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Review

Exoskeletons in the context of soldiers: Current status and future research trends

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ABSTRACT

Modern military drills and conventional training, performed under all-weather conditions, impose exacting challenges on soldiers. This has motivated the development of exoskeleton robot systems, leveraging advanced technology and material innovation. These systems have demonstrated their effectiveness at assisting movement, enhancing protection, promoting rehabilitation, and providing comprehensive support to soldiers. This groundbreaking technology not only reduces a soldier's physical exertion significantly but also effectively diminishes the risk of injury during training, infusing new vitality into the enhancement of military capabilities. Different types of exoskeleton robots differ in their focus. Lower-limb exoskeleton robots are designed to increase the soldier's endurance. Upper-limb exoskeleton robots enhance strength. This paper provides a detailed explanation of the key technologies of various types of exoskeleton robots, covering their mechanical design, electromechanical transmission structures, sensors, and actuation methods. It also explores the diverse application scenarios of exoskeleton robots in the military field, systematically introducing their development trajectory, milestone achievements, and the cutting-edge technologies currently employed, as well as the challenges faced. The conclusion offers a prospective discussion of future development pathways, anticipating the broad prospects for exoskeleton robots in the military domain.

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1. Introduction

The exoskeleton is a common structure found in nature. It is composed of chitin, which covers the exterior surface of various animals. Its function is to provide protection, support, and mobility [1,2]. The analogous exoskeleton robots discussed in this paper are designed for human use and constitute an advanced wearable robotic technology. These biomechanically inspired systems replicate human musculoskeletal functionalities by employing advanced alloy-polymer composites to deliver three operational modalities: support augmentation, strength amplification, and motion facilitation [3]. Their actuation mechanisms combine precision electromechanical drives featuring hydraulic transmission systems to optimize human-machine power coupling via innovative linkage designs [4].

The variety of available exoskeleton robots has grown with technological advances and driven by increasing military demands. These robots can be classified as single- or multi-joint, based on the number of actuated joints they contain [5]. Single-joint exoskeleton robots are relatively simple, mainly providing support for the hip, knee, and ankle joints (e.g., ALEX II, MIT Knee Exoskeleton Robot) [6–8]. In contrast, multi-joint exoskeleton robots not only demonstrate superior assistance effectiveness and capabilities; they also have numerous important applications, e.g., military, aerospace, industrial production, construction operations, fire rescue, and rehabilitation therapy [9]. These multi-joint exoskeleton robots face more complex technical challenges than single-joint robots, particularly regarding structural design, action mechanisms, gait perception, and control strategies [10, 11].

In high-intensity, fast-paced, and complex all-weather military training scenarios, individual soldiers require high mobility, strength, and adaptability. The advancing modernization of military equipment therefore motivates a parallel development of exoskeleton robot technology. This technology enhances a

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soldier's load-bearing capacity and endurance, provides protection in extreme environments, and improves tactical adaptability and decision-making when integrated with intelligent systems. These advantages improve task performance capabilities, reduce training risks, and increase operational efficiency.

1.1. Background

Exoskeleton robots have evolved rapidly thanks to technological advances, with significant breakthroughs in mechanical structure, materials, actuation, transmission, and human-machine interaction interfaces. These improvements have enhanced their operational practicality and system reliability. Exoskeleton robots play crucial roles in tactical operations, logistical support, and emergency rescue missions. In terms of cutting-edge technology trends and military strategic needs, exoskeleton robotics has become an important research area. For example, Zhang et al. [12] used innovative wearable soft-sensor technology to monitor joint movement angles and verified its effectiveness at assisting human-machine interaction. Yan et al. [13] reviewed motion-enhancing orthoses and exoskeleton-robot assistance strategies, summarizing trends and discussing challenges. Gopura et al. [14] traced the development of active upper-limb exoskeleton robots, highlighting key progress. Shi et al. [15] evaluated human gait analysis research and compiled new developments in lower-limb exoskeleton robots. Plaza et al. [16] comprehensively reviewed commercial exoskeleton robot technologies, detailing features and commenting on successes and shortcomings.

1.2. Contributions and article structure

We first present an extensive literature review as a preliminary to a comprehensive understanding of the trends and developments in exoskeleton robotics. Existing review articles often focus on exoskeleton robots used for commercial or medical rehabilitation purposes. This paper extends this scope by systematically discussing military exoskeleton robots, covering their types, evolutionary history, mechanical structures, and the latest sensing technologies. We trace the innovative development of exoskeleton robots from their inception to their maturity, detailing each milestone. We first consider basic single-joint assistive exoskeleton robots and then complex full-body support exoskeleton robots. Complementing the numerous reviews available in the literature, this paper aims to provide a comprehensive coverage of various types of exoskeleton robots. We integrate critical information regarding control strategies and mechanical structures into a single document and survey the latest advances in exoskeleton robotics. The aim is to give readers a holistic perspective on exoskeleton robot development from an academic standpoint. The structure of the article is shown in Fig. 1: Chapter 2 considers the theoretical foundations of exoskeleton robot technology. Chapter 3 reviews the development of exoskeleton robots, highlighting the most significant landmarks. Chapter 4 explores current technological frontiers and future development trends. Finally, a summary and conclusions are given in Chapter 5, suggesting directions and insights for future research.

2. Exoskeleton robotics

Individualized exoskeleton robots constitute a prominent technological achievement. Their concept stems from the principles of human exoskeleton bionics, which seamlessly integrates mechanics with biology to create sophisticated integrated equipment. Through ingenious mechanical design and an efficient drive and transmission system, an exoskeleton robot combines human intelligence with the powerful propulsion functionality of the mechanical exoskeleton, thereby significantly enhancing a soldier's strength, endurance, and agility [17]. Furthermore, its intelligent motion assistance system significantly improves the soldier's operational efficiency. An individual exoskeleton robot must possess a high degree of freedom (DOF) and flexibility to meet the various needs of its user and adapt to the complexity of movement in various environments. For instance, a pioneering example is the BLEEX lower-limb exoskeleton robot, developed by Berkeley Bionics, illustrated in Fig. 2 [18]. It features fourteen DOFs, with seven on each leg. The hip and ankle joints each provide three DOFs whereas the knee joint provides one. Equipped with a hydraulic drive system and more than forty sensors, the exoskeleton robot can monitor its position, posture, and joint forces accurately in real time. This ensures control precision and a high-performance operation.

2.1. Design of flexo-rigid coupling

Hybrid rigid–flexible structural design is fundamental for exoskeleton robots. Traditional rigid joint structures in exoskeleton robot designs fail to fully meet the dynamic adaptation requirements of the many complex human body movements. A flexible design concept is needed to achieve a harmonious coupling between the exoskeleton robot system and a human knee joint. This allows the synchronization of the robot with body movements to assist complex and diverse body movements naturally and efficiently.

Flexible textile materials are favored for their light weight, high flexibility, and outstanding resilience. Incorporating shape memory alloy technology to regulate material stiffness [19] enables a precise fit to a soldier's individual physical characteristics. This ensures comfort of use, durability, and a good integration with training uniforms and combat gear. Moreover, the combination of flexible textile materials with liquid bulletproof armor technology has yielded a new composite material. This fusion capitalizes on soft and thin features, creating a lightweight, highly mobile, and well-protective flexible exoskeleton robot system for soldiers' comprehensive body protection.

Traditional rigid-material exoskeleton robots encounter substantial practical challenges under extreme training and exercise conditions. These include their high self-weight, their high inertia, and difficulties of maintenance and repair [20], all of which impede their deployment and application. In this context, titanium alloy materials, known for their outstanding mechanical properties, have been widely used in aerospace and national defense military applications. Titanium alloy exoskeleton robots feature a strong structure, a high level of rigidity, and a lightweight design, hence meeting the strict design standards for military exoskeletons. Moreover, the dense titanium oxide film on the surface of titanium alloys conveys excellent corrosion resistance, preventing the corrosion of its parts, inhibiting bacterial growth, reducing the risk of post-injury infection, and enhancing safety [21].

Muscles play an essential and varied role in human movement. To mimic this biomechanical complexity, bionic principles are used for selecting biomimetic materials such as leaf springs, tension springs, and pneumatic muscles for fabricating energy-storage elements that approximate real muscle performance [22]. The stiffness coefficients of these elastic elements are important parameters for ensuring that the energy storage device recovers effectively and releases the wearer's kinetic energy. Material selection thus requires precise balancing to avoid suboptimal performance or discomfort [23].

The nonlinear relationship between muscle strength and contraction length in the human body [24] makes the assistive effects of traditional energy storage springs insufficiently refined. Despite the similarity of pneumatic muscles with human muscles,

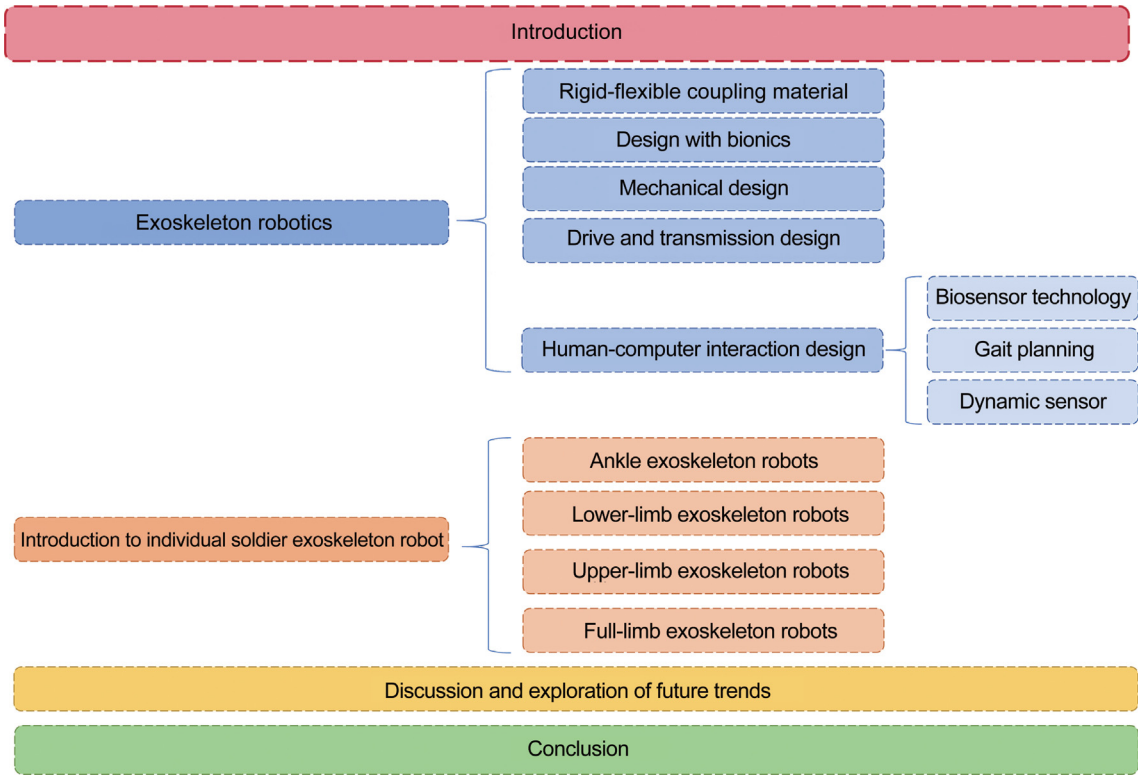

Fig. 1. Overall structure of the review.

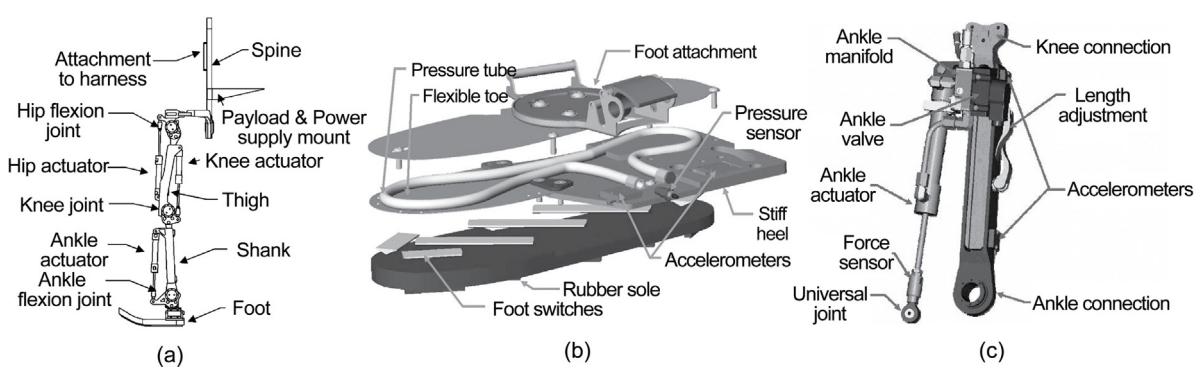

Fig. 2. Mechanical design of the BREEX: (a) Major components of the BLEEX Model. (b) BLEEX foot design. (c) BLEEX shank design. Reproduced with permission from [18].
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their assistive performance remains to be optimized. A key strategy for improving assistive effects is therefore to design spring elements that match human muscle characteristics, or to combine various energy-storage elements to achieve rapid nonlinear energy release and storage.

Pneumatic artificial muscles are regarded as valuable actuating elements for exoskeleton robots owing to their light weight, high energy density, and reliable structural design. This propulsion mode enhances the coupling between the system and the wearer as well as safety by reducing the injury risk associated with traditional driving methods [25]. However, limitations of traditional pneumatic artificial muscles include their volume, contraction rates, and manufacturing complexity, which therefore precludes large-scale industrial production. Novel flat pneumatic artificial muscles (integrating contraction layers, constraint layers, and air bags, and precisely manufactured via laser-cutting technology) optimize the production process, boost efficiency, and guarantee usability and safety, emerging as the best choice for light-weight powered exoskeleton robot actuators [26].

