key Technology Analysis

According to the classification of LEEX, the characteristics of RLEEX and CLEEX are analyzed in combination with their functions and applications and under which conditions they are more advantageous. RLEEX is more suitable for medical rehabilitation, paralysis walking aid, load enhancement and other scenarios that need to support the human body for treatment and operation. CLEEX is more suitable for elderly individuals with degraded physical function to enhance strength and endurance and for common people who need to travel a long distance. The key technologies of LEEX in different application scenarios are also quite different. For example, military, construction, logistics, industry and other related fields pay more attention to protection and support load and have multifunctional characteristics so that the exoskeleton can truly become a good helper for them to perform tasks or work. Therefore, the key technology is biased toward structure, driving and power endurance technology. In the field of medical rehabilitation, research focuses on continuous passive motion (CPM) [147], range of motion (ROM), gait and motion feature analysis, auxiliary therapy, etc. Therefore, the key technology is the environment and motion intention perception and rehabilitation intelligent control strategy. For ordinary civil consumption areas, the future prospect, mainly for healthy endowment and taking a long time standing or walking, such as the elderly, a tour guide, police, athletes, photographers, or such as niche business, mainly emphasizes comfort, convenience, and maintenance is convenient as characteristics, therefore the key technology is a flexible structure and flexible technology. The following analyzes the current key technologies from four aspects: bionic structure and driving technology, human–robot interaction and intent-aware technology, intelligent control strategy optimization, and power-assisted walking efficiency evaluation.

4.1 Analysis of Bionic Structure and Driving Characteristics

In the structural design of LEEX, safety, reliability, wearing comfort and ease of use, distribution of robot joint freedom, lightweight robot structure and material selection of structure should be fully considered. And a structural design with "humanoid" characteristics should be adopted. To provide assisted locomotion for people with different movement tasks and states, LEEX should have anthropomorphic and ergonomic characteristics. And LEEX should follow the principle of human-centered design. Specifically, the joint distribution of LEEX needs to be consistent with the human lower limb, with all movable joints active to avoid instability of motion. The structure of LEEX must be rigid enough to support human body. The Center of Gravity (COG) of LEEX should be as high as possible to avoid increasing leg inertia to facilitate walking [148].

The basic biomechanical factors to be considered in LEEX design mainly include the number of Degree of Freedom (DOF), Range of Motion (ROM), structure form, actuation form and so on.

First, in order to determine DOFs of LEEX and the distribution of driving joints, it is necessary to study the motion properties of each joint of the human lower limb. According to the analysis of human motion anatomy, the basic axes include sagittal axis, coronal axis and vertical axis. These three main axes define three datum planes, namely sagittal plane, coronal plane and transverse plane, as shown in Fig. 13a. In order to simulate the behavior of the human physiological lower limb, LEEX needs to consider the locomotion of all three anatomical planes, and the layout of the necessary controllable DOFs should be consistent with the human leg.

Figure 13b shows the skeletal structure of human lower limb joints. Human hip joint is a 3-DOF ball-and-socket joint with hip flexion/extension, hip adduction/abduction, and hip intorsion/extorsion. It consists mainly of the acetabulum and the femoral head, connecting the pelvis to the femur. With strong flexibility, it can make the joint around all directions. The ball-and-socket structure increases the area of muscle attachment points, which can attach strong muscles and provide a strong power source for lower limb locomotion. Thanks to the ball-and-socket structure, the contact area between femur and pelvis is increased, which reduces the force on the unit area and maintains the stability of the hip joint in the process of force transmission [53]. Human knee joint is a 1-DOF hinge joint with knee flexion and extension. It consists of the lower end of the femur, the upper end of the tibia and the patella. The anatomy of the knee joint shows complex functions, and the natural flexion of the knee joint is very important for the locomotion and balance of the lower limbs. On the one hand, knee flexion

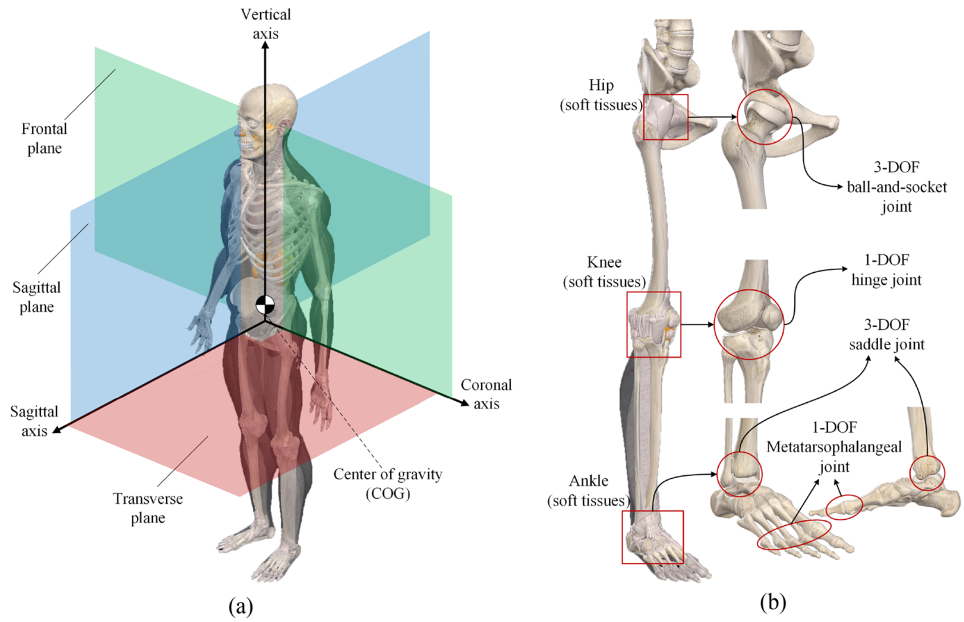


Fig. 13 Human anatomy diagrams: **a** anatomy planes, basic axes and COG; **b** skeletal structure of the human lower limb joints

