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A review of the design of load-carrying exoskeletons

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The increasing necessity of load-carrying activities has led to greater human musculoskeletal damage and an increased metabolic cost. With the rise of exoskeleton technology, researchers have begun exploring different approaches to developing wearable robots to augment human load-carrying ability. However, there is a lack of systematic discussion on biomechanics, mechanical designs, and augmentation performance. To achieve this, extensive studies have been reviewed and 108 references are selected mainly from 2013 to 2022 to address the most recent development. Other earlier 20 studies are selected to present the origin of different design principles. In terms of the way to achieve load-carrying augmentation, the exoskeletons reviewed in this paper are sorted by four categories based on the design principles, namely load-suspended backpacks, lower-limb exoskeletons providing joint torques, exoskeletons transferring load to the ground and exoskeletons transferring load between body segments. Specifically, the driving modes of active and passive, the structure of rigid and flexible, the conflict between assistive performance and the mass penalty of the exoskeleton, and the autonomy are discussed in detail in each section to illustrate the advances, challenges, and future trends of exoskeletons designed to carry loads.

load carrying, lower limb exoskeleton, joint torque, load transfer, load-suspended backpack

1 Introduction

Heavy load-carrying work has accompanied the development of human society since the emergence of human beings. To some extent, the improvement of load-bearing capacity even determines the advancement of human society. In the long-term development, researchers have proposed various mechanical solutions for carrying heavy objects. However, the modern developed automated load-bearing devices still cannot cover all working scenarios among which people have to carry out the load-bearing work themselves. Unfortunately, the human body's ability to carry heavy loads is limited by its physiological structure. Our musculoskeletal system (e.g., the lower limbs and lumbar spine) has a limited ability to resist external forces, muscles are prone to fatigue

after prolonged heavy-load work, external forces acting on the trunk can cause damage to the cardiopulmonary system, and our soft tissues and skins have limited ability to withstand pressure and shear forces. These unfavourable factors ultimately lead to a compromised load-carrying capability by which long-term load-carrying tasks could cause irreversible physical damage to the human musculoskeletal system.

Statistically speaking, the incidence of disability in the U.S. Army has increased six-fold since the 1980s, predominantly owing to increases in musculoskeletal injuries, with load carriage implicated as a possible mechanism [1]. Annually, more than 40% of laborers in the European Union suffer lower back pain due to over-exertion in manual handling tasks [2]. Additionally, the primary cause of disability in the workplace is associated with manual workers carrying heavy loads [3]. As a result, augmenting the human load-carrying ability remains a much sought-after goal.

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Stronger muscles, tendons, and better motor skills [4–6] acquired through long-term training can improve the efficiency of carrying a load. However, such improvement in the load-carrying ability cannot be achieved quickly for most people. Fortunately, the explosion of exoskeleton technology presents possibilities for people to acquire surprising load-carrying abilities with the slightest effort. The Defense Advanced Research Projects Agency initiated the Exoskeletons for Human Performance Augmentation program in 2000 and the Warrior Web program in 2012, promoting the progress of rigid and flexible exoskeleton technologies. Rigid support exoskeletons [7,8] can help people carry heavier loads. Non-autonomous [9], autonomous [10] and passive [11] lower-limb exoskeletons, which are motivated by flexible technology, emerged sequentially after 2013. Subsequently, lower-limb exoskeletons that reduce the metabolic cost of carrying loads in walking have gradually become a reality [12–14]. Additionally, special exoskeletons such as the load suspension backpack and supernumerary robotic limbs are developed to improve the economy of walking and assist in the handling (e.g., lifting, moving, holding, and operating) of loads. All these robots are considered as exoskeletons that augment the load-carrying ability in this review.

Different aspects of the load-carrying ability need to be augmented in different scenarios. When locomotion demands are high (e.g., in walking and running), the reduction in the metabolic cost is an important indicator of the load-carrying augmentation performance, aiming to achieve longer distances and greater endurance. In the case of high-load tasks, where the primary consideration is that people should have sufficient strength to safely handle the load, the increase in the maximum explosive power is another important indicator. Another augmentation of the load-carrying ability is for long-term repetitive load-handling tasks which can lead to bone abrasion and muscle strain. The objective in this situation is to reduce physical damage to the musculoskeletal system by improving the human biomechanical response (e.g., lowering the spinal stress concentration). Other indicators used in evaluating the exoskeleton include the range of motion, stability, safety, reliability, comfort, and so on.

Considering the aforementioned human load-bearing physiological basis, working scenarios, and the development of exoskeleton technologies, this paper generally divides the exoskeletons for augmenting the load-carrying ability into four categories according to their design principles. First, the load-suspended backpack which could improve the load-carrying ability during walking by regulating the load motion and adjusting the fluctuation of system center of mass. Second, the lower-limb exoskeleton providing joint torques which could reduce the biological torque generated by joints, reducing the metabolic cost of human walking while carrying a load. Third, rigid support exoskeleton that can improve the maximum load capacity by transferring the load to the ground through rigid lower-limb structures. Last, the exoskeletons which could provide external pathways of force to achieve load transfer between body segments to assist workers in handling loads, reducing physical damage to the human body.