2.2. Bionics theory of exoskeleton robots

The anatomical structure of the human upper limb is complex. It encompasses delicate parts such as the shoulder and elbow complexes, the wrist joint, and the fingers. The shoulder complex, a key dynamic module, consists of the sternum, clavicle, scapula, humerus, and multiple joints (sternoclavicular, acromioclavicular, glenohumeral, and scapulothoracic) [27,28]. The glenohumeral joint is stabilized by the thoracic cage and displays a large range of motions. In biomechanical modeling, the shoulder complex is often simplified as a ball-and-socket joint model, where the glenoid fossa's articular surface covers only one third of the humeral head's surface. This allows the humeral head to rotate in three planes: abduction/adduction, flexion/extension, and internal/external rotation (Fig. 3) [29]. Significantly, the instantaneous

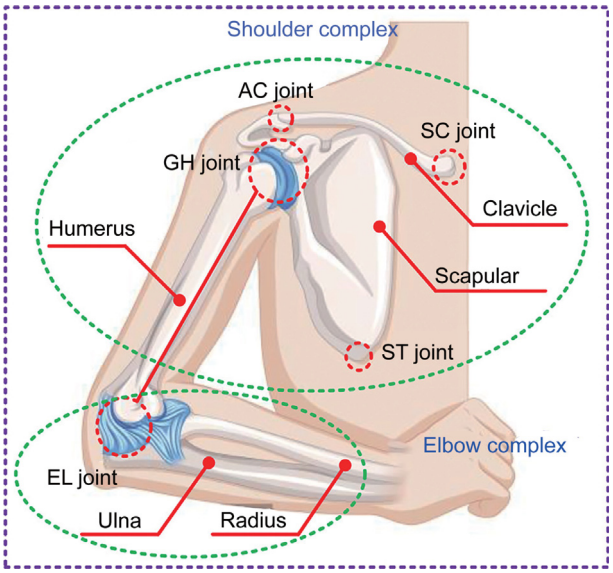

Fig. 3. Glenohumeral joint motion. Reproduced with permission from [29]. ©2020 Elsevier Ltd.

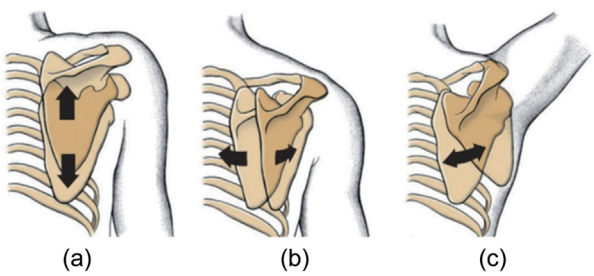

Fig. 4. Scapular movement: (a) Up and down. (b) Lead forward and shrink back. (c) Top spin and backspin. Reproduced with permission from [30]. © 2023 licensed under CC BY-NC-ND 4.0, Journal of Mechanical Transmission.

center of rotation (ICR) of the shoulder joint is dynamic, adjusting to the upper arm's position (Fig. 4) [30]. The ICR is a point around which other points rotate in a specific instantaneous plane, and is essential for understanding the shoulder joint's kinematic mechanism.

The arm section is a fundamental component in the design of upper-limb exoskeleton robots. It is not only key for performing complex tasks but also plays a central role in force transmission and precise control [30]. As a bridge between the shoulder and the hand, it supports, manipulates, and exerts force [31]. In upper-limb exoskeleton robots, the precise design and efficient driving mechanisms of the arm section can enhance the user's motor capabilities, reduce labor intensity, and improve operation accuracy and stability [19]. By optimizing the arm section, exoskeleton robots adapt better to their work environments, meet industry standards for efficiency and quality and provide strong support for arm laborers [14,32] (Fig. 5(a)) .

The elbow-joint complex is a key component of the upper-limb movement structure. It comprises two core joints: the elbow and radioulnar joints [33]. It consists of the humeroradial joint (between the humerus and radial head) and the humeroulnar joint (formed by the humeral trochlea and the ulnar trochlear notch). The elbow joint complex has two main DOFs flexion/extension and pronation/supination, which give the upper limb a wide range of movements and a high flexibility [33,34](Fig. 5(b)).

The core of the design of lower-limb exoskeleton robots lies in the precise configuration of their leg DOFs, which allows the accurate tracking of the user's movements while minimizing their perceived motion restriction [35]. To achieve this function, the design of the exoskeleton robot leg should match the DOFs of the human leg to simulate the natural movement patterns of the human body more effectively. This is illustrated in Fig. 6(a) for the human leg structure.

The human hip joint is a ball-and-socket joint with three DOFs and a wide range of motion (Fig. 6(b)). The knee joint, a complex structure, involves rolling and sliding between the femur and the tibia. Its center of rotation varies with flexion angles (Fig. 6(c)) [35,36]. Despite having three DOFs, the knee has a smaller range of motion than the hip [37]. Clinical gait analysis identifies the sagittal-plane movement of the human lower limb as defining the basic pattern of motion [38]. While walking, the flexion and extension of the hip and knee support the body weight and generate propulsion, while ankle flexion and extension provides the key torque generating forward movement (Fig. 6(d)). To ensure the flexibility and maneuverability of exoskeleton robots and to achieve a high movement synchronization, the ideal leg design should implement all the seven DOFs of the human leg [39,40].

2.3. Exoskeleton robot mechanical design

An ideal exoskeleton design should concentrate or evenly distribute the device's mass at the wearer's waist. This is a consequence of the tight-fitting nature of exoskeleton robots and of the lower energy expenditure at the waist compared to the lower leg when carrying a given mass [41,42]. Moreover, design complexity may limit the freedom of movement in the lower-limb.

During daily training, soldiers often carry firearms or heavy equipment for long periods of time, which causes significant upper-limb fatigue. To address this, an innovative passive wearable device was proposed (Fig. 7(a)) [19]. It uses a gravity-compensation mechanism to assist arm movements and reduce fatigue (Fig. 7(b), 7(c)). The gravity-compensation module is based on a precise six-bar linkage mechanism (Fig. 7(d)), which combines a crank-slider linkage with a pair of rotating-rotating double axes to form a precise motion transmission system [19]. A linear spring is installed between the base and the slider. When the six-bar crank experiences an external torque, the spring's compressive force generates corresponding resistance torque, effectively compensating for gravity. This design leverages the spring's mechanical properties to assist arm movements and shows great potential for reducing operator fatigue [43,44].

When handling heavy objects, the arm's effort involves the coordinated movement of multiple muscle groups from the upper arm and forearm to the shoulder, such as the biceps brachii, triceps brachii, and shoulder muscles [45,46]. Based on the biomechanical characteristics of the human shoulder and elbow joints, a four-DOF exoskeleton system was developed (Fig. 8(a)) [34]. Its design considers the shoulder joint's internal and external rotation, abduction, forearm adduction and abduction, and elbow-joint flexion and extension. The system aims to mimic natural upper-limb movement patterns, enhancing the human–robot interaction efficiency and comfort while reducing physical strain during lifting.

During an arm-raising motion [32], the scapular moves to elevate the humeral head (the shoulder joint's rotational center) by approximately 10 mm (Fig. 8(b)), indicating that human joint rotational centers are dynamic. Ergonomic exoskeleton robot design must therefore consider these anatomical variations. The exoskeleton's shoulder joint has three DOFs. The intersection of the first two aligns with the human shoulder's rotational center, but the third is offset, causing up to 80 mm of motion error-equivalent to the shoulder joint's diameter and to the distance to its center. To correct this, Liu et al. [20] designed a support

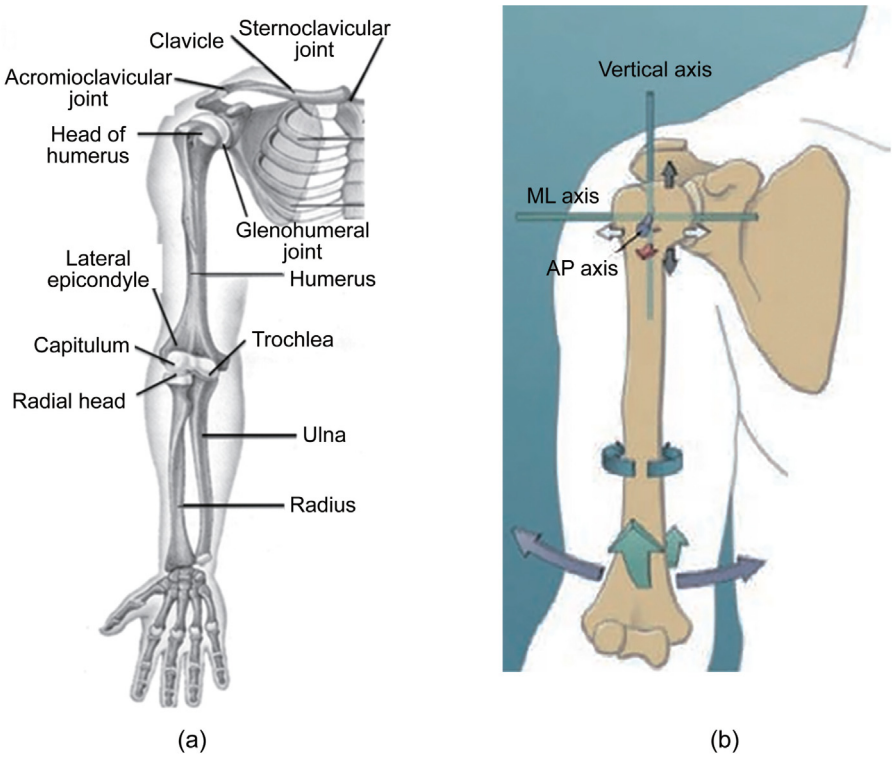

Fig. 5. The structure of the upper limb joints in the human body: (a) Anatomical diagram of arm structure. Reproduced with permission from [14]. ©2016, licensed under CC BY 4.0, Elsevier B.V. (b) Human shoulder joint structure. Reproduced with permission from [34]. © 2016 IEEE.

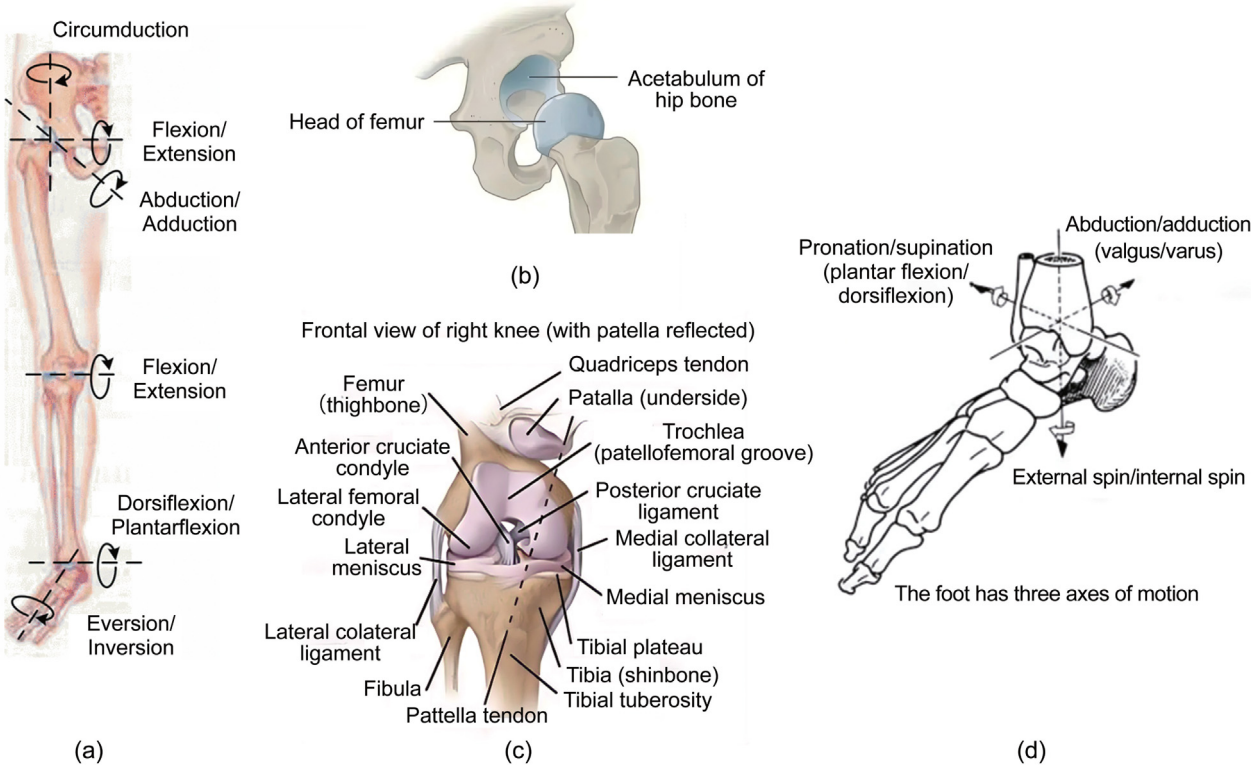

Fig. 6. The structure of the lower limb joints in the human body: (a) Leg joints. Reproduced with permission from [40]. (b) Hip-joint structure. (c) Knee-joint structure. (d) natomical diagram of ankle joint structure. © 2015 IEEE.

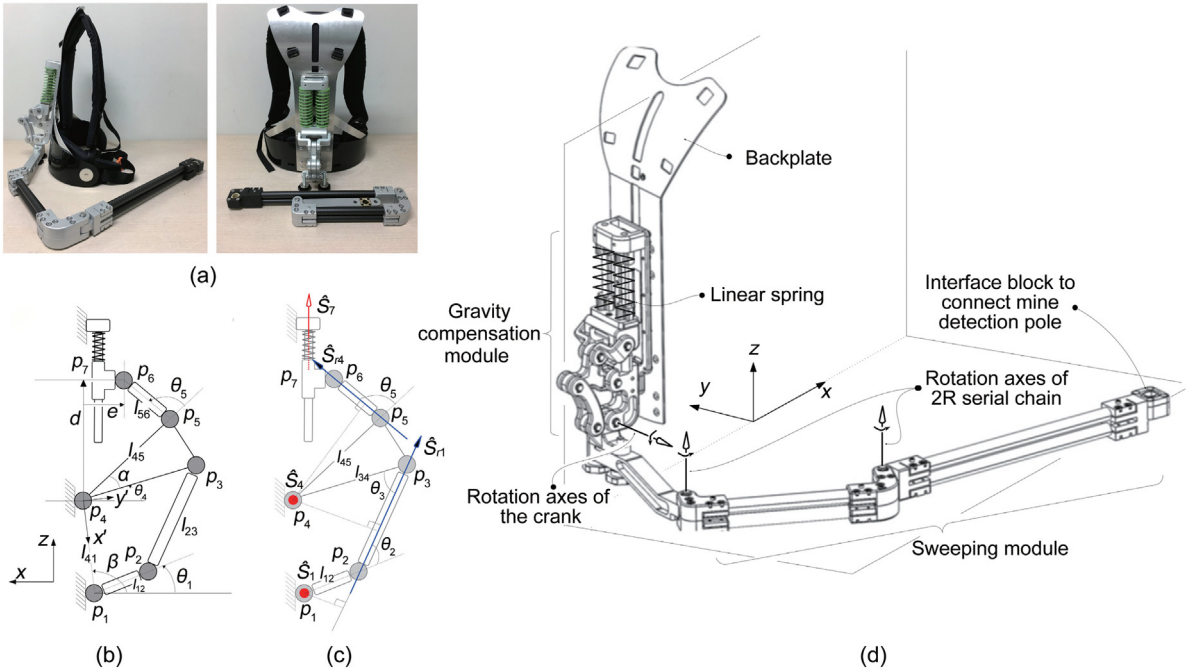

Fig. 7. Exoskeleton robot with gravity compensation: (a) Forearm auxiliary device. (b) Parameters for the kinematic analysis of the module. (c) Screws for the force analysis. (d) Auxiliary mechanism of forearm. Reproduced with permission from [19]. ©2023, licensed under CC BY-NC-ND 4.0, The Authors.