shortens the length of the lower limb in use, allowing the body to complete leg swing smoothly and facilitating the completion of multiple lower limb locomotion. On the other hand, in the standing stage, the micro-flexion shape of the knee joint helps to absorb the impact force and transfer force to the lower limbs, which enhances the smoothness of the human locomotion process. Human ankle joint is a 3-DOF saddle joint with ankle flexion/extension, ankle adduction/abduction, and ankle intorsion/extorsion. It consists of the articular surfaces of the lower tibia and fibula with the talar carriage. Inferior articular surface of the tibia and the ankle joint surfaces form a kind of articular fossa that is wide anteriorly and narrow posteriorly. When the foot is dorsiflexion, the wider front of the talus slide enters the fossa, improving the stability of the ankle in interaction with the outside world. When the foot is plantarflexed, the narrow back of the talus slide enters the fossa and the ankle loosens to allow lateral movement. The structure of saddle joint ensures the stability and flexibility of ankle joint during direct interaction with the ground. Human metatarsophalangeal joint is a 1-DOF joint with metatarsophalangeal joint dorsal flexion. The metatarsophalangeal joint plays an essential role in maintaining stability and agility during the push-off phase of human movement [149, 150]. Moreover, the stiffness of the metatarsophalangeal joint varies with the stiffness of the plantar flexors. This variable stiffness property enhances the flexibility of foot locomotion during the stance phase, allowing the body to move forward more effective and faster, improving walking economy [54]. In short, the metatarsophalangeal joint plays an important role in improving the stability and functionality of human locomotion. Tendon is a soft tissue connected with muscle and consists of dense connective tissue. Its elastic properties play an important role in body locomotion [151]. Together with muscles, it forms the soft tissues around the joints.

The external performance properties of lower limb joints are closely related to the intrinsic functional properties of muscle system. The roles played by the muscular system in different movements of the human body are complex and diverse. Existing studies have pointed out that the functions of the muscular system can be divided into four categories: 1) motor, which provides the main force through muscle contraction; 2) spring, which stores and releases energy through the elastic properties of muscle; 3) brake, which dissipates energy through muscle elongation; 4) strut, which supports through muscle isometric contraction to provide force [152, 153].

Second, in order to ensure the safety of LEEX, it is necessary to determine the rotation range of each joint. It should be determined according to the total physiological ROM of each human joint [154]. And ROM of each joint of LEEX should be slightly smaller than each human joint to ensure the safety of the human body in the whole accessible motion space of LEEX, as shown in Table 2.

Third, different structure design forms correspond to different kinematics and dynamics modeling analysis methods. For RLEEX, since the axes of exoskeleton joints connected in series cannot all intersect at the human joint center, especially for the 3-DOF hip joint, there exists a misalignment problem between these multi-DOF exoskeletons and the human limb. To ensure the comfort of wearing and the flexibility of human–machine collaboration, an exoskeleton should theoretically replicate human joints so that they have the same motion structure [155]. Furthermore, the leg inertia

Table 2 ROM of each joint for human lower limb and LEEX

Joint	Total DOF	DOF of joint movement	Total physiological range of motion	A safety range of LEEX
Hip	3	Flexion/extension	– 25° to 125°	– 9° to 120°
		Adduction/abduction	– 30° to 60°	– 30° to 35°
		Intorsion/extorsion	– 30° to 60°	– 25° to 25°
Knee	1	Flexion/extension	0° to 145°	2° to 144°
Ankle	3	Flexion/dorsiflexion	– 30° to 50°	– 15° to 40°
		Adduction/abduction	– 35° to 15°	– 30° to 15°
		Intorsion/extorsion	– 15° to 10°	– 10° to 10°
Metatarsal phalanges	1	Dorsal flexion	0° to 45°	0° to 40°

will be significantly increased when the powered actuators are connected directly to the ankle or knee joint of LEEX. CLEEX is inevitably affected by external force impact, collision and other problems in the process of movement. Therefore, the selection of materials in structural design should meet the needs of strength and stiffness.

Finally, the choice of driving method depends on the LEEX application scenarios. Common driving methods include hydraulic pressure, electric motors, SEA, air pressure/artificial muscles, and cable-driven. Table 3 describes the advantages and disadvantages of various driving methods.

Rigid actuators are often used as power sources for LEEX because of their strong position tracking ability, high power and simple control. However, as mentioned above, there are limitations in the performance of rigid actuators in terms

Table 3 Comparison of driving methods

Drive type	Pros	Cons	Types and prototypes
Hydraulic pressure	(1) Simple structure, stable operation, high reliability (2) High power density, strong load capacity (3) Overload protection, convenient to achieve stepless speed regulation	(1) It is difficult to manufacture precision components, pressurized hydraulic oil is easy to leak (2) Sensitive to load and oil temperature changes (3) It is difficult to realize constant ratio transmission	More common in RLEEX: BLEEX [27], HULC [33], XOS2 [156], etc
Electric motor	(1) High degree of standardization (2) The control level is easy to realize (3) Simple structure, no pollution	(1) Low power density (2) Poor movement balance (3) Large inertia, slow commutation	More common in RLEEX: HAL [70], Indego [133], ReWalk [38], etc
SEA	(1) Energy storage to improve exercise efficiency (2) Physical flexibility, with shock resistance characteristics (3) It can better realize the measurement of output torque	(1) Hardware implementation is difficult and unreliable (2) Complex upper motion control (3) High cost, poor economy	More common in RLEEX: LOPES [157], MINDWALKER [71], WPAL [84], etc
Air pressure/artificial muscle	(1) Low impact and good flexibility (2) Easy to implement, adapt to high temperature environment, no pollution (3) Simple structure and low cost	(1) Small working pressure, small power, poor bending resistance, small stroke (2) Slow response, difficult to accurately control, compressed air condensation water (3) Gas is easy to leak, resulting in force and velocity fluctuations	More common in CLEEX: KNEXO [158], Airlegs [159], CEXO-WPA02 [160], etc
Cable-driven	(1) Small size, light weight, flexible (2) The center of gravity of the system can be moved to the human's waist (3) Reduce the inertia of limb end movement	(1) Low transmission efficiency of the system (2) Impossible to precisely force control (3) Lasso has hysteresis, dead zone	More common in CLEEX: Soft Exosuit [100], XoSoft [108], exosuit [117], etc

of comfort and portability of LEEX. Flexible actuators, on the other hand, mimic the biological properties of muscles. The human muscle system has the advantages of small size, lightweight, good flexibility, large short-time drive power and high energy utilization. More and more scholars want to reproduce the function of lower limb muscles during human locomotion through engineering technology. At present, there are three main categories of actuator designs with biological properties: the first category is Series Elastic Actuator (SEA) that imitates the buffering and energy storage property of muscles [71]; The second category is artificial muscle that simulates the performance of muscle stretching and movement [161–163]; And the third category is variable stiffness actuator that reproduces the stiffness "rigid-flexible combination" property of muscle [164], as shown in Fig. 14.

As a kind of bionic actuator, SEA introduces elastic elements with fixed stiffness between the servo motor and the load to enhance the flexibility of the actuator. The introduction of elastic elements can alleviate the impact between the driving element and the load, weaken the fluctuation of human COG caused by the impact of the ground reaction force in the walking process of LEEX. And it reduces the effort of the human upper limbs to maintain balance [165]. Moreover, SEA also has the advantages of high force control accuracy, good safety, and adjustable power, so it is widely used in the design of LEEX. Artificial muscle actuator simulates the motor behavior of muscle contraction by contracting a cavity made of flexible material through fluid action to generate tension. The artificial muscle actuator has the advantages of high power, light weight and good flexibility. At present, there are many achievements in artificial muscle research. But limited by power and control accuracy, there is no large-scale application in LEEX. In order to reproduce the "rigid-flexible combination" dynamic property of human lower limb joints, researchers designed a variety of variable stiffness structures [166], such as linkage mechanisms, lever structures, and cam mechanisms. Although different structures, the principle of variable stiffness behavior is similar, which uses a special motor to change shape variable of the spring. The addition of additional motors not only increases structure and size of the actuator, but also makes the control algorithm of LEEX more complex. And it is easier to realize the variable stiffness behavior through the impedance/admittance control algorithm. Therefore, even though the existing variable stiffness actuators have various structural designs, they are rarely applied to the design of LEEX.

4.2 Analysis of HRI and Intent-Awareness

HRI requires two-way communication between humans and exoskeletons in both physical and cognitive aspects. On the one hand, the exoskeleton needs to acquire and interpret human motion intentions from the wearer's physical motion state and human biological signals through sensors and control the drive to follow or transfer mechanical power to the human body, which is the physical HRI (pHRI). This involves a net flux of power between both actors. On the other hand, the exoskeleton returns its actual state to the wearer through human sensory organs to make the human aware of the possibilities of the robot while allowing them to maintain control of the robot at all times, which is called cognitive HRI (cHRI). Here, the term "cognitive" alludes to the close relationship between cognition—including the high-level function of human brain processing, comprehension and use of speech, visual perception, calculation, attention (information processing), memory and executive functions such as planning, problem-solving, self-monitoring and perception—and motor control [3]. Human–Robot-Environment Interaction (HREI) further requires robots to perceive the external environment on the basis of human perception and transmit rich environmental information to the human to replace or expand human perception to assist the human–robot system in motion planning, which belongs

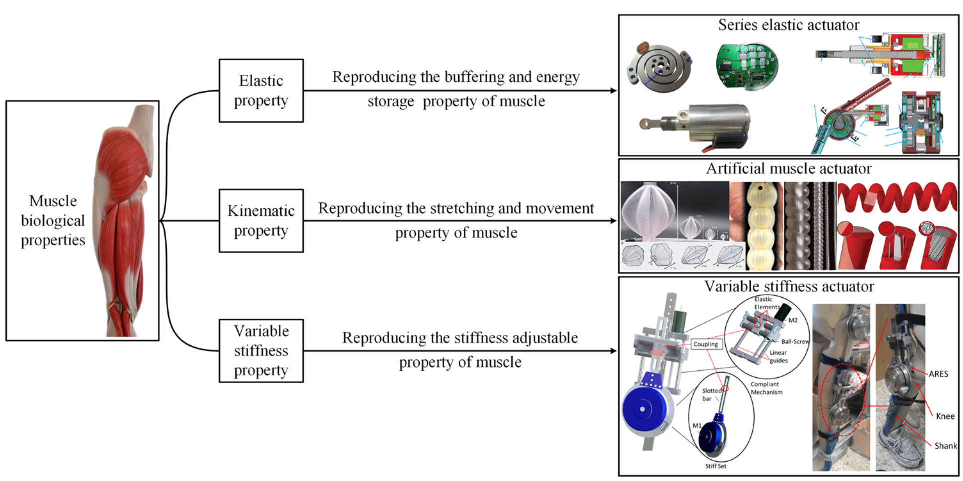


Fig. 14 Engineering schemes to reproduce biological properties of human lower-limb muscles

to the category of cHRI. For example, stairs are the most common structures in an artificial environment. Zhao et al. [167] detected and modeled stairs through computer vision, achieving the expected precision and providing the possibility of cognitive interaction for hemiplegic patients trained to use LEEX on stairs. Inspired by human perception, Wang et al. [168] proposed an end-to-end detection method for stair environments based on deep learning, which achieved high performance in terms of both speed and accuracy and provided the possibility for visually impaired people to navigate up and down stairs using LEEX. Figure 15 shows the units of human–robot, human–environment and robot-environment interactions in the process of human–robot-environment interactions.