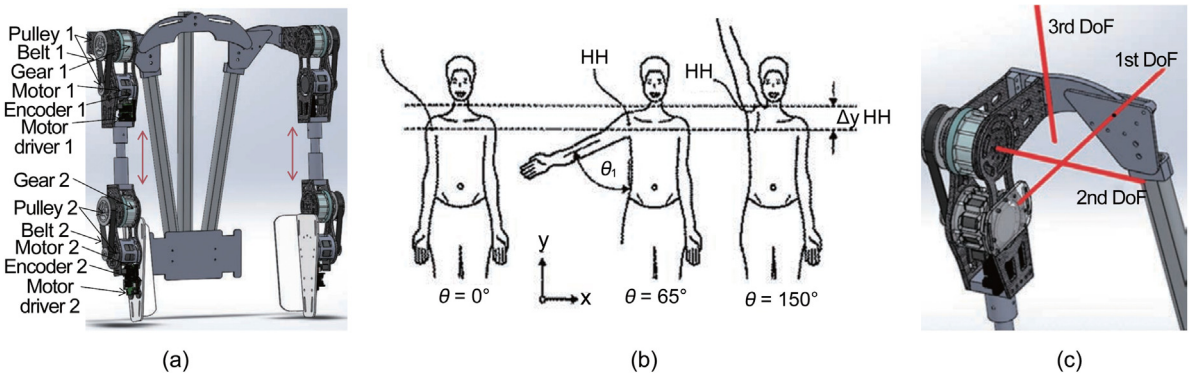

Fig. 8. Four-degree-of-freedom exoskeleton robot: (a) Shoulder exoskeleton robot. (b) umeral head movement. (c) Mechanical structure of exoskeleton robot. Reproduced with permission from [34].
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mechanism (Fig. 8(c)) that rotates around a support point, allowing up to 90-100 mm displacements in the horizontal and vertical directions. The exoskeleton uses belts and shoulder straps to reduce weight and improve wearability, thereby ensuring comfort and stability.

To enhance safety and reduce contact and collisions with the environment and their operators, lower-limb exoskeleton robot mechanisms adopt deeply anthropomorphic strategies. This design philosophy ensures a high-level functional fit between the exoskeleton robot and the human lower limb, complementing natural human movements [47].

In human walking, the knee joint plays a fundamental role in transmitting the body weight to the ground. It therefore sustains significant pressure (Fig. 9) [40,48]. To relieve knee-joint pressure, the exoskeleton robot system should support both the human and its own weight. The human lower limb can be modeled as a six-DOF joint system (Fig. 10(a)), with the hip serving as a ball joint, the knee enabling flexion and extension, the femur-tibia displaying rolling and sliding motion [20], and the ankle movement mainly lying in the sagittal and frontal planes [47]. Sang et al. [49,50] developed the XoR2, a hybrid-driven lower-limb exoskeleton robot platform (Fig. 10(b)) based on the XoR platform. It features 14 precisely controlled joints, six of which are powered flexion-extension joints. These joints use artificial muscles and servo motors to compensate for gravity and coordinate with external forces, thus ensuring normal user walking and enhancing the exoskeleton robot's performance and practicality.

The design of exoskeletal joints for human hip and ankle joints can include both passive and quasi-passive joint technologies. In daily applications, the exoskeleton robot's ankle mechanism, similarly to the human ankle, is essential for connecting the wearer to the robot and for supporting both the wearer's cargo and the robot's weight [51]. Many studies use high-elasticity passive ankle-joint designs made of ultra-high-performance carbon materials capable of bearing a weight equivalent to the entire upper limb. This design enables the wearer to store energy during the swing, stance, and heel-rise phases of walking through the ankle joint's elastic deformation and to release it when required, thereby providing natural walking assistance.

Recent research has shown that the ankle joint in exoskeleton robot systems no longer depends solely on actuators, and that

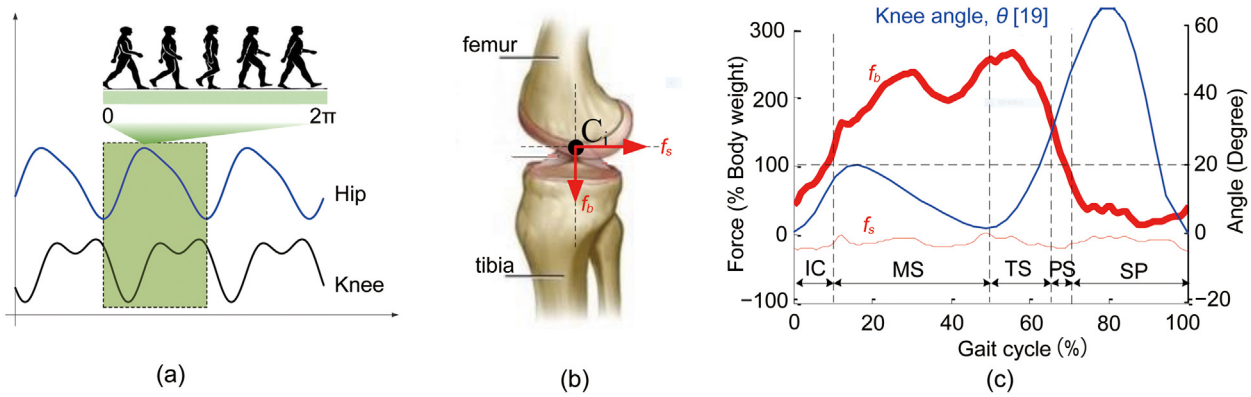

Fig. 9. Force on the knee joint:(a) Definition of the gait cycle. Based on the hip joint trajectory, a complete gait cycle is divided into [0, 2π]. Reproduced with permission from [48]. (b) Static force model. Reproduced with permission from [40]. (c) Body force model. Reproduced with permission from [40].
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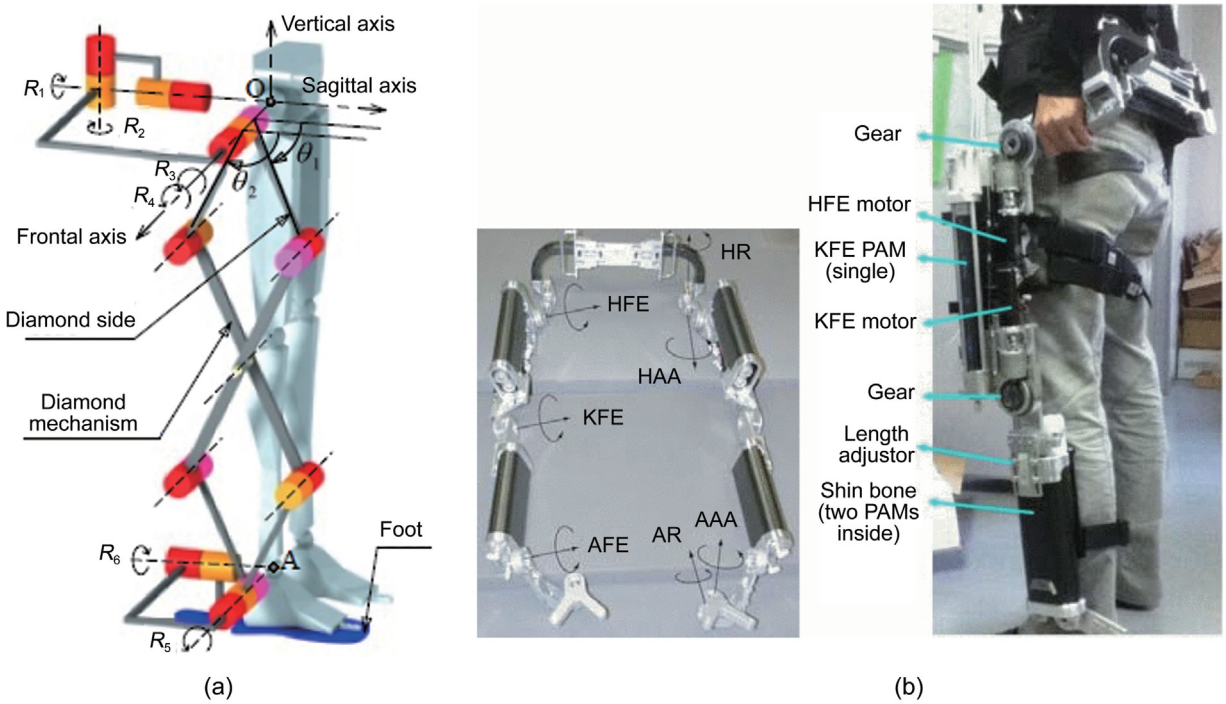

Fig. 10. Lower limb exoskeleton robot:(a) Distribution of freedom of lower limb mechanical structure. Reproduced with permission from [20]. (b) XoR2 mechanical structure. Reproduced with permission from [50].
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its stiffness can sometimes be adjusted. Under underactuated conditions, the ankle joint's elastic adjustment ability is crucial, as it regulates its own range of motion and also that of adjacent passive joints [52]. The multifunctionality of the ankle-joint mechanism in exoskeleton robots is manifested in several ways: it connects the wearer to the robot, transmits the weights of the exoskeleton robot upper-part and of the wearer's cargo to the ground, provides a stable experience through torque restriction or energy conversion, and supports forward momentum during walking, which in turn optimizes the exoskeleton robot's performance and the wearer's walking efficiency.

Lower-limb joint stability is particularly important in the design of infantry exoskeleton robots, especially with regard to the precision of the ankle-joint alignment. This study emphasizes the need to match the exoskeletal ankle module's rotational center with the soldier's ankle joint center accurately to reduce risks and fatigue during tasks. During the stance phase, the exoskeleton robot and its payload are centered around the ankle joint's rotational axis. The displacement of this center requires larger (wider) leg braces to bear the extra load. The increased size and weight produce discomfort to the wearer, widen the step width, and increase the distal mass. As shown in Refs. [53–55], these changes raise the wearer's metabolic energy expenditure and exacerbate fatigue.

To address this issue, Ref. [56] proposed an innovative RCM ankle with three DOFs for military exoskeleton robots (Fig. 11). Using two RRR spherical chains, it ensures that the intersection of the rotation axes of revolute joints aligns with the ankle's rotational center. This innovation enhances the exoskeleton robot's performance, improves the wearer's experience, and supports agile military operations.

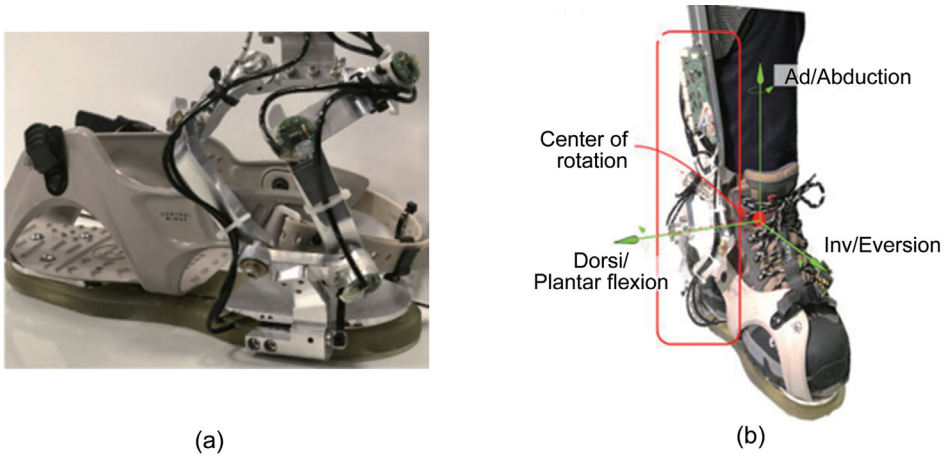

Fig. 11. Ankle joint exoskeleton robot: (a) RCM ankle mechanism composition, Three-degree of freedom ankle joint mechanism of military exoskeleton robot. (b) RCM ankle. Reproduced with permission from [56].
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2.4. Electromechanical driving unit and transmission mechanism of the exoskeleton robot

Exoskeleton robots are classified as active or passive depending on their internal power supply. Active models have built-in power systems that utilize various sources such as electric motors [57–61], pneumatic drives [62–65], and hydraulic drives [66–68] to ensure a stable power output. By integrating bioelectric [69–73] and mechanical signal sensors [74–76], the wearer's motion intentions can be captured and transmitted to the exoskeletal system. With well designed control strategies [77–79], these robots can perform assistive tasks with precision and provide strong motion support to the wearer.

Electrical drive technology, known for its ability to store and deliver energy efficiently, is mainstream in exoskeletal system design. A range of electrical actuators of different sizes are favored for their reliability and precise control [80]. Among them, brushed DC motors are particularly valued for their wide application scope and mature technology, followed closely by brushless DC motors for their efficiency. The preference for brushed DC motors stems from the simplicity of their structure and drive components.

Compared with other motors, brushless motors are particularly reliable owing to their brushless design, lower rotor inertia, and higher power-to-weight ratio, which together ensure outstanding dynamic performance. In exoskeleton robot system design, the careful selection of appropriate actuators with the correct size is crucial for the system to achieve light-weight characteristics and a high responsiveness [81,82].

The core requirement of exoskeleton robot technology is to avoid interfering with the user's natural movements while delivering both comfort and safety. Series elastic actuators (SEA) [83–85] incorporate springs or elastic elements in series with electric actuators to create a compliant user-motor interface. SEAs convert torque or force control into position control based on the deformation of a spring, thus promoting torque-control strategies. They enable smooth force transmission, precise control, low output impedance, better impact resistance, and optimized energy use. They also support reverse driving in human–robot interactions.