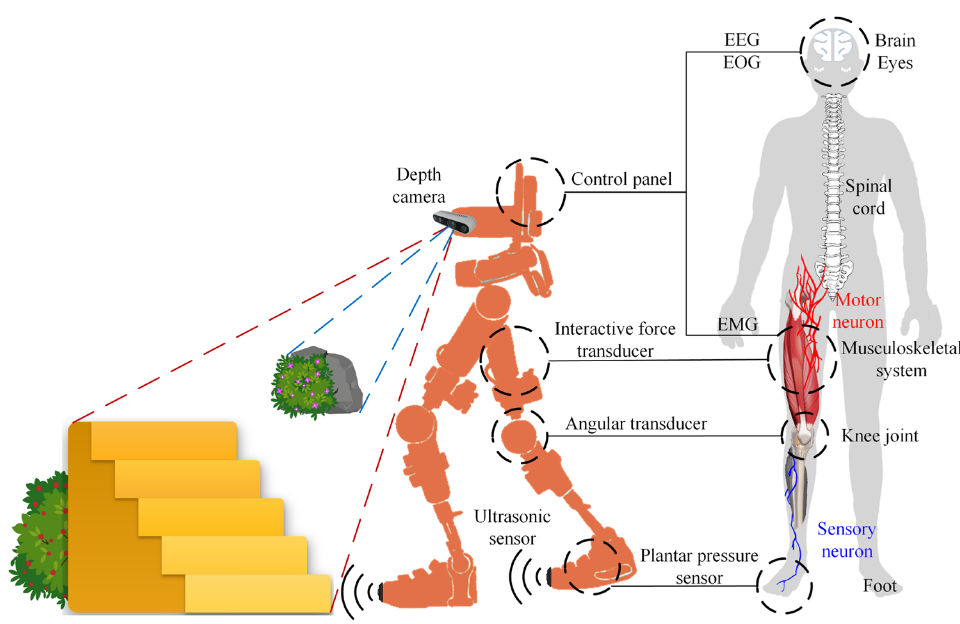
Generally, the sensing mode of a human motion intention perception and recognition system can be divided into mechanical physical type and bioelectrical signal type. Common mechanical physical sensors include inertial measurement units (IMUs), angle sensors, plantar pressure sensors and tension pressure sensors, which are mainly used to obtain the physical (force and position) information of lower limb movement. Bioelectrical signal sensors include Electroencephalogram (EEG) [169, 170], Electromyography (EMG) [171], and Electrooculography (EOG) [172]. Bioelectrical signals can provide physiological impulse information of humans directly, and the intention of human movement can be obtained by decoding this information. Body sensory feedback can be divided into invasive feedback and noninvasive feedback. Invasive feedback is through the nervous system to the human body central nervous or peripheral groups electrodes implanted chip to accept or make the person produce corresponding feelings. The advantage is that people can experience more real and natural feelings for more fine control; the disadvantage is that the body has experienced trauma, which the immune system will reject as "foreign", causing inflammation. At present, invasive technology is not mature and has not been applied to LEEX. Noninvasive feedback is usually achieved through sensory substitution [173], such as visual, auditory and tactile feedback, which is not harmful to people and is more easily accepted by the public but requires a long training time to master.

4.3 Analysis of Control Strategy

The control system is the "soul" of LEEX. Its design goal is to make the robot have enough "intelligence" to achieve a high degree of human–robot integration. For LEEX, the control problem can be solved using a generalized control framework, that is, a hierarchical control strategy [6], which is a three-layer structure like the structure and function of the human central nervous system. Figure 16 shows the control flow in the human–exoskeleton–environment loop coupling process and the framework relationship corresponding to the three levels. The top level is recognition, perception and decision-making, the middle level is intentional action planning, and the bottom level is drive control.

The top-level controller is the core of the LEEX control. It is the "brain" of the robot, which is responsible for human intention recognition, environment perception and deciding whether to distribute tasks. Its control object is a coupled system, mostly information (signal), such as activity mode detection based on classifiers (naive Bayes, Linear Discriminant Analysis (LDA), Quadratic Discriminant Analysis (QDA), Finite State Machines (FSM), Gaussian Mixture Models (GMM), Dynamic Bayesian Networks

Fig. 15 Interaction diagram of the human–robot environment-coupled system



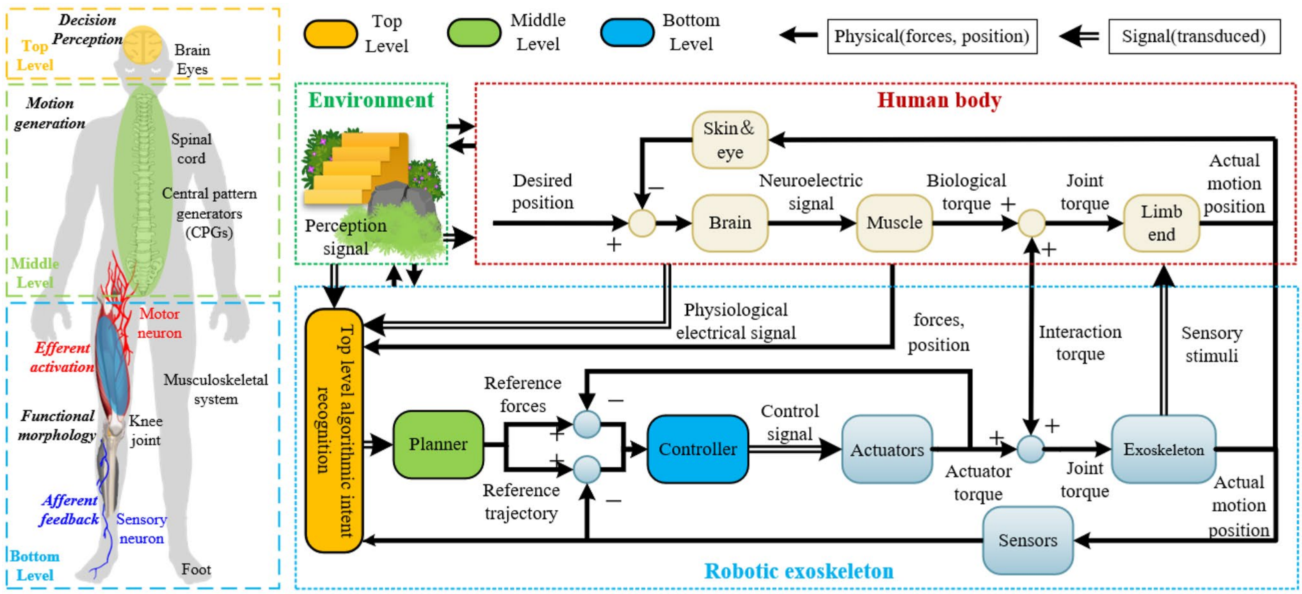


Fig. 16 Control diagram of the human–exoskeleton environment-coupled system

(DBN), Support Vector Machines (SVM), Artificial Neural Networks (ANN), Long Short-Term Memory (LSTM) [174], Genetic Algorithm(GA) and Convolutional Neural Network (CNN) [175], etc.), and direct volitional control based on bioelectrical signals (EEG, EMG, EOG, etc.). The algorithm is different depending on the specific LEEX application. For example, medical rehabilitation LEEX mostly adopts a direct volitional control mode. However, activity mode detection is mostly used in power-assisted LEEX. Therefore, the design of the top-level control algorithm should be customized according to specific functional requirements.