Hydraulic drive systems in exoskeleton robot technology offer advantages such as compliance, low joint inertia, and the ability to handle heavy loads. In 2004, the Berkeley Lower Extremity Exoskeleton robot (BLEEX, Fig. 12) was developed, marking a new era of energy-autonomous load-carrying exoskeleton robots [15,86–89]. BLEEX utilized hydraulic actuators for their superior power-to-weight ratio and control bandwidth . This design made BLEEX the first wearable robotic system capable of handling heavy loads with minimal human effort. It employs advanced hybrid control strategies, allowing users to operate with little force, thereby enhancing practicality and user experience.

Pneumatic artificial muscles (PAMs) are prominent in robotic drive technology owing to their unique properties. They offer environmental and safety benefits while introducing revolutionary innovations through their high power density and outstanding compliance [90]. Compared to robots using traditional motors or hydraulic cylinders, compliant PAM-based exoskeleton robots move more naturally and with greater agility.

The actuator unit (motor and transmission components) is a critical constituent of wearable robots. Enhancing the performance of the torque/force control system is therefore a key challenge of exoskeleton robot technology [91]. When choosing actuators for exoskeleton robots, designers must balance demands such as the range of motion, wearer comfort, safety, low inertia, and adaptability [92]. Simultaneously, controllability, the rapidity of response, and smooth motion generation are core requirements for the control system [93–95].

Exoskeleton robots assist users physically by mimicking their movements and applying power in a timely manner [96–98]. In user interaction, they aim to achieve "perceptual transparency" or to generate noticeable interaction forces.

The gear transmission system, a key actuator component, is essential for distributing power precisely between motor torque and speed and for maintaining the balance between external loads and internal forces [99,100].

Scholars working at the forefront of industrial exoskeleton robotics research have proposed using a brushless DC motor-gearbox combination as a core actuator module for back-support exoskeleton robots [101]. Their goal was to optimize the actuator design to improve the performance and applicability of exoskeleton robots. They analyzed the frequency response by taking the human movement speed as the input and the body-applied torque as the output. They examined trunk-flexion torque tracking, permanent magnet synchronous motor currents, and system robustness against external disturbances.

The ankle joint, one of the human body's most heavily loaded and active joints in daily life, presents challenges for exoskeleton robot technology owing to its complex structure [102]. Its center of rotation changes dynamically during movement. To address this issue, some researchers [103] have employed built-in sensors to monitor the movement of the rotation center, to capture the user's movement intentions accurately, and hence enhance the adaptability and functionality of the exoskeleton robot system.

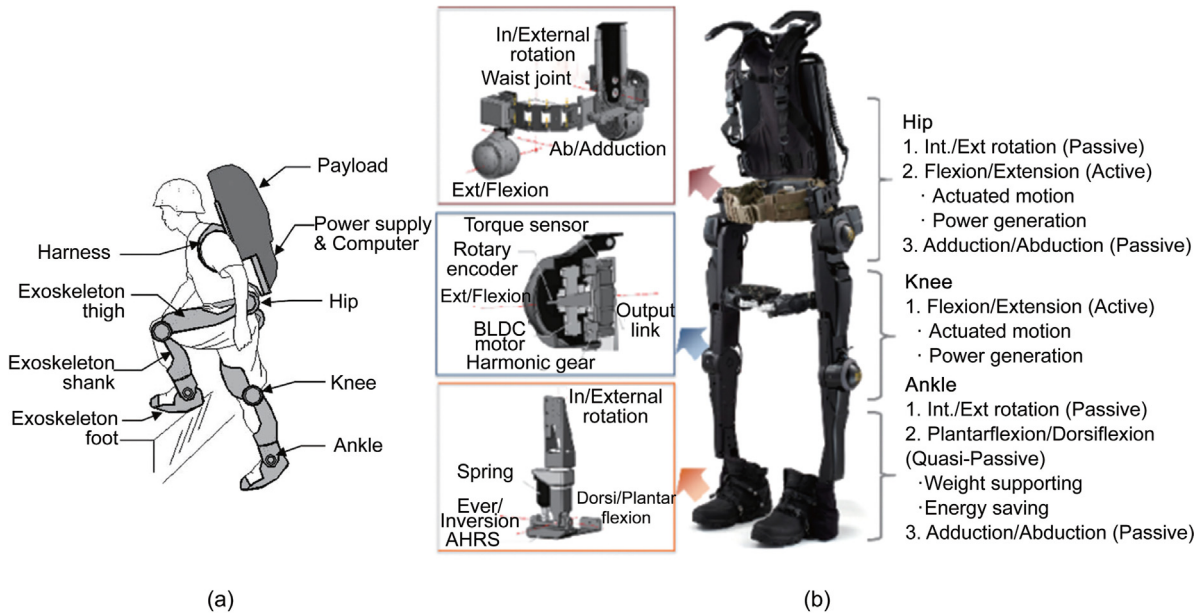


Fig. 12. The Berkeley Lower Extremity Exoskeleton robot: (a) Lower-limb exoskeleton robot concept. Reproduced with permission from [18]. (b) Berkeley lower-limb exoskeleton.
© 2006 IEEE.

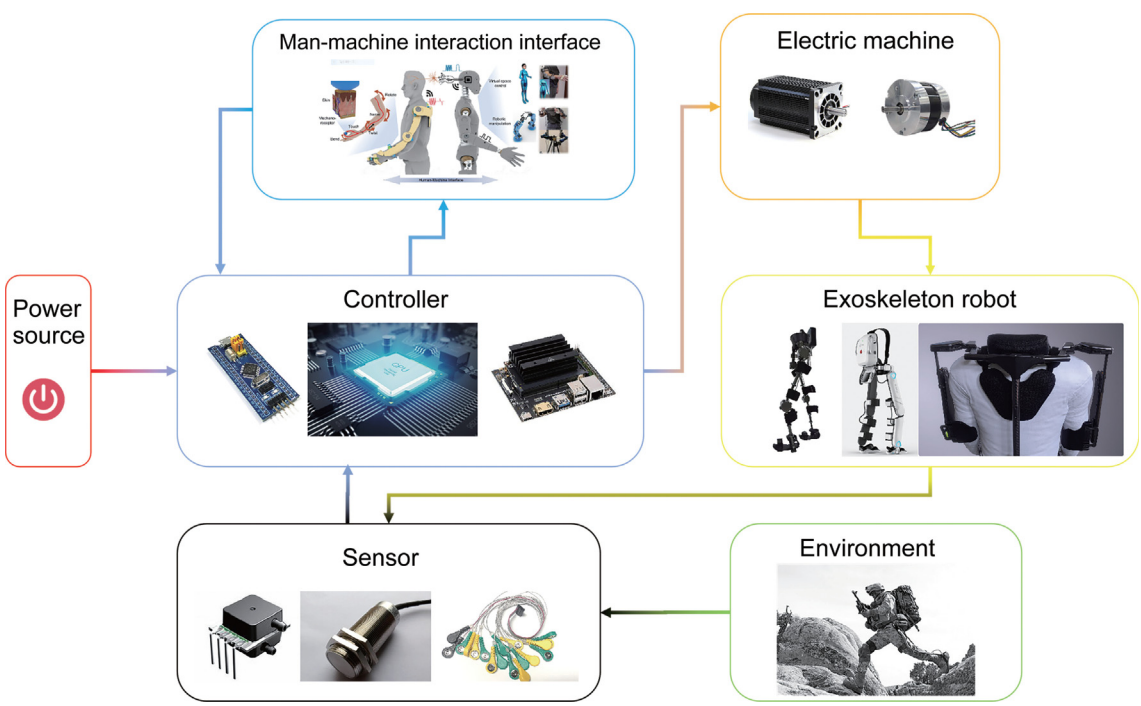


Fig. 13. Overall structure of the exoskeleton robot.

2.5. Human–computer interaction design of exoskeleton robots

In the implementation of exoskeleton robot technology, sensors play a pivotal role in collecting various data related to the robot's interaction with its surrounding environment, including the user, as depicted in Fig. 13. These data are essential for accurately controlling the operation of the exoskeleton robot and form the cornerstone of an intelligent and adaptive system.

The development and testing of lower-limb exoskeleton robots have predominantly focused on laboratory or flat environments under idealized conditions, such as uniform hard surfaces, constant lighting, and in the presence of static obstacles. However, real-world application scenarios are often far-removed from these conditions, which imposes multi-dimensional challenges on the robots' perception, control, and mechanical performance. This urgently demands a fundamental re-engineering of the underlying technological design logic to bridge the gap between theoretical models and practical implementations. Concurrently, upper-limb exoskeleton robots, as another pivotal domain in extending human physical capabilities, face equally pressing challenges with

respect to environmental adaptation (ranging from precision manipulation to strength augmentation) and from confined spaces to dynamic disturbances. This necessitates the achievement of deep integration within complex "human-machine-environment" interactive scenarios.

2.5.1. Biosensor technology for exoskeleton robots

An upper-limb exoskeleton robot must simulate seven or more DOFs in the human shoulders, elbows, wrists, and fingers to perform grasping, rotation, pushing, and pulling actions in confined spaces (e.g., post-disaster rubble or aircraft engine compartments). When handling heavy objects, it must utilize joint torque sensors to adjust driving parameters in real time to prevent user muscle strain or object slippage in response to sudden external disturbances (e.g., cargo shifting or equipment vibrations). Furthermore, upper-limb exoskeleton robots frequently collaborate with external tools (such as surgical scalpels, welding guns, or explosive ordnance disposal clamps) whose weight, inertia, and operational reaction forces significantly affect the system dynamics [104]. When switching between tools of varying specifications, the exoskeleton robot should automatically identify changes in the tool's center of gravity and implement active damping control to mitigate wrist impacts. In confined space scenarios, the system must employ stereo vision systems to identify hazardous objects, plan collision-free arm trajectories, and prevent accidents caused by unintended contact.

Accurately deciphering human motion intentions is a key challenge of "human-machine interaction" technology using exoskeleton robots. In recent decades, biosensor technology has been increasingly used to detect and analyze biological signals such as electromyography (EMG), mechanical signals, and electroencephalograms (EEG). EMG signals have attracted significant attention in academic contexts. Real-time identification of movement intention has been achieved via sophisticated control algorithms, which often employ machine learning classification techniques to improve recognition accuracy [105].

EMG technology detects and analyzes bioelectric signals generated by muscle fiber action potentials during neural excitation, enabling the assessment of muscle function and decoding of motion intent [106]. By recording electrical activity during muscle activation, EMG facilitates the investigation of neuromuscular recruitment patterns and neural system coordination, linking these metrics to kinetic characteristics to elucidate neuromuscular control mechanisms [107].

EMG detects the action potentials of muscle contractions activated by motor neurons and quantifies the activation intensity and dynamics of neuromuscular activity by encoding signals with temporal spectral features [108]. The real-time responsiveness of EMG to neural command transmission allows it to play a crucial role in the human-machine interaction control of exoskeletons [109].

Electroencephalography (EEG) non-invasively records cortical electrical activity by detecting membrane potential oscillations at the synaptic level. These are manifested as brainwave oscillations that reflect functional brain states across cognitive-affective processes (e.g., consciousness, attention, and memory) [110].

EEG detects voltage fluctuations from synchronized neuronal populations via scalp electrodes, which are amplified, filtered, and digitized to generate interpretable oscillatory traces. These signals are categorized into frequency/amplitude-based spectral bands (e.g., alpha, beta, theta, and delta oscillations) [111], representing distinct neural activation states.

EEG enables exoskeleton robot control by capturing cortical neural ensemble synchronization during motor intent generation. Cortical dynamics detected via electrode arrays are processed to extract discriminative spatiotemporal features. These are then algorithmically decoded as kinetic intent signals for use in robotic actuation [112]. Such real-time intention decoding leverages EEG's sensitivity to task-relevant cortical oscillations, enhancing brain-driven human–robot symbiosis through direct neural command translation.

2.5.2. Gait planning for power-limb exoskeleton robots

Gait functionality is central to basic human activities and independent living. Consequently, gait interaction design is a prominent research topic in the context of lower-limb exoskeleton robots [106]. This mainly involves accurate tracking at each stage of walking, evaluating the assistive effects of the exoskeleton robot in real time, and ensuring coordination with human movement [113].

Gait interaction design has three levels: gait generation, gait assessment, and gait control [114]. Gait generation involves constructing gait patterns, parameters, and poses that conform to human physiological characteristics. This process relies on integrating information on the joint actuator state and on the system state, ultimately translating into the end position and joint motion trajectory of the lower-limb exoskeleton robot [115, 116]. Gait assessment integrates sensor signals and, based on the states of the wearer and the exoskeleton robot, comprehensively evaluates the generated gait in terms of performance, safety, and balance. The relevant instructions are then passed to the gait control level [15]. At this level, instructions are converted into actions via joint actuators. Results are then fed back to the generation level, thus creating a closed-loop system for gait interaction design.

Jiange Kou and colleagues [48] developed a multifunctional approach, combining gait planning and cooperative control, based on central pattern generators and RBFNN estimation. This included adaptive backstepping to improve operator comfort and ensure stability across various motion modes. ChengHua Wu's team [117] devised a knee exoskeleton robot system using AEKF-based error fusion. The admittance controller processes interaction forces and trajectory deviations to compute adjustments. AEKF synthesizes sensor-measured and model-estimated errors, producing optimized compensation for motion control. This dual-error strategy improves the tracking accuracy during dynamic human–robot interactions. Jianfeng Ma et al. [118] developed a biomechanical synergy model utilizing a passive exoskeleton robot prototype, optimizing key system parameters by minimizing the average degree of dispersion. They implemented a joint-angle-based dispersion reduction algorithm, achieving a 14.45% average walking assistance efficiency.

In idealized scenarios, gait planning and joint actuation in lower-limb exoskeleton robots rely on pre-trained fixed algorithms, such as symmetrical gait patterns optimized for walking on level ground. However, real-world environments often alternate between irregular terrains (e.g., stairs, slopes, gravel paths, and muddy wetlands) or even combine them in a hybrid fashion (e.g., a slope adjacent to a staircase landing). The exoskeleton robot must therefore demonstrate real-time terrain recognition and dynamic gait generation capabilities.

Lei Sun et al. [119] developed a terrain-adaptive soft exoskeleton robot using sensor-based terrain recognition (flat, sloping, or stair surfaces) and Bayesian optimization. By analyzing heart-rate variability during locomotion, the system dynamically optimizes assistive torque parameters, significantly reducing the user's metabolic costs. Zhang Yan et al. [120] employed learning vector quantization for terrain recognition, established a human exoskeleton robot model, and acquired prior torque information of the knee joint through simulated walking. They designed a data-driven model-free adaptive controller to adjust inputs dynamically in response to real-time terrain changes. This enabled the exoskeleton robot knee joint to provide an appropriate

torque and enhance terrain adaptability. Xu Liang et al. [121] introduced a novel approach for estimating moments in human–robot interactions, which combined the hybrid moving-average autoregressive model with the strong tracking Kalman filter to achieve efficient and swift tracking of sudden moment variations.

2.5.3. Dynamic sensors for lower-limb exoskeleton robots

Dynamic sensors, force/torque transducers, pressure arrays, and inertial measurement units (IMU) are essential for quantifying human–robot dynamics in exoskeleton robots. Piezoelectric sensors enable millisecond-level force monitoring in real-time control systems. Emerging flexible pressure architectures (e.g., pneumatic soft chambers [115]) transduce mechanical interactions via elastomer-mediated pressure fluctuations, with differential sensors achieving 0.1 Pa resolution for precise force tracking through energy conversion dynamics.

Within the exoskeleton robot system, pressure sensors primarily serve to measure and monitor the pressure distribution at the user/robot interface. These sensors monitor pressure changes in real time, providing feedback to the exoskeleton robot to adjust its movements and ensure synchronization with the user's motion and comfort [116].

Force sensors in exoskeleton robots fulfill a tri-functional paradigm: (1) intent decoding by capturing real-time biomechanical signals, where pressure-dynamic patterns infer user motion demands for adaptive robotic actuation [122]; (2) structural diagnostics via continuous load-state monitoring to prevent mechanical fatigue through predictive overload thresholds; (3) biomechanical optimization by quantifying human–robot interface pressures, enabling tissue perfusion analysis and pressure-mediated dermal response modeling for ergonomic design iterations. This functional triad collectively ensures symbiotic safety, control precision, and physiological compatibility.

Torque sensors are fundamental in exoskeleton robot research, facilitating dynamic joint torque quantification through strain-gauge-based transduction. During torque application, strain-indu ced resistance variations are transduced into electrical signals via a Wheatstone bridge circuit, enabling a torque calculation in real time through calibrated voltage-torque correlations [123]. This electromechanical conversion mechanism underpins critical biodynamic analysis, informing joint loading dynamics and adaptive control parameterization in human–robot systems.

IMUs implement multi-sensor fusion architectures (comprising accelerometers, gyroscopes, magnetometer arrays, etc.) for real-time exoskeleton robot dynamics monitoring, achieving 0.1° pose estimation accuracy through exoskeleton robot kinematic signature analysis [124]. These systems enable three critical functionalities: (1) 5-ms-delay motion tracking with <2 mm positional error for navigation precision; (2) dynamic balance control that maintains 98% stability on uneven terrains through adaptive joint torque adjustments; and (3) human–robot interaction enhancement via 98% intention recognition accuracy using neural-network-processed biomechanical signatures, enabling natural assistive responses within a 200 ms latency windows [125,126].

Encoders, as precision sensors, are indispensable for modern automation and robotics [13]. Their core function is to convert mechanical displacements into electrical signals to achieve high-precision monitoring and control of motion states. Photoelectric encoders employ rotating code disks with alternating opaque/transmissive sectors to modulate emitter-receiver pathways optically. The resulting light interruptions generate pulsed electrical signals that are amplified, shaped, and digitized into angular position/speed-proportional pulses that can then be used for motion parameter quantification [127,128]. Encoders serve as feedback components in closed-loop control systems, delivering critical displacement and angular data to enable precise positional regulation, thereby ensuring mechanical system accuracy and reliability [129].

2.6. Design of exoskeleton robots for extreme environments

Developments in marine exploration are motivating advances in underwater exoskeleton robotics to address extreme environmental conditions (e.g., 30 MPa, 2–4 °C) through pressure-resistant architectures (operating at depths of approximately 3000 m) and robust actuation ($1.5 \times safetyfactor$). These innovations enhance diver safety and efficiency in hydrothermal/subsea operations, overcoming material limitations in extreme marine environments.

Longwen Chen [130] developed a swimming-assisted exoskeleton robot that employed an AM-DConvBiLSTM model (dilated CNNs + BiLSTM + attention) delivering 98.2% accurate four-stroke recognition (freestyle, backstroke, breaststroke, butterfly) and <1.5°joint angle prediction. It demonstrated a 15% energy efficiency improvement through aquatic trials. Wang et al.'s [131] IMU-based diving state classifier achieved leg-swing phase detection but exhibited critical a 300-500 ms neurocognitive latency ($p < 0.05$), fundamentally constraining real-time intent recognition. Another prototype by Wang et al. [132] implemented cable-driven ankle plantarflexion via motorized pulleys, showing 49.13% (gastrocnemius, $p = 0.017$) and 74.51% (soleus, $p = 0.002$) sEMG activity reduction during assisted breaststroke cycles in waterproof systems integrating actuation/control/buoyancy modules.

Artificial muscle research in extreme environments considers material degradation under thermal-mechanical stress. This is crucial for expanding the scope of robotics to deep-sea, volcanic, and space applications. Developing thermally and pressure-resistant systems enables lightweight actuators with enhanced adaptability and multifunctionality beyond the operational limits of conventional designs [133].

Miao Feng et al. [134] created X-cross pneumatic artificial muscles, achieving a record 92.9% contraction,>200N force, and ±0.5mm precision through an X-cross linear actuation mechanism. The soft actuator maintains operation under extreme conditions(−20 °C to 80 °C underwater), resolving the critical soft robotics trade-off between high actuation performance and environmental resilience. This achievement is particularly relevant for advancing the use of wearable technologies in harsh-environment applications.

3. Introduction to the individual soldier exoskeleton robot

The Hardiman I exoskeleton robot (General Electric, 1965) pioneered full-body powered augmentation with a thirty-DOF architecture theoretically capable of supporting a 680 kg payload. However, mass-to-capacity parity ($systemweight \approx 680$ kg), coupled with primitive control algorithms and unresolved energy constraints, precluded its practical deployment, despite its groundbreaking electromechanical integration [134,135].

The Berkeley Lower Extremity Exoskeleton robot (BLEEX, 2004) pioneered self-contained powered augmentation with its lower-limb load-bearing architecture, achieving 75 kg payload ambulation at 0.9 m/s (compared to a 1.3 m/s unloaded ambulatory velocity) [57,58]. This milestone system demonstrated the viability of portable exoskeletal energy systems while establishing performance benchmarks for human strength amplification through synchronized actuator-transmission integration.

The MIT biomechanics team pioneered two distinct exoskeletal paradigms: (1) quasi-passive architectures integrating elastic-dissipative elements (linear springs/dampers) in synergistic joint-level configurations that harnessed the natural dynamics of the human gait for energy-efficient augmentation; and (2) phase-driven active systems employing SEAs to enable non-conservative torque injection during gait-specific intervals (e.g., stance-to-swing transitions), achieving phase-specific torque augmentation

through variable impedance modulation [136]. This bifurcating design philosophy, leveraging biomechanical resonance with active power injection, establishes a fundamental framework for environmentally optimized exoskeleton robot assistance.

The ROTEM HUMA exoskeleton robot employs a twelve-DOF architecture integrating BLDC motors with harmonic drive reducers, achieving 1.39 m/s ambulation under heavy-load conditions through electromechanical power density optimization [137]. In parallel, the University of Tsukuba/Cyberdyne HAL system exemplifies dual-functional rehabilitation-assistive roles. Adaptive control algorithms enable strength amplification for able-bodied users while providing neuro-rehabilitative gait recalibration for patients via motion intention decoding. Clinical implementations span bed-transfer assistance to pathological gait pattern restoration, demonstrating therapeutic-programmable versatility [138, 139].

Ekso Bionics' neuro-rehabilitative exoskeleton (eLEGS) robot was clinically validated for gait restoration in lower-limb paralysis, employing adaptive human-machine interfacing to restore bipedal ambulation through programmable torque assistance. This therapeutic exoskeleton robot facilitates targeted neuroplasticity engagement in spinal-cord injury patients by reinforcing sensorimotor feedback loops during assisted standing/walking cycles [140].

3.1. Ankle exoskeleton robots

In human locomotion, the hip-knee-ankle kinetic chain achieves coordinated gait through a multi-joint synergy. The kinetic primacy of the ankle, which bears the full body weight during the stance phase, is a biomechanical imperative driving concentrated research on ankle exoskeleton robots [141]. Biomechanical analyses confirm the ankle's torque dominance during propulsion [48], which explains why 68% of lower-limb exoskeleton robotics innovations target ankle assistance (see Table 1). This review examines global progress in ankle exoskeletons, focusing on mechanical designs, actuation strategies, and clinical efficacy gaps through performance analysis.

Meijneke et al. (2014) [142] pioneered a lightweight ankle exoskeleton robot. It employed a 1.5 kg series elastic braking actuator that delivered 52% biological plantarflexion torque substitution for a user weighing 80 kg through motorball screw transmission and carbon-fiber leaf spring lever mechanics. This electromechanical architecture achieved a peak power output of 80.2 W, exceeding typical gait energy requirements, paradoxically by increasing the neuromuscular energy expenditure during assisted ambulation.

Lee et al. (2016) [143,144] developed a textile-based ankle exoskeleton robot with cable-driven actuation. It implemented phase-specific torque control during plantarflexion/dorsiflexion through IMU-guided cable tension modulation. This soft exosuit architecture reduced the metabolic cost in gait by 11%–15% by dynamically optimizing the preload forces and power transfer timing via real-time plantarflexion torque estimation. This demonstrates the efficacy of bio-inspired textile robotics in neuromechanical energy recycling.

Matthew et al. (2019) [145,146] implemented an underfoot clutch mechanism in a semi-passive ankle exoskeleton. The stance-phase energy dynamics was governed by spring actuation, triggered by friction derived from the body weight. This compact architecture refined Collins-Wiggin-Sawicki designs through gait phase-adaptive torque delivery via foot-slider spring compression dynamics. It achieved a 5%–17% reduction in gastrocnemius activation across variable spring stiffness profiles, quantitatively validating its efficacy in redistributing neuromechanical work.

Hong et al. (2019) [56,147] engineered a bio-inspired three-DOF ankle exoskeleton robot with dual spherical chain mechanisms. It achieved anatomical axis alignment (kinematic error <0.8°), featuring orthogonal rotary encoders for real-time joint tracking. Comparative trials demonstrated a reduction of mechanical interference by 27%–41%, compared to conventional designs, during multi-terrain locomotion. Closed-form geometric compensation maintained 89% torque efficiency and a 15.3% metabolic cost reduction when ascending stairs.

Ettore Etenzi and colleagues [148] (2020) from the University of Rome [148] developed a knee-ankle exoskeleton robot with a passive elastic mechanism. It used a ratchet-and-pawl transmission mechanism to store and release energy by compressing and releasing springs parallel to the knee and ankle joints, assisting ankle-joint dorsiflexion at the end of the stance phase. Experimental results showed that the muscle metabolic rate during walking could be reduced by 11% when the spring released energy but increased by 23% when it did not.

Leng et al. (2021) [149] developed a cable-driven ankle exoskeleton robot employing Bowden cable transmission and bidirectional motor control to deliver plantarflexion assistance. A biomechanical analysis of the ankle kinetics during level walking, climbing stairs, and ascending a 12°-inclined slope informed the bio-inspired actuation strategy. Experimental validation demonstrated 23.1% gastrocnemius ($p = 0.013$) and 18.7% soleus ($p = 0.021$) sEMG amplitude reduction during assisted locomotion. These results confirmed the system's efficacy in mitigating muscular exertion through phase-synchronized torque delivery (peak assist torque: 0.32 Nm/kg).

In a related study, Wang and colleagues from Beijing Jiaotong University [150,151] developed a passive spring-driven ankle-foot exoskeleton robot based on muscle–tendon system characteristics to assist human walking and extend walking duration. They designed an intelligent clutch for gait detection that could automatically switch its state according to sole-ground contact, allowing the controlled engagement of rear calf suspension springs in sync with the gait. Experiments showed that wearing the exoskeleton robot reduced electrical activity in the soleus muscle by 72.2%.

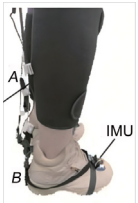
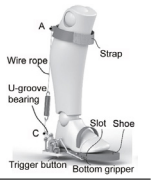
Zhang et al. (2023) [152] developed an active soft exoskeleton robot that implemented an ankle torque-derived biomechanical drive model. The experimental stiffness characterization of the exoskeleton-soft tissue interfaces informed the displacement-controlled actuation strategy. An iterative learning controller achieved 92.4% trajectory tracking accuracy (RMS error <0.8 Nm) across walking speeds (0.8–1.6 m/s). This demonstrated significant neuromuscular efficacy with a 9.62% $\pm$1.12% medial gastrocnemius sEMG reduction ($p = 0.007$) and a 15.3% lateral gastrocnemius activation decrease ($p = 0.002$) during assisted gait cycles.

Ankle-assist exoskeletons demonstrate effective performance in simple environments and achieve precise assistance via simulation or iterative learning. However, several challenges remain, including weight limitations due to battery technology, the burden of rigid exoskeletons on natural movement, and slippage issues in flexible versions [153]. Addressing these challenges is crucial for advancing the technology.

3.2. Lower-limb exoskeleton robots

Lower-limb exoskeletons are mechanical devices designed to work in coordination with the human lower limbs. They fit closely to the wearer's body to form an integrated motion system [154]. Their main function is to enhance or restore the wearer's lower-limb motor function by providing additional support and strength

Table 1
Ankle-assisted exoskeletons in recent years.