As the "spinal cord" of the robot, the middle-level controller is responsible for human state estimation and control strategy fusion, gait planning, and the generation of the desired reference torque and trajectory. The control object is mainly physical, such as position control, torque control and impedance control. Middle-level controllers are mainly divided into two types. The first is a gait-phase-based controller, such as a motion control mode based on a predetermined trajectory, which cannot make the wearer actively participate in the control system loop and is mostly used for rehabilitation training of patients with stroke and paralysis. The other is a non-gait-phase-based controller, which is divided into force-feedback control and Complementary Limb Motion Estimation (CLME). Force-feedback control includes Sensitivity Amplification Control (SAC) and zero-force control, which are relatively mature. CLME starts from the correlation between joint coordination and different joints and deduces the motion of the affected limb from the residual limb movement. However, it is difficult to obtain nonpathological data of the affected limb, which may lead to patient discomfort. HRI force control and variable impedance control based on impedance and admittance are also hot spots at the present stage [176–178]. Its advantages can not only make joints show flexibility to reduce the center of gravity fluctuation caused by the impact of the ground reaction force to improve human–robot stability [165] but can also store energy during movement to improve energy utilization efficiency [179]. The control algorithm is simple and clear, without obtaining prior knowledge from the environment. Therefore, it provides the possibility to create a safe, natural and comfortable physical interface for users, thus improving the wearable experience [180]. For example, recently McGill University in Canada designed a new adaptive impedance control strategy, which combined backstepping control, time-delay estimation, and interference observer. The computed control input does not require any precise knowledge of the dynamic model of the robot, nor of built-in torque sensing units, to provide desirable physiotherapy treatments [181].

The bottom-level controller is the end of LEEX control, which is the "limb" and responsible for the actual movement of the robot. Its control object is the robot joint actuator. The purpose of the bottom-level control is to drive the actuator to complete the desired action, calculate and then correct the error between the current state and the desired state. Common control methods include Proportional-Integral-Derivative (PID) control and its variants [182, 183], Active Disturbance Rejection Control (ADRC) [184], Sliding Mode Variable Structure Control (SMVSC) [185, 186], adaptive control [187], and feedforward and feedback control [188]. In terms of error evaluation and correction, the bottom-level controller can not only rely on feedback information, but also use feedforward information to regulate the motion of the actuator. Feedforward control requires a mapping model based on input signals and device states to predict the state of the system to reduce negative interactions due to mass, inertia and device friction. Feedback control, on the other hand, does not require a specific model, but merely records the current state and compares it with the desired state, thus adjusting the device to perform the desired trajectory. Therefore, although the structure of the bottom-level controller is very simple, it has a significant impact on the performance of the actual motion of LEEX. At present, the key to bottom-level control is the efficient computing power of the Microcontroller Unit (MCU) and the accurate, fast tracking of the desired signal. In terms of actuator drive, the bottom-level controller is usually selected according to the actuator of LEEX. For the motor driving mode, Field Oriented Control (FOC) or vector control can accurately control the size and direction of a magnetic field so that the motor motion torque is stable, low noise, high efficiency, and has a high-speed dynamic response. At present, it is one of the best control methods for Brushless Direct Current (BLDC) motors and Permanent-Magnet Synchronous Motors (PMSMs).

Regardless of the purpose of LEEX, three major challenges persist in the control strategy design: human intention and surrounding environment detection, motion control algorithm, and control optimization [189]. The essence of LEEX control is to establish a stable two-way communication between LEEX and the human. Perception and prediction of the surrounding environment then enables LEEX to be more intelligent and better understand the user's situation to plan a more appropriate control strategy. Therefore, human intention detection and environmental perception are both important. Motion control algorithms pave the way for more agile human–machine collaboration. Control optimization makes it possible for control strategies to adapt to different individuals and different tasks.

4.4 Analysis of Locomotion Efficiency Evaluation

The evaluation of the walking aid efficiency of LEEX can be divided into two categories: the object evaluation index, and the subject evaluation index. The object evaluation index can be divided into a mechanical system index and a control system index. The mechanical system index requires good structural strength and stiff toughness, must be light weight, and have low energy consumption, long life, uniform distribution of interaction force, and adaptation of human–robot kinematics and dynamics characteristics. The evaluation method can be obtained using force position sensors, reliability tests, stride length, stride speed, height from the ground, plantar pressure, joint torque, endurance time, and weight and fatigue life. [190, 191]. In terms of the control system index, real-time performance and safety stability are needed. The evaluation methods include testing system response delay, safety and stability. The subject evaluation index can be divided into a biological system index and a subjective evaluation index. In terms of the biological system index, the impact of human physiological functions is evaluated, such as the users' fatigue and health status, which can be learned by monitoring the EEG, blood sugar, blood pressure and body temperature during a long walk. For the evaluation of assisted tests, unified indicators can be used, such as an EMG signal, heart rate and oxygen consumption [192, 193]. The evaluation of medical rehabilitation tests requires professional evaluation in stages according to the degree of recovery of patients. These include spasm assessment (modified Ashworth grading method), motor function assessment (Carr-Shepherd assessment), balance function assessment (TUG standing and walking timing test), coordination function assessment (Ataxia Rating Scale ICARS), and walking function assessment (RLA gait system analysis). [194, 195]. All the above methods can obtain quantitative parameters, and it is easy to accurately characterize the power-assisted walking efficiency. In terms of the subjective evaluation index, a comfort satisfaction questionnaire, usage feeling questionnaire and human fatigue questionnaire are usually used to analyze the subjective evaluation of humans and LEEX [196] and improve, iterate and upgrade the LEEX according to the feedback of the questionnaire.

Assisted walking function evaluation is common in the field of medical rehabilitation. Among all kinds of rehabilitation training methods, the development of rehabilitation training through medical rehabilitation LEEX is an efficient method. A professional evaluation system should be developed for patients with different diseases, such as an acceleration-based gait analysis index specially developed for rehabilitation evaluation of knee joint diseases [197]. In addition, the evaluation of patient rehabilitation degree combined with big data, machine learning and artificial intelligence scientific systems is a popular new evaluation method. Most of these methods optimize the evaluation results driven by data, and the accuracy of evaluation and analysis is directly related to the amount of data, especially in applications with many categories. However, it is difficult to obtain the data of patients with different diseases and different degrees of disease, resulting in a lack of horizontal expansion ability of this evaluation method, which can only be used as an auxiliary means for clinicians in practical application.

5 R&D Issues and Challenges

Based on the above research progress and analysis of key technologies, there are still some key problems and challenges to be solved related to LEEX research and development, mainly reflected in structure, intention perception, online intelligent planning, endurance and so on.

5.1 Structural Bionics and Modularization

The biomimetic, lightweight and portable LEEX structure is the basis of its wide application. How to choose the appropriate bionic materials and their layout, improve the comfort of wearing and the flexibility of human–robot collaboration for walking, and at the same time, the highly integrated, miniaturized and lightweight actuators are the challenges faced by both rigid and compliant exoskeletons. At present, for most LEEX, the mismatch of the human–robot joint rotation center limits people's own movement, which greatly reduces the user's sense of experience and comfort. In addition, the unfriendly weight makes it difficult to apply in outdoor applications alone. Achieving the biomimetic and lightweight portability of exoskeleton structures will be the direction of continuous research breakthroughs in materials, mechanisms and dynamics in the future. At the same time, the target population of exoskeletons varies greatly. In the face of different users, the needs of the hip, knee and ankle joints are different. For example, in the field of rehabilitation medicine, patients with single-joint dysfunction do not need to wear the whole set of a multi-joint LEEX [198], which requires personalized and targeted design of the exoskeleton for the needs of the users. According to different functional requirements, it is also a development trend of future exoskeletons in the future to design modular, detachable and reconfigurable mechanisms of joint structures. Therefore, it will be a key challenge for R&D to achieve a comprehensive breakthrough in biomimetic, lightweight, portable and modular exoskeletons.

5.2 HRI Intention Perception

The control system is an important part of the complete LEEX system design. The control mode can provide effective assistance for a user only when it is suitable for specific occasions. In most applications, the LEEX control system needs to have real-time response speed, which requires it to predict the motion intention of the human body and respond in time.

In the field of power assistance, most LEEX interact based on mechanical and physical sensing design controllers through a negative feedback mechanism [199]. The advantage lies in the strong stability of the system, but the overall control output depends on the sensor. If the physical information of the human motion can be accurately fed back to the controller in real time, the exoskeleton robot can respond to the intention of body movement in time. However, according to the actual test experience, because the sensor information acquisition recognition process and human intention cannot be synchronized, they inevitably lag. At the same time, a sensor will be affected by external environmental factors, resulting in larger signal error, so it is difficult to provide the exact human–robot interaction information and identify people's complex motion intentions. In a classical control strategy, SAC brings people into the feedback control loop and leads people to participate in the adjustment movement to stabilize the man–machine system [200]. It is an algorithm that adopts a positive feedback loop to increase the sensitivity of the controller to man–machine interaction without force perception. It is easy to deploy and has been successfully proven on the BLEEX and HULK. However, this algorithm is limited by the accuracy of the dynamics model, so much identification work is needed to improve the accuracy of the model, and the involuntary motion caused by the adjustment of the sensitivity amplification factor still needs to be solved.

In the field of medical rehabilitation, mechanical physical sensing is not as common as bioelectrical signal sensing for patients with lower limb functional injury who lack movement and balance ability. This is because the lack of lower limb function makes it more difficult for sensing based on mechanical physics to collect the information of human motion intention, while the biological electrical signal becomes a suitable solution. However, using bioelectrical signals as feedback reduces the accuracy of intention recognition due to the interference of electrode offset, individual differences, body posture and other comprehensive nonideal factors.

Achieving accurate and stable human–robot interaction (HRI) has increasingly become the bottleneck of human–robot confluence (HRC) and has become a hot research issue [201, 202]. In the future, artificial intelligence methods led by multi-sensor fusion and multipattern recognition fusion will be the breakthrough point to achieve HRC. Real-time perception of human motion intentions in complex environments will be the greatest challenge for research and development.

5.3 Gait Planning and Gait Synchronization

Gait planning refers to planning the robot's joint position information (that is, the motion trajectory) during operation, which is usually expressed in the form of time series and angles. It is necessary to ensure the continuous smoothness of position, velocity and acceleration and prevent oscillations and shocks. According to the time series of the motion trajectory, it can be divided into offline, online and hybrid gait planning. Offline gait planning is suitable for algorithms with a large amount of computation and cannot be controlled in real time, such as neural network learning and gait database planning strategies. Online gait planning is more suitable for gait estimation and cooperative motion control.

Hybrid gait planning combines the advantages of offline and online gait planning, but there are still many problems to be solved, which should be the focus of attention in the future. According to the generation method of the motion trajectory, it can be divided into anthropomorphic gait planning, model gait planning and intelligent gait planning. First, an anthropomorphic gait planning method uses the gait motion data of both legs as the basis of gait planning, then compensates and modifies according to individual difference factors, and finally plans a gait trajectory suitable for the user. However, everyone's bone size and gait parameters are different, so the gait data designed by an anthropomorphic motion planning method are not universal. A model gait planning method simplifies the human–robot integration system into a general model and then calculates a gait trajectory according to the user's personal height and weight data as the input of the model. These are commonly connecting rod and inverted pendulum models. However, this method sets too many assumptions, and although the planned gait data are stable, wearing comfort is lost. An intelligent gait planning method has a strong adaptive ability, such as neural network algorithms, differential evolution algorithms and iterative learning algorithms, but it requires high computing power for the bottom-level controllers, and has obvious limitations in the case of control costs or limited computing resources.