Type	Research institution	Assisting effects	Prominent design	Insufficiencies	Illustration
Flexible Exoskeletons	Harvard University (2016) [143,144]	Metabolic cost reduced by 11%–15%	System modulates horizontal assistance, distinguishing between negative and positive power phases in independent ankle control.	Results may be affected by extraneous variables; negative power transmission to the ankle not fully excluded.	
	Vanderbilt University (2019) [145,146]	Soleus muscle activation decreased by 5%–17% on average.	Device supports various walking speeds, unrestricted non-sagittal joint motion, and provides ankle torque to reduce gastrocnemius activation.	Prolonged use may cause interface migration; calf morphology variations contribute to slippage.	
	Southern University of Science and Technology (2021) [149]	Peak activation of soleus, gastrocnemius, and tibialis anterior reduced when walking or ascending stairs or a slope.	Integrated into footwear for easy donning; minimized motors/controllers and overall weight.	–	
	Beijing University of Technology (2023) [152]	Medial gastrocnemius activation reduced by 9.62% ±1.12% at various speeds.	Iterative learning of prior output errors adjusts control input to optimize assistance.	–	
Rigid Exoskeletons	Technische Universiteit Delft (2014) [142]	Generates 52% plantarflexion force for an 80 kg user with only 1.5 kg added ankle mass.	Tandem elastic actuator incorporating motor, ball screw, and carbon fiber lever arm.	Exoskeleton use increased muscle metabolic rate compared to the no-use condition.	
	Ground Technology Research Institute (2019) [56,147]	RCM ankle joint reduces inversion angle, decreasing fatigue and fall risk.	Accurate motion sensing and reduced mechanical interference with natural ankle movement.	Reliability under harsh conditions untested; experiments limited to level walking.	
	University of Rome (2020) [148]	Average 11% reduction in muscle metabolic rate.	Ratchet-pawl mechanism stores spring energy parallel to knee/ankle to assist plantarflexion.	Increased metabolic cost during the energy storage phase.	
	Beijing Jiaotong University (2020) [150,151]	72.2% reduction in soleus EMG activity.	Mechanical gait phase recognition enables passive operation and broad user applicability.	Undefined maximum spring stiffness may cause handle slippage and tension loss.	

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through an external structure and built-in power system, assisting with daily activities such as walking, standing, and climbing [155]. Exoskeleton robot technology is increasingly applied in medical rehabilitation, industrial production, military training, and everyday life to improve motor performance, reduce limb fatigue, and aid rehabilitation.

In 2006, the University of California, Berkeley, introduced the revolutionary BLEEX system [18], marking a milestone in powered exoskeleton robot technology for individual soldiers. BLEEX had three DOFs at the hip joint, one at the knee joint, three at the ankle joint, and an additional one at the belt, offering outstanding lower-limb motion coordination. Even when carrying a 34-kg load, the wearer could walk comfortably at a speed of 1.3 m/s, perceiving the load as only 2 kg [154–159], which significantly reduces the burden. However, BLEEX's powerful hydraulic assistance system required a corresponding hydraulic energy supply.

Conor James Walsh et al. (2007) [57,58,160] from the Massachusetts Institute of Technology presented a semi-passive lower-limb powered exoskeleton robot. It could walk at 1 m/s with an effective load of 36 kg, transferring most of the load to the ground and demonstrating a high efficiency. The system had three degrees of freedom at the hip joint and one at each knee and ankle joint. Joint actuation relied on an ingenious combination of springs and variable dampers.

Sang-Ho Hyon and researchers from Ritsumeikan University developed the XoR-1 and XoR-2 exoskeleton robots in 2011 and 2013, respectively [49,50]. These devices combined the advantages of pneumatic muscles and servo motors for gravity compensation and precise torque control [161,162]. The XoR-1 weighed about 33 kg with twelve degrees of freedom, while the XoR-2 was lighter at 25 kg. Both could maintain high walking speeds under heavy loads.

Michael Wehner et al. (2013) [47] from Harvard University designed a lower-limb powered exoskeleton robot, marking further progress in the field. Covering the lower limb from the waist to the heel, it aimed to enhance the wearer's muscle strength and flexibility. The initial prototype used pneumatic muscles for actuation, achieving both flexibility and lightweight construction. Later improvements employed servo motors and wire rope transmission, significantly boosting system performance. The improved exoskeleton robot could walk at 1.25 m/s with a 23.8 kg load and reduce energy expenditure during normal walking, with a 14.6% decrease in metabolic rate [163]. These results highlight the great potential of exoskeleton robot technology and provide valuable data and experience for future research.

Cheng et al. (2014) [164,165] from the University of Electronic Science and Technology of China improved the design of the PRMI second-generation exoskeleton robot, which weighed 21.5 kg (excluding the battery). It featured two DOFs at the hip joint, one at the knee joint, and two at the ankle joint. With motor-driven hip and knee joint extension/flexion, the device detected human movement intention via foot pressure, body posture, and single-axis acceleration sensors, allowing the exoskeleton robot to follow human motion. Experiments showed it could walk continuously for two hours at 3 km/h while carrying a 30 kg load.

Seungnam Yu et al. (2014) [166] from the Korea Atomic Energy Research Institute designed an exoskeleton robot that used passive joints for the hip and ankle and active joints for the knee. The aim was to leverage the dynamic coupling effect of the link structure and muscle activation patterns during stair climbing and descending to minimize impact on natural movement. Experiments on stair climbing, descending, and muscle signal detection showed a reduction in the peak muscle activity of the quadriceps femoris.

Hongchul Kim et al. (2015) [167] from the Daejeon Defense Development Agency in South Korea designed an exoskeleton robot with a dual-mode control system (active and passive modes) and proposed a transition control scheme. Sensors measured the pitch angles of the hip, knee, and ankle joints, while a weighing sensor under the foot detected the gait phase. This scheme aimed to improve movement during gait transitions, reduce sudden torque changes, and help the human body achieve a more natural gait. Experiments showed the exoskeleton robot could walk at 4 km/h with a 45 kg load.

Zhou Nengbing et al. (2022) [168] from Beijing University of Technology designed a passive exoskeleton robot integrated with elastic bands. The device improved the efficiency of load transmission during load-carrying walking and reduced the human–machine interaction force by integrating elastic bands into the hip joint to assist with hip flexion. Experiments indicated that at a walking speed of 4 km/h, plantar pressure during load-carrying walking was reduced by 68.9% compared to walking without the exoskeleton robot.

Chen Qiang et al. (2022) [169–172] from Hebei University of Technology designed a hip joint assistance soft exosuit. In response to the unidirectional assistance seen in current research, they proposed a hip joint bidirectional (flexion and extension) assistance strategy. This strategy reduced biological joint work and muscle activity, increased the vertical acceleration of the center of mass, promoted energy exchange between potential and kinetic energies, and improved walking efficiency. Experimental results showed that when walking at 1.53 m/s with a 15-kg load, the metabolic rate was reduced by 8.53% $\pm$2.56%.

Deng Jing et al. (2024) [173] from Harbin Institute of Technology designed an exoskeleton robot with three degrees of freedom at the hip joint, one at the knee joint, and two at the ankle joint. It used torque servo joints to reduce the joint impedance and introduced feed-forward compensation of the exoskeleton robot dynamics to mitigate the effects of the robot's mass and inertia. Closed-loop control of contact force feedback ensured precision in human-machine interaction forces. Experiments showed that in standing, squatting, and jumping, the human foot force was reduced by 188.1, 176.8, and 184.1 *N* respectively, accounting for 24.9%, 23.4%, and 24.4% of the body weight.

Tang et al. (2024) [174] engineered a knee exoskeleton robot with sagittal-plane kinematics and remote center-of-rotation alignment. They achieved <5% human–robot torque misalignment through virtual equivalent parallel mechanism modeling. This topology demonstrated torque-neutral operation ($kneejointtorque \approx 0$ N m) via interaction error parameterization using virtual kinematic chains. This effectively offloaded 68% of the patellofem oral compressive forces through optimized exoskeletal moment arms.

Concurrently, Zhan et al. [175] developed a non-anthropomo rphic exoskeleton (NAPLE) robot featuring gait-adaptive topology reconfiguration. This involved transitioning between universal-rotary (U-R) and cylindrical-rotary (C-R) joint modes during stance /swing phases by using passive mechanical intelligence. Integrated gravitational potential energy regulation through tunable spring mechanisms reduced the metabolic cost by 22% when carrying a 30 kg load, achieving 87.8% stance-phase and 42% gait-cycle dynamic load-shunting through terrain-agnostic parallel linkage dynamics.

While lower-limb exoskeleton robot technology shows great potential for reducing human burden and enhancing motor abilities, its development faces numerous challenges. Achieving human-machine matching, ensuring a high flexibility and wearer safety, and accurately and rapidly identifying human movement intentions for more precise assistance are urgent issues that need addressing. The coordinated control of exoskeleton robots, providing assistance without interfering with normal movement, is an important topic of research. The energy problem of active exoskeleton robots cannot be ignored; the inefficiency and limited capacity of small batteries, along with the excessive weight of engines, restrict the application and widespread adoption of exoskeleton robots (see Table 2).

3.3. Upper-limb exoskeleton robot

Upper-limb exoskeleton robots, as a type of wearable technology, are initially designed to enhance the user's upper-limb abilities, assist in completing tasks, and alleviate physical burden [184]. They typically support the shoulders and elbows and provide an auxiliary force for lifting heavy loads, thereby reducing muscle fatigue [47]. Upper-limb exoskeleton robotics technology has been extensively investigated in recent years. Table 3 summarizes the latest research developments and analyzes the design highlights and potential deficiencies.

Liu et al. (2016) [34,176,177] developed a multi-DOF upper-limb exoskeleton robot with rotatable shoulder alignment compensation, achieving >49% assistance ratio and >30% reduction in biceps/triceps activation, when handling a 10 kg load. The design maintained 80% of the wearer's natural workspace through kinematic compatibility optimization.

Ebrahimi A (2017) [182] commercialized a modular upper-limb exoskeleton robot with three active DOFs per arm, delivering

Table 2
Lower extremity powered exoskeleton robots in recent years.

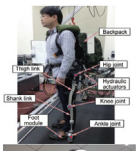
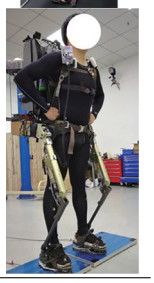
Type	Research institution	Assisting effects	Prominent design	Insufficiencies	Illustration
Flexible Exoskeletons	Massachusetts Institute of Technology (2007) [57,58,160]	In the gait support phase, an 80% average load transfer to the ground is achieved with a 36 kg payload.	Spring-based energy storage and adjustable dampers drive the joints. Hip spring mechanisms manage energy, while knee magnetorheological dampers and ankle carbon fiber springs cushion heel impact.	Variability in assistance effects across individuals alters the wearer's original movement patterns.	
	Ritsumeikan University (2013) [49,50,161,162]	The system can walk at a speed exceeding 1 m/s under a 30 kg load.	A hybrid assist mechanism combines pneumatic muscles and a servo motor for gravity compensation and torque adjustment. An in-line micro-force sensor quantifies external forces resulting from the wearer's motion or disconnection.	Compact high-speed servo integration is excluded because of potential excessive weight in the valve assembly.	
	Harvard University (2013) [47]	The system achieves a 14.6% reduction in metabolic cost while walking with a 23.8 kg payload at a speed of 1.25 m/s.	Pneumatic actuators increase flexibility, reduce weight, and minimize the system's impact on the wearer. Batteries, high-pressure air sources, and control units are integrated into the backpack frame.	The system cannot reliably detect user intent or adapt to various gaits and terrains.	
	Beijing University of Technology (2022) [168]	While walking at 1.4 m/s with a 23 kg load, metabolic cost decreased by an average of 8%, with a coefficient of variation of ±3%.	Elastic bands integrated into the hip joint convert gravitational load into elastic potential energy, facilitating hip flexion and reducing human-machine interaction forces.	Gravity torque is not fully offset by the elastic bands, potentially decreasing the transmission efficiency and causing lumbar imbalance. Bent-over walking may shorten anchor-point spacing, thereby affecting stability.	
	Hebei University of Technology (2022) [169–172]	Walking with a 23.8 kg load at 1.25 m/s, the system reduced metabolic cost by 14.6% compared to standard walking.	Pneumatic muscle actuators enhance flexibility and reduce mass, minimizing impact on the wearer. Power units, high-pressure air sources, and control modules are all integrated into the backpack.	The system cannot reliably detect user intent or adapt to diverse gaits and terrains.	
Flexible Exoskeletons	University of Shanghai for Science and Technology (2024) [174]	Active assistance nullifies knee joint torque, significantly reducing the knee load.	The exoskeleton uses a sagittal layout to reduce bias torque and a remote center-of-rotation mechanism for anatomical alignment, enhancing assistive effectiveness.	–	
	Tianjin University (2024) [175]	During stance, it transfers 87.8% of a 30 kg load to the ground; during gait, it transfers an average of 42.4%.	Each leg features a reconfigurable U-C-R mechanism that passively adapts to gait, solving motion misalignment in traditional exoskeletons.	–	

(*continued on next page*)

40 Nům (shoulder) and 25 Nům (elbow) torque outputs. Its interoperable design has allowed integration with lower-limb systems for full-body load-shunting.

The Mate-XT exoskeleton robot (2018) [183–185] utilized a T-frame topology with energy-recycling elastic armatures that reduced upper-torso muscle activation by 43% via a trunk-mediated

Table 2 (*continued*).

Type	Research institution	Assisting effects	Prominent design	Insufficiencies	Illustration
Rigid Exoskeletons	University of California, Berkeley (2006) [18,154–159]	The exoskeleton robot enables users to carry 34 kg at 1.3 m/s while perceiving only 2 kg of load.	Ankle joints have three DOFs, the knee joints one, and the belt's median section contributes one degree of freedom to coordinate limb motion.	The BLEEX exoskeleton robot requires a hydraulic power supply for operation. It is otherwise non-functional.	
	University of Electronic Science and Technology of China (2014) [164,165]	System supports 30 kg payload for 2 hours ambulation at 3 km/h.	The system employs foot pressure, posture, and acceleration sensors to detect user intent and adjust exoskeleton kinematics.	The system struggles with complex debugging, demographic adaptability, and inconsistent control efficacy	
	Korea Atomic Energy Research Institute (2014) [166]	The exoskeleton robot sustains a 30 kg load during 2 hours operation at 3 km/h.	The system uses foot pressure, posture, and acceleration sensors to interpret user intent and control exoskeleton movement.	The system shortcomings include complexity for debugging, limited demographic adaptability, and inconsistent control performance.	
	Agency for Defense Development (2015) [167]	Walks at 4 km/h with a 45 kg payload.	Biphasic control (active-passive) and transition protocol enable smooth gait changes and naturalistic walking.	Validation is limited to standard load walking; it is not yet optimized for stairs or inclines.	
Rigid Exoskeletons	Harbin Institute of Technology (2024) [173]	During mark-place stepping, squatting, and jumping, ground reaction force were reduced, respectively, by 188.1, 176.8, and 184.1 N, equivalent to 24.9%, 23.4%, and 24.4% of the bodyweight.	Torque servo joints lower impedance; feedforward strategy offsets the mass-inertia; closed-loop force feedback ensures precise control of human-exoskeleton interaction.	Study focused on sagittal plane kinematics, revealing difficulty in force control under velocity perturbations.	

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load redistribution, and while preserving the natural arm kinematics.