In the aspect of gait synchronization (namely, gait switching), there are two main strategies: one is a triggered cooperative strategy, and the other is a walking adaptive strategy. A triggered cooperative strategy is a widely used scheme that triggers decomposing a single gait or complete continuous gait according to the human body state. In addition to the form of directly using buttons to trigger the gait, a Finite State Machine (FSM) is a more common method to switch different control strategies for different motion states of the human body. However, it is difficult to maintain continuous FSM method control quantity in the switching process, and it is easy to make the system enter a critical or unstable state, causing discomfort for the user. Moreover, this method heavily depends on the accuracy of the system's recognition of the body state. The incorrect recognition of the body state will lead to the incorrect switching of the step control strategy and even a fall. For the walking adaptive strategy, a walking speed adaptive strategy, which synchronizes the exoskeleton and the user's body by adjusting the speed of the exoskeleton joint movement, is generally adopted. The synchronization strategy is suitable for the continuous walking gait pattern. For example, Ahmed et al. [203] proposed a step speed estimation model based on a plantar double reaction force sensor and an Adaptive Central Pattern Generator (ACPG) algorithm to control joint trajectory frequency. This is a fusion algorithm of the top-level and middle-level control, which blurs the boundary between human state recognition and expected trajectory generation, avoids the dependence on the established reference trajectory, and realizes the control of the LEEX system through a continuous control strategy. The advantage is that the control process and controller parameters are greatly simplified. However, this strategy requires users to spend a large amount of time to learn and adapt to the motion mode of LEEX; otherwise, it will easily lead to uncoordinated human–robot movements and even hinder the normal movements of users.

Representative pairs of gait planning and gait synchronization strategies are shown in Table 4. In terms of practical applications, the current technology can achieve a stable and reliable fixed gait trajectory for LEEX in medical rehabilitation. However, a fixed gait lacks adaptability and rationality. Blindly using LEEX to force patients to perform predetermined and invariable training trajectories may bring secondary harm to patients. A gait trajectory that can be adjusted according to a patient's wishes is obviously more in line with the actual situation. At present, gait planning is mainly based on offline adjustment, with weak online adjustment ability and poor adaptability to the environment and users. Therefore, it is a key issue in the research of LEEX gait generation methods to design an adaptive online adjustment method for gait trajectories with low learning costs, improve the efficiency of online real-time gait planning, and seek an online adjustment method for smooth and comfortable gait transitions.

5.4 Endurance and Low Carbon Energy Saving

LEEX needs an energy system to provide power, which requires high energy, portability, reliability and safety. At present, battery-powered drive schemes have been widely used in most LEEX designs due to their advantages of low vibration, low heat, high reliability and easy control. However, existing batteries are limited by energy density, resulting in a contradiction of battery volume, quality and capacity selection. To improve the endurance, it is necessary to (1) improve the battery energy and power density and (2) reduce the system power consumption. This is not only the current industry situation faced by LEEX developers but also a bottleneck to be broken through.

6 Prospects

In terms of structure and drive, Chiara Daraio and Yifan Wang [206] proposed a 3D-printed structural fabric based on topologically interlocked granular materials. Its stiffness and strength can be greatly improved through structural changes, and the optimal structure with maximum stiffness can be found using machine learning topology optimization. It also has the advantage of shape reconfiguration: it can be adjusted to an arbitrary shape in a flexible state and then

Table 4 Comparison of gait planning and gait synchronization methods

Time series of motion trajectory	Generation method of motion trajectory	Gait synchronization strategies	Prototypes
Offline gait planning	Anthropomorphic gait planning: Gait database planning	Trigger type, body tilt angle, wrist-watch	ReWalk [67]
	Anthropomorphic gait planning: Preset fixed gait	Trigger type, FSM	Indego [133]
	Model gait planning: Based on inverted pendulum model	Trigger type, button triggered	WPAL [204]
	Intelligent gait planning: Gait database planning, Neural network learning	Trigger type, FSM	ROBIN [205]
	Anthropomorphic gait planning: Center of gravity transfer gait planning	Trigger type, button triggered, FSM	MINDWALKER [71]
Online gait planning	Anthropomorphic gait planning: Healthy leg trajectory, Posture coordination motion control	Adaptive type, kinesiological information from the nonparetic leg	HAL's single-leg version [82]
Hybrid gait planning	Anthropomorphic gait planning: Gait database planning, Gait estimation	Adaptive type, ground reaction force	HAL's two-leg version [81]

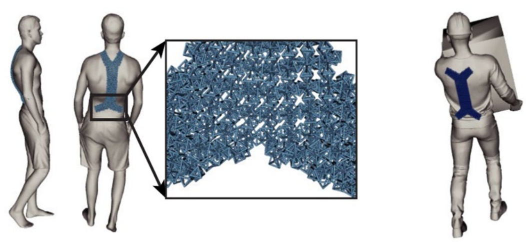


Fig. 17 Tentative ideas on the application of structured fabrics in LEEX

fixed to the shape through a jamming phase transition and the stiffness can be adjusted with controllable impact resistance. Structural fabrics are expected to be widely used in LEEX in the future, as shown in Fig. 17. In addition, modularization and reconfiguration are also important trends to improve the universality of the mechanical design of LEEX [207]. In the future, the configuration and reconfigurability mechanism can be studied, a human–exoskeleton system dynamics model can be established based on body stiffness characteristics, human–robot error and compensation can be carried out, and high-precision low-level control methods can be explored. At the same time, to improve the energy utilization efficiency of LEEX, an efficient drive can be designed in the future based on human–robot energy flow characteristics and energy storage components.

In terms of HRI, the interaction between the human–robot and the environment is mostly when the user obtains environmental information and then transmits the motion intention to the robot through HRI. There are few ways for LEEX to interact with the environment. At present, only plantar pressure perception is widely used to evaluate the walking support phase and swing phase. However, it is rare for LEEX to perceive and store fine environmental information autonomously for real-time calculation and path planning. In the future, LEEX could obtain environmental information that humans cannot directly obtain from their senses and expand or replace human perception through interactive methods such as intelligent dialog, visualization and sensory stimuli. In addition, human perception and cognitive ability could be integrated for decision-making, strengthening human-centered interaction, and improving the robustness of the man–machine system to avoid security risks. This is the concept of hybrid-augmented intelligence with human-in-the-loop [208]. At the same time, it is more important to make it more friendly and become an intelligent "partner" of mankind, not just a machine that is operated, which will be of great help to special groups such as the disabled.