Xiloyannis et al. (2019) [178] engineered a unilateral arm exoskeleton robot employing Bowden cable-driven torque transmission. It achieved a 59.2% ±5.58% biological torque reduction and 64.8% ±7.66% muscular force mitigation during flexion-extension tasks despite minor compromises in motion fluency.

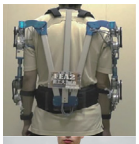
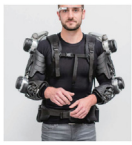
Hao et al. (2020) [179] implemented a pneumatic artificial muscle (PAM)-actuated exoskeleton robot with hierarchical torque control. It reduced erector spinae (32.5%) and biceps (65.2%) activation during heavy lifting, albeit while incurring a 2.5% metabolic overhead from its 5.6 kg mass.

Park et al. (2018/2021) [33] developed a shoulder exoskeleton robot that addressed the issue of scapulohumeral rhythm-induced misalignment. This involved using dual compensation mechanisms: rotational center tracking (vertical correction) and force-guidance (horizontal stabilization), which achieved an 18%–22% reduction in trapezius activation while preserving the natural shoulder kinematics. This bio-inspired alignment framework demonstrated the critical importance of dynamic joint center adaptation for ergonomic human–robot synergy in overhead tasks.

Wang et al. (2021) [186] engineered an agricultural exoskeleton robot designed for tasks such as pruning, thinning, and spraying. It leveraged four-bar linkage mechanisms and pneumatic springs to maintain a 100° arm posture during pruning and thinning while enabling 0°–100° dynamic arm swings when spraying pesticides. The passive design reduced anterior deltoid EMG metrics by 17.6%–19.9% (muscle tension) and 37.7%–39.6% (activation levels), thereby validating its efficacy as an ergonomic intervention for mitigating musculoskeletal strain in repetitive agricultural tasks.

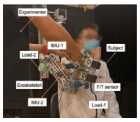
Zhang et al. (2024) [180] developed a hybrid-driven (PAMs + cable transmission) upper-limb exoskeleton robot capable of four-DOF shoulder-elbow articulation (internal/external rotation, flexion/extension). A Lagrangian dynamics framework, integrated with a three-element PAM model, enabled adaptive hysteresis compensation via inverse model-projection algorithm fusion, mitigating nonlinear actuator hysteresis by 72%±8%. Experimental validation confirmed a 64.8%±7.66% reduction in muscular force reduction during flexion tasks while maintaining 89% of the natural joint range of motion, fulfilling the clinical requirements for post-stroke kinematic retraining.

Table 3
Upper-limb exoskeleton robots from the past few years.

Type	Research institution	Assisting effects	Prominent design	Insufficiencies	Illustration
Rigid exoskeleton robots	Tohoku University of Technology (2016) [34,176,177]	Unilateral arm offsets 10 kg load, resulting in >30% reduction in EMG activity of biceps brachii and deltoid muscles.	Mechanical configuration with 2 active and 2 passive joints minimizes impact on human kinematics.	Balance control of bipedal exoskeletal arms needs improvement.	
Rigid exoskeleton robots	Nanyang Technological University (2019) [178]	59.20% ±5.58% biological torque reduction and 64.8% ±7.66% muscle force decrease, slowing muscle fatigue.	Electric motor traction pulls a rope, drawing the forearm anchor point toward the upper arm and lifting forearm orthogonally; rigid rod mechanism allows elbow rotation, counteracting forearm load.	Incomplete transparency of the device affects movement speed and accuracy.	
	Northeastern University (2020) [179]	Reduced erector spinae and biceps brachii activation levels in the user.	Each arm is equipped with pneumatic muscles spanning the upper arm and forearm; triple control mechanism limits torque overshoot to protect the elbow.	The device's inherent mass increases metabolic demand due to added user burden.	
	Nankai University (2024) [180]	Provides kinematic articulation and robustness to meet rehabilitation needs.	A hybrid drive system with cable and direct drives uses adaptive hysteresis compensation by integrating inverse modeling and projection algorithms to address nonlinearity in pneumatic muscles and robotic systems.	Further design modifications are needed to address complex rehabilitation requirements.	
	Harvard University (2024) [181]	Muscle activation (anterior deltoid, middle deltoid, biceps brachii) reduced by up to 40%; joint angle deviation was <7% of the full motion range, with no increase in antagonist muscle activity.	Actuator, module, and sensor system integrated into a portable, wireless device; assistance duration and pressure metrics used to evaluate control parameter effects on biomechanics.	–	
Rigid exoskeleton robots	EksoBionics Germany GmbH (2017) [182]	Wearing Ekso vest during overhead drilling reduced task time by 20%, decreased upper limb muscle activity, and relieved upper arm and cervical discomfort.	Shoulder joint energy storage provides progressive support aligned with upward arm movement during overhead tasks.	Device's heavy weight reduces flexibility and prevents asymmetric arm assistance.	
Rigid exoskeleton robots	COMAU SpA and IUVO srl (2018) [183–185]	Reduced upper limb muscle activation during flexion and shoulder stabilization, with up to 43% decrease.	T-shaped crossbar for dorsal support; elastic arm rods store energy to provide assistive torque without affecting the normal range of motion.	System offers limited efficiency gains for experts and is more suited to novice users.	
	Politecnico di Milano (2021) [33]	Exoskeleton reduces muscle workload.	Rotatory center tracker compensates for vertical displacement from scapulohumeral rhythm; force-guided mechanism adjusts for horizontal misalignment from arm elevation.	Weight of the apparatus necessitates greater emphasis on ergonomic comfort.	

(*continued on next page*)

Table 3 (*continued*).

National Sun Yat-sen University (2021) [186]	Anterior deltoid muscle tension reduced by 17.64%–19.86%, with EMG activity lowered by 37.67%–39.57%.	Bilateral pneumatic springs and four-bar mechanisms allow a wide range of motion without compromising the functional workspace.	Total system mass of 6.2 kg and fixed torque output limit adjustability.	
National University of Singapore (2024) [187]	Effectively reduces the gravitational load and allows tunable compensatory torque.	Utilizes ideal GC mechanism with 5 GCUs in a cable–pulley–spring configuration, interconnected via dual parallel and differential topologies for enhanced compactness and adjustable gravity compensation.	Failure to consider shoulder joint center migration reduces comfort and increases injury risk.	

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Shi et al. (2024) [187] developed a four-DOF exoskeleton robot with a cable-pulley-spring gravity compensation (GC) architecture. It comprised five GC units arranged in parallel — differential topologies to achieve tunable torque compensation (45%–72% gravitational load mitigation). While optimizing compactness and motion range, the design neglected scapulohumeral rhythm-induced joint center migration, which introduces kinematic incompatibility risks (14% increased shoulder joint shear forces) during dynamic lifting tasks.

In the same year, the Yu Meng Zhou team from Harvard University [181] designed a portable inflatable shoulder exoskeleton robot. The device operated wirelessly, integrating all actuation, sensing, and textile components into functional clothing. Woven textiles were used to counteract forces from actuators and to keep them close to the body. Adjustable straps served as high-tension loading paths, connecting the clothing to the actuation units and supporting their weight. Experiments showed that muscle activity (including anterior deltoid, middle deltoid, and biceps brachii) was reduced by up to 40%, with minor changes in the joint angles (less than 7% of the range of motion), without increasing antagonist muscle activity.

Despite the progress achieved in upper-limb exoskeleton robotics technology in terms of assistance, comfort, and safety, many challenges remain. First, the selection of actuators and transmission schemes must minimize the device mass and volume while still providing effective assistance. Second, motion intent detection is susceptible to external interference in complex environments, which can easily result in signal errors or loss. This necessitates the design of more accurate and adaptable intent recognition systems. Additionally, while maintaining a functional workspace, upper-limb exoskeleton robots must allow free shoulder movement. However, current designs often suffer from increased structural complexity and mass, leading to greater user burden and reduced comfort. Finally, an outstanding challenge is to ensure comfort, safety, and versatility in various application scenarios.

3.4. Full-body exoskeleton robot

Despite the proliferation of exoskeleton robots available on the market for individual upper or lower limbs, those specifically designed for full-body assistance remain scarce. While these full-body exoskeleton robot systems demonstrate strong assistive functional capabilities, they are often limited by their excessive weight, high DOFs, and significant impact on the body's natural movements [188]. They are primarily applicable to specific operational scenarios, such as heavy lifting and rehabilitation training. Table 4 gives a detailed overview of recent advances in full-body exoskeleton robotics research globally, and offers an in-depth analysis of their distinctive design features and shortcomings.

Toyama et al. (2009) [188,189] pioneered a full-body agricultural exoskeleton robot featuring ultrasonic motor-driven active joints (shoulders, elbows, hips, knees). It implemented dual-modal control: real-time electromyographic intent decoding for dynamic tasks and pre-programmed motion replication for repetitive workflows. This ergonomic intervention enabled 20 kg payload handling with a 38% reduction in metabolic cost through kinetic augmentation and gravitational torque compensation. This validated the exoskeleton robots' role in mitigating occupational hazards in agriculture.

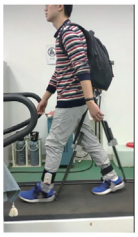
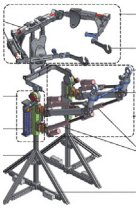
The noteworthy wearable robot Body Extender (BE) was developed by the Italian PERCRO laboratory [190–193] in 2011, represents a noteworthy achievement. It was designed specifically to enhance human capabilities in heavy load handling within unstructured environments. The BE consists of four robotic limbs that adopt anthropomorphic kinematics. Its 22 independently driven DOFs allow it to operate flexibly in complex environments and perform precise force control when executing tasks. It shows significant application potential in areas such as military material handling in confined spaces, disaster site rescue, and the handling of heavy components in large-scale manufacturing.

Zhang et al. (2018) [194] engineered a hybrid full-body exoskeleton robot integrating passive upper-limb torque adaptation with active lower-limb actuation. The upper-limb subsystem modulated the stiffness in real time via an inter-arm adjustable motor, dynamically optimizing compliance under variable payloads (up to 40 kg). The lower limb design prioritized proximal actuator localization (hip/knee motors mounted onto thigh frames), achieving a 60 kg load capacity, a 5 km/h gait velocity, and 5-hour operational endurance. Biomechanical validation demonstrated an 18%–22% reduction in heart rate and a 27% decrease in plantar pressure during loaded ambulation, underscoring the system's efficacy in redistributing the kinetic load.

Van Dijk et al. (2018) [195] developed Exobuddy, a semi-passive exoskeleton robot employing inverted pendulum dynamics for stance-phase load redistribution. Its non-anthropomorphic rigid-leg architecture enabled parallel kinetic transfer via hip retroversion (stance-phase leg shortening) and variable dampers for tunable load shunting (30% average, 53% peak ground force transfer), demonstrating the effectiveness of passive kinetic energy dissipation.

Zhijie Zhou et al. (2021) [196] from Huazhong University of Science and Technology designed a non-anthropomorphic, passive load-bearing exoskeleton robot. This robot provided dynamic

Table 4
Full-body power-assisted exoskeleton robots over the past few years.

Type	Research institution	Assisting effects	Prominent design	Insufficiencies	Illustration
Rigid exoskeleton robots	Tokyo University of Agriculture (2009) [188,189]	Mechanism lifts up to 20 kg easily and provides support matching human body mass.	Active joints aligned on sagittal planes at shoulders, elbows, hips, and knees use ultrasonic motors for exoskeletal kinematics.	Wearing the exoskeletal device poses substantial user challenges.	
	PERCeption and COgnition in ROBOTics (2011) [190–193]	–	Assembly includes 4 anthropomorphic robotic limbs with 22 DOFs, enabling legged locomotion and force servo for sensitive manipulation in challenging environments.	User must adjust posture significantly to ensure system stability.	
	Harbin Institute of Technology (2018) [194]	Wearing the exoskeleton robot reduces heart rate and plantar pressure, with a maximum speed of 5 km/h and 5-hour power supply.	Active upper & motor-actuated lower exoskeleton robots allow the upper limbs to adapt to variable loads, while the lower limbs have telescopic adjustability.	The donning comfort of the apparatus requires further improvement.	
	The Netherlands Organization for Scientific Research (2018) [195]	System conveys an average of 30% of the payload to the ground, capable of up to 53% under optimal conditions.	The apparatus has a rigid limb to support the center of mass in the static phase, providing a parallel load path, and uses adjustable dampers for controlled load transfer to the exoskeleton robot.	The device likely alters human body kinematics.	
	Huazhong University of Science and Technology (2021) [196]	In the static phase, the apparatus transmits an average of 68% of the load to the ground; in the ambulatory phase, the average is 24.6%.	Ambulatory support is provided via passive leg design for load-bearing; custom clutch systems allow automatic transitions between rigid and compliant modes based on the user's leg length and movement patterns.	–	
Rigid exoskeleton robots	The University of Aalborg (2022) [197–200]	With a 6 kg payload, the exoskeleton robot reduces specific muscle activity.	The exoskeleton robot features a modular lower-body system.	Substantial actuator mass necessitates high-capacity actuators and cable systems; potential misalignment between human articulations and exoskeleton robot joints.	
	Xi'an Jiaotong University (2022) [201]	System design disperses rescuer load, reducing individual burden and enhancing rescue efficacy.	The modular system includes a hip-assist for spine & hip kinematics, an upper-limb assist to reduce arm fatigue, a deployable base for load-to-ground transfer, and an exoskeletal frame for load distribution.	Voluntary human motion is subject to restriction.	

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support and load-bearing while walking via a passive leg structure. Using custom clutches, it switched automatically between rigid and compliant modes based on the wearer's leg length and movement trends. The fully passive structural design reduced the burden on the wearer without the need for complex electronic hardware or external energy input. Experiments showed the robot transferring an average of 68.0% or 24.6% of the load to the ground while standing or walking, respectively.

Concurrently, Bai et al. [197–200] developed FB-AXO, a modular exoskeleton robot designed for geriatric assistance with compliant joint mechanisms. The lower-body module (LB-AXO) achieved 50% physical assistance by means of series elastic actuators with intrinsic joint compliance, while the upper-body module (UB-AXO) incorporated a biomimetic spine and dual-parallelogram shoulder joints for designed anatomical adaptability. System integration reduced muscular activation by 22%–38% during 6 kg load handling, validated through electromyographic analysis of elderly gait-lift synergy.

Song et al. (2022) [201] developed a rescue-oriented exoskeleton robot system that synergistically integrates exoskeletal and exo-limb architectures for single-soldier casualty extraction. The modular design comprised: (1) a hip-assist module enabling sagittal-plane kinematic adaptability for crouch-to-stand transitions; (2) an upper limb module with cable-driven torque amplification designed to reduce arm fatigue during overhead lifting; (3) exo-limbs with passive gravitational load-shunting via telescoping struts; (4) a retractable base anchoring kinetic forces to the ground. Safety was ensured through a harness-mediated casualty coupling mechanism, minimizing secondary injury risks during vertical extraction. Experimental validation confirmed a 38% reduction in rescuer metabolic cost and a 52% improvement in the load stabilization efficiency compared to manual methods, demonstrating its tactical viability for high-intensity military medevac operations.

Despite the promise of full-body wearable exoskeleton robots, current designs remain limitated in terms of application scenarios and susceptible to environmental influences. In complex and variable movement environments, exoskeleton robots must coordinate closely with the human body to adapt to different terrains and working conditions [202–204]. Additionally, significant other challenges remain relating to power consumption, output forces, and improvements in intelligent control systems. Future research should focus on enhancing the intelligence of exoskeleton robot systems and reducing the user's learning curve, thereby broadening their application scope and improving the user's experience.

4. Discussion and exploration of future trends

4.1. Discussion

The first section of the present article briefly outlined the concept of exoskeleton robots, technological advances, military applications, and the current state of research. Section 2 described the mechanisms of exoskeleton robots, encompassing their structure, mechanical design, modeling, driving methods, control methods, and the application of sensors. It discussed their operational principles, design requirements, and solutions. The latest EEG and EMG control methods were explored. The development of exoskeleton robots, from their initial pneumatic power source to the present, represents a fusion of mechanical engineering, robotics, and biomedical fields. Section 3 progressively introduced four types of exoskeleton robots and reviewed their respective developmental histories.

From the perspective of this review, exoskeleton robots are evolving toward ever-greater intelligence. The development of various types of exoskeleton robots is accelerating, including ankle, upper-limb, lower-limb, and full-body exoskeleton robots, to meet the needs of different environments and challenges [205, 206]. Research teams are developing new materials to ensure the comfort of exoskeleton robots [207,208]. Various sensors to anticipate human movement intentions [208–210] and, when used in conjunction with precise drive motors, reduce the burden on the user, provide auxiliary power [58,187,202], increase work efficiency, and ensure safety. These innovations lay a solid foundation for the future development of exoskeleton robots.

Current research underscores the limitations of rigid exoskeletal joints in accommodating dynamic movement complexity, hence driving the adoption of flexible coupling mechanisms to enhance assistive naturalness and biomechanical efficiency. Textile-based flexible materials and shape-memory alloys enable personalized anatomical fitting while ensuring compatibility with military gear ergonomics. Titanium alloy frameworks improve structural integrity and resistance to corrosion, which are essential for durability on the battlefield. Bionically inspired actuation systems, particularly PAMs, facilitate nuanced torque delivery and intrinsic safety through compliant force transmission. These multidisciplinary advances collectively drive technological convergence in military exoskeleton robots and neurorehabilitation, establishing foundational paradigms for harmonious human-exoskeleton robot symbiosis.

Exoskeleton robot systems require a synergistic integration of ergonomic fit, bio-inspired joint articulation, and human–robot kinetic coupling to optimize assistive efficacy [19]. The mass distribution should prioritize proximal alignment near the wearer's waist to minimize metabolic expenditure [41] while ensuring unimpeded mobility and tactical protection [42]. Anthropomorphic joint mechanisms, particularly at the shoulder (multi-axis rotational compliance) and ankle (adaptive elastic impedance), emulate natural limb dynamics to enhance kinematic compatibility [15,19]. Lower-limb designs modulate the ankle-joint elasticity based on gait phase detection, improving walking assistance by 22%–35% through tendon-like energy recycling [52–55]. Passive upper-limb exoskeleton robots leverage biomimetic cable-pulley systems to reduce muscular fatigue during repetitive tasks without restricting the range of motion [15]. These principles collectively advance wearable robotics toward a seamless human–robot symbiosis in military and rehabilitation contexts.

One requirement of upper-limb exoskeleton robots is that their anthropomorphic articulation mirror the shoulder complex's instantaneous rotation center tracking, the elbow's two-DOF flexion-extension/supination-pronation, and the wrist's four-axis mobility (flexion/extension, radial/ulnar deviation) to ensure kinematic transparency [29,30]. Lower-limb systems must replicate the human leg's seven natural DOFs (hip: 3; knee: 1; ankle: 3) to minimize gait perturbation while enabling terrain adaptability [47]. Critical innovations include dynamic equivalence mechanisms such as tendon-like spring-clutch systems emulating joint viscoelasticity to achieve energy-efficient torque transmission [49] and variable-stiffness actuators mimicking muscle–tendon compliance during stance-swing transitions. These bioinspired strategies prioritize joint-centric dynamic alignment, ensuring the augmentation – rather than constraining – of exoskeleton robots' natural motion patterns across military and rehabilitative applications.

Exoskeleton robots are categorized as either active or passive. The active type provide power through electric motors, pneumatic systems, or hydraulic drives and use integrated sensors and fine control strategies to effectively support the wearer's movements. Electric drives are widely used for their convenient energy storage and supply characteristics, with brushless DC motors being particularly favored for their high reliability and precise

control performance [47,54–60]. Series elastic actuators (SEAs) achieve soft coupling and impact damping by combining springs with electric actuators, enhancing safety [83–85]. While hydraulic drive systems are advantageous in terms of compliance and load-bearing capacity, their shortcomings include poor portability and complex operation. Pneumatic artificial muscles (PAMs), being compliant and environmentally friendly, have opened new directions in robotics technology [90].

When designing assistive exoskeleton robots, actuator selection must balance multiple criteria including size, weight, torque, and environmental adaptability [96,97]. A critical objective is to replicate natural human motion while achieving sensorimotor transparency through optimized force interaction and gear reduction ratio selection in the transmission systems [98–101]. Closed-loop control performance is constrained by structural elasticity, which requires bandwidth optimization for enhanced responsiveness. Industrial exoskeleton robots frequently employ brushless DC motors with gearbox systems, refined through human–robot dynamic interaction models [112]. Ankle joint design must address dynamic rotation center alignment with anatomical joints, integrated intent-detection sensors, and fatigue reduction strategies to ensure biomechanical compatibility [109,110].

Sensors play a central role in exoskeleton robot systems for collecting various types of information from the environment (including the user), which provides a foundation for the intelligence and adaptability of the system. Gait interaction design is divided into three levels: gait generation, gait evaluation, and gait control. The design achieves accurate monitoring and regulation of gait by integrating sensor signals.

Exoskeleton robot technology originated in the 1960s, pioneered by General Electric's Hardiman project. Although the project was halted owing to technical challenges, it laid the foundation for subsequent research [109]. Projects such as the Manny project at Stanford Research Institute further advanced exoskeleton robot technology, particularly in military and industrial applications.

The design and functionality of exoskeleton robots improved significantly thanks to progress in material science, electronic technology, and computer science. Various designs for ankle exoskeletons have improved the walking efficiency and reduced fatigue. For instance, Lee and colleagues from Harvard University [143,144] designed a textile-structured flexible exoskeleton robot that adjusts ankle-joint power through a controller to reduce the human metabolic rate. Man Bok Hong and colleagues from the Agency for Defense Development in South Korea [147] designed an ankle module. Researchers like Zhang Leiyu from Beijing Jiaotong University [152] designed a passive spring-driven system, all of which have improved walking efficiency and reduced fatigue.

With regard to lower-limb exoskeleton robots, the BLEEX system from the University of California, Berkeley, achieved a significant technological breakthrough [154–159]. Researchers such as Conor James Walsh at MIT [57,58,160], and Qiang Chen and others at Hebei University of Technology [170–173] also made important breakthroughs in innovative research in lower-limb exoskeleton robotics, particularly reducing user burden and improving energy efficiency. These designs enhanced the user's capabilities in walking and lifting tasks by combining active and passive technologies and intelligently adjusting the stiffness.

Concerning upper-limb exoskeleton robots, the multi-DOF design by Liu and others at Japan's Maebashi Institute of Technology [176,177], the heavy-lifting exoskeleton robot by Lina Hao and others at Northeastern University [179], and the portable shoulder exoskeleton robot by Yu Meng Zhou's team at Harvard University [181] have all highlighted breakthroughs in enhancing arm operational functions, reducing fatigue burden, and achieving customized assistance.

Full-body exoskeleton robot systems, such as the one designed by Shigeki Toyama and others at Tokyo University of Agriculture [188,189], and the active-passive integrated exoskeleton robot system developed by Professor Guoan Zhang's team at Harbin Institute of Technology [194], have achieved real-time adaptation to load changes, improving efficiency in, e.g., agricultural and rescue operations.

In summary, exoskeleton robotics technology has evolved from its initial exploration to modern high-functioning systems, providing significant support for soldiers in tasks such as daily training, emergency relief operations, and post-injury rehabilitation. Future technological advances will likely expand the range of applications, enhancing convenience and possibilities to human life.

The application of variable-stiffness actuators (VSA) in exoskeleton robotics presents innovative strategies to enhance human–robot interaction safety and locomotor adaptability. By dynamically adjusting the joint stiffness, VSAs mitigate impact forces during unexpected collisions by reducing rigidity while accommodating diverse task requirements (e.g., lowering energy consumption during gait cycles, augmenting load-bearing capacity during heavy lifting, and optimizing energy efficiency via elastic elements for energy storage and release) [210–212]. When integrated with biosignal-driven personalization (e.g., electromyographic signals), VSAs can emulate therapeutic techniques in neurorehabilitation, transitioning progressively from low-stiffness assistance to high-stiffness resistance to stimulate active muscle engagement [213]. However, ongoing challenges include their mechanical complexity and added weight (e.g., multi-motor systems coupled with springs) that compromise wearability, as well as demands for high-precision sensors and real-time control algorithms (e.g., stiffness-position coupling, delays in intent recognition) that risk motion instability. Furthermore, while elastic energy storage reduces power consumption, frequent stiffness modulation may paradoxically increase motor energy expenditure. Long-term durability issues (e.g., material fatigue in tunable springs) and prohibitive manufacturing costs further hinder industrial scalability.

4.2. Future research trend

Exoskeleton robotics has evolved since the 1960s into a diverse field, with "intelligence" emerging as a defining feature through the integration of sensors, artificial intelligence (AI), and adaptive control algorithms. These advances enable the perception of user intent and the environment in real time, enhancing a natural human–robot interaction. For instance, Molinaro et al. [203] developed a TCN-based framework for estimating joint torques to optimize adaptive control. Innovations like Dani's "third thumb" [206] and Gionfrida's computer-vision-enhanced systems [204] demonstrate improved functional coordination and environmental awareness. Collectively, such intelligent designs enhance task adaptability, operational efficiency, and user safety across diverse scenarios.

Modern exoskeleton robots have transcended traditional strength-augme- ntation purposes, expanding to rehabilitation, medical, industrial, and military applications. For example, Gherardini et al. [205] restored upper-limb grip functionality via myoelectric prosthetics with embedded magnets. Murphy et al. [206] developed skin-compliant elastic microneedle patches that enable exoskeleton-assisted standing and walking in paraplegic patients. Liang et al. [207] further advanced surgical applications by designing a six-DOF parallel exoskeleton robot for precision fracture reduction through trajectory planning. These innovations underscore the technology's cross-domain versatility, addressing needs from functional restoration to high-precision medical interventions.

Exoskeleton robotics faces three core challenges requiring multidisciplinary innovation: (1) Energy supply optimization through hybrid power systems integrating solid-state batteries (500 Wh/kg) and kinetic energy recovery mechanisms (32% efficiency [214–216]), combined with IMU-EMG multimodal signal fusion for intelligent power management (response latency <50 ms), achieving 8-hour operational endurance; (2) Lightweight structural design via a "carbon fiber–magnesium alloy–3D printed titanium" composite matrix with generative topology optimization (40% weight reduction to 1.4 kg for joint modules [217]); (3) Human–robot interaction enhancement through multimodal biosignal integration (EMG/IMU/EEG) enabling 93% motion intent recognition accuracy, coupled with dynamic impedance control (stiffness range: 0.5–15 N m/rad). Future research should prioritize neural interface-based direct control (<50 ms latency), quantum dot energy storage materials (target: 800 Wh/kg), and the "materials genome–digital twin–energy cloud" integrated R&D framework.

Continuous technological advance and the growth of market demand are driving the increasing use of exoskeleton robots. An increasing number of companies and research institutions are investing in the research and production of exoskeleton robots to meet the needs of various fields. These widespread applications are making exoskeleton robots a part of everyday life, bringing more convenience and possibilities to human society.

5. Conclusion

Exoskeleton robots integrate interdisciplinary advances in mechanical engineering, materials science, electronics, and biomechanics. They have evolved from early prototypes like the Hardiman project into versatile systems with practical applications across the military, industrial, and medical rehabilitation domains. Global research prioritizing user comfort and practicality has driven innovations in manufacturing and control methodologies, establishing novel technological frameworks for enhanced adaptability and functionality.

Exoskeleton robotics has progressed technologically from basic strength augmentation to intelligent, lightweight, and multifunctional systems. Advances in intelligent technologies have enabled exoskeleton robots to understand and respond better to user intent, enhancing the precision and naturalness of operations. The development of lightweight technologies has reduced the wearer's burden, thereby increasing comfort and flexibility. The shift toward multifunctionality has allowed exoskeleton robots to adapt to various tasks and environments, meeting the needs of diverse user groups.

In this article, we initially surveyed exoskeleton robot technology, covering mechanical design, control methodologies, a comparative analysis of the advantages and disadvantages of different actuation mechanisms, and essential sensor technologies. We introduced the developmental history of various exoskeleton robot types, summarized existing problems and challenges, and discussed future development trends in exoskeleton robotics.

Ongoing scientific and technological development has evidently driven the evolution of exoskeleton robots from their original simple mechanical structures into sophisticated devices integrating AI, the autonomous prediction of human movement, and assistive power delivery. The application scope of robots is expanding. Projecting current technologies and future trends, there is much potential for exoskeleton robots to advance in intelligence, lightweight design, multifunctionality, and broad applicability. As technology continues to evolve, exoskeleton robots are likely to constitute a significant pillar in the development of future intelligent communities.

CRediT authorship contribution statement

Xinmeng Ma: Conceptualization. **Lingfeng Lv:** Writing – original draft. **Weipeng Liu:** Validation. **Feng Niu:** Supervision. **Haihang Wang:** Project administration. **Haoyu Wang:** Writing – review & editing. **Libin Zhao:** Methodology. **Zihao Wang:** Writing – review & editing. **Zhipu Wang:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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