In terms of gait planning, for people with lower limb dysfunction do not have enough leg strength to cope with emergencies. They need to use crutches to support their upper limbs to maintain the balance of the human–robot system. We should focus on the impact of gait generation and adjustment methods on the stability of the human–robot system to avoid safety accidents caused by its instability. However, most current gait generation and adjustment methods pay insufficient attention to system stability, and gait planning methods based on the center of gravity transfer sacrifice walking speed, so they are not practical. Therefore, future research should be extended to the judgment of the environment. Artificial intelligence technology is used to assist in planning travel routes and joint trajectories, such as control mode switching and dynamic stability prediction of landing points in different scenarios such as stairs, rugged roads, uphill and downhill. It is used as a safety guarantee for the stability of the human–robot system in multiple scenes. Furthermore, stable and naturally assisted locomotion by incorporating musculoskeletal models directly into a multidomain gait generation process [209] is also a future focus direction.

In terms of the control strategy, the current research focuses on the accurate identification and planning integration of top-level and middle-level controllers, as well as the rapid response and accurate tracking of bottom-level controllers, while the new research breakthroughs focus on the development of intelligent control algorithms. Torvi et al. [210] used a deep learning algorithm to predict the symptoms of Freezing of Gait (FOG) for Parkinson's disease patients in advance and further studied the performance of an adaptive (transfer learning) algorithm to address the differences between different patients to develop a better prediction model for specific patients. Tucker et al. [49, 211] developed the human-in-the-loop gait learning algorithms COSPAR and LINECOSPAR for the Atalante LEEX. The algorithms use human walking preference as feedback. The LEEX gait is optimized to improve user comfort by learning individual users' gait preferences in high-dimensional gait parameter space. In the future, a larger dataset can be used to train a gait controller to customize LEEX comfort. Li et al. [212–214] used a new barrier energy function in the design of the control strategy, where the human–robot manipulation space is reformulated as a human-voluntary and a robot-constrained region. Thus, constraining the lower limb motion of the user to a compliant region around desired trajectory. And by designing an adaptive controller, a smooth motion transition can be achieved between the human and robot regions. In the future, control strategies that consider the patient's active motor awareness and guarantee safety will be further developed to allow patients to truly walk independently without crutches or other external stabilization tools.

In terms of overall power consumption and energy endurance, two ways to improve endurance are mentioned in Sect. 5.4. The first point is to increase the energy and power density of the battery, and the second point is to reduce the system power consumption. For the first point, replacement of spare batteries can be adopted to ensure endurance, but it is very inconvenient for patients with mobility difficulties, so the essence needs to rely on the breakthrough of high energy density power supply technology. The second point is that it is relatively easy to realize at present, such as developing intelligent energy management algorithms, energy-saving control technology and energy recovery technology [215]. However, it depends on the model accuracy of the battery. Therefore, in the future, on the one hand, the battery model complexity should be constantly updated to improve the accuracy of the model; on the other hand, the influence of temperature, self-discharge current, external interference and other factors on the power consumption of the system should be considered to improve the energy consumption ratio.

In addition to the material, structure, drive, HRI, gait planning, control strategy, energy endurance and other aspects mentioned above, the LEEX data and system supporting software are becoming increasingly important because as a human-centered robot from the perspective of users, it is inevitable to continuously optimize user experience in the future. Especially for medical scenarios, the data-based system software of LEEX can not only present movements such as balance and gait training in 3D but also process and collect the feedback information of gait symmetry and posture with the help of cloud analysis tools to continuously optimize its compensatory gait mode. An intelligent rehabilitation system that can adjust adaptively with changes in patient motor function and rehabilitation needs, as well as LEEX with self-learning ability and multifunctional treatment, which integrates physiotherapy functions such as electrotherapy, phototherapy, massage, acupuncture and cupping, is the development direction of the future medical rehabilitation LEEX system. However, it is difficult to obtain many patients' data with different diseases and different degrees of disease, so more time and effort are needed to improve the data in the future. At the present stage, it is urgent to develop a data center with intelligent LEEX development that can not only be upgraded with the accumulation of data but also allow medical personnel to intervene in knowledge to realize the effective integration of data and experience and provide a basis for LEEX evaluation and patient rehabilitation evaluation.

7 Conclusion

LEEX can not only enhance human function, but also have great significance to help tens of millions of people with lower extremity dysfunction to regain lower extremity locomotion functions. Although the existing research achievements of LEEX are remarkable, it still cannot achieve human–machine integration or HRC, nor can it assist human movement smoothly and freely. LEEX still has limitations in material, structure, actuation, interaction, planning, control, energy endurance, software, and data. In order to break through the performance limitations of LEEX, researchers should explore the humanized (bionic) design basis of LEEX from multidisciplinary research achievements such as biomedicine, bionics, materials science, engineering, robotics, and artificial intelligence. And through the leading engineering technology to better reproduce the biological characteristics of human lower limbs, until the perfect match. Meanwhile, researchers should also explore the way of human–machine integration and HRC.

It is of great research significance for improving the performance of LEEX for assisted locomotion. In this paper, the design development history and related engineering technology research status of LEEX for assisted locomotion are introduced. The key challenges limiting the performance of LEEX are summarized. It aims to provide some references for researchers working on LEEX for assisted locomotion. First, the LEEX research evolution process is explained in detail, typical products and state-of-the-art prototypes are introduced. Second, the key LEEX system technologies are analyzed, such as bionic structure, driving characteristics, HRI, intent-awareness, control strategy and efficiency evaluation. Finally, the research problems and current challenges are described, research trends related to the challenges are prospected, and some feasible solutions are given.

Acknowledgements We wish to express our gratitude to the participants who took part in this article.

Author contributions SQ: conceptualization, methodology, writing—original draft. ZP: discussion, funding acquisition, and supervision. CW: discussion. ZT: discussion, funding acquisition, supervision, and writing—review and editing.

Funding This work is supported by the National Basic Research Program of China (Grant No. 2016YFC0802700) and the National Natural Science Foundation of China (Grant No. 50975010, Grant No. 51075017).

Data Availability Statement Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval Not applicable.

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