The development of biomechanical analysis and bioinformatics measurement technology has promoted the understanding of human load-bearing mechanisms, providing a physiological basis for the design principle of expanding load-carrying capacity. Additionally, the development of exoskeleton technology, including flexible-drive technology (e.g., cable and soft materials), compliant drives (e.g., series elastic actuators), soft material technology (e.g., textile architecture), and mechanism design methods (e.g., active-passive combination), furthers the expansion. However, current exoskeleton technology remains insufficient for practical applications.

Although there have been many literature reviews on the structure [15,16], actuation [15,16], functional performance [3,17,18], and control [17,19] of wearable robots for locomotion improvements, as well as the corresponding human physiological response [1,20–22], few reviews have systematically discussed the design of exoskeletons for load-carrying augmentation. This paper, therefore, focuses on the human physiological basis of load-bearing and four types of load-carrying exoskeletons. A systematic discussion is presented, focusing on the assistance principles, structural designs, actuation techniques, measures of the load-carrying ability (e.g., maximum load capacity and energy cost) and application scenarios.

2   Load-suspended backpacks

The most common way of load-carrying in daily life is using a backpack. However, the traditional backpack would oscillate vertically with the human body during walking, which does not serve the purpose of load transport but increases the metabolic energy consumption and compromise load-carrying capabilities. To assist the most common load-carrying activities, a special category of exoskeleton named load-suspended backpack (Figure 1) became a possible solution. This kind of exoskeleton achieves the goal of improving load-carrying capabilities by introducing a relative motion to the load and the human body, adjusting the distribution of the load force with time, and improving the human-load interaction.

The principle of bringing in a relative motion comes from examples in the natural world and in our daily lives. In the natural world, by investigating mammal bodies, it can be found that the biomechanical and energetic advantages accumulated through evolution partially come from the elastic
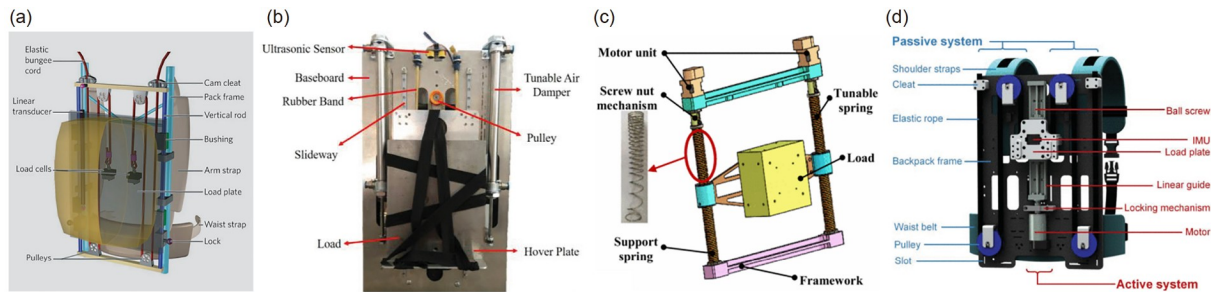
Figure 1   (Color online) Load-suspended backpack. (a) Suspended backpack with elastic bungee cords [23]; (b) suspended backpack with tunable air damper [24]; (c) suspended backpack with tunable spring stiffness [25]; (d) suspended backpack with disturbance observer-based acceleration control to minimize the inertial force [26].

tissues connecting different parts of the body which could produce relative motions (e.g., horses nodding [27], fat fluctuations in obese people [28], and jockeys vibrating their legs [29]) to reduce fluctuations of the system centre-of-mass [30]. In our daily life, the shoulder pole, which is commonly used in Asia by labourers in heavy object transports, makes the relative fluctuations possible between the load and the human mass centre, and improves the load-carrying ability by reducing the metabolic cost by 5% compared with rigid-pole weight bearings [31]. Moreover, the vertical displacement and the inertial acceleration of the load could also be restrained, resulting in reduced stress on the human shoulder [32]. These phenomena suggest the possibility of applying this dynamic load motion method to improve the human body's load-carrying capabilities.

To improve the efficiency of human walking with loads, researchers began using various engineering approaches based on the above findings to regulate the load movement and achieve higher load-carrying capabilities. The most representative attempt is the passive solution shown in Figure 1(a), which proposed a suspended backpack with an elastic cord where the elastic element connects the load to the human body [23], allowing the displacement of the load in the vertical direction to be almost inverse to the displacement of the human body, reduces metabolic consumption by 6.2% and the peak load accelerative vertical force by 82%.

Although the aforementioned passive suspended backpack could adequately achieve the goal of improving the load-carrying capability, what properties of the backpack affect its performance still needs to be answered to achieve further improvement. Considering there is no external power input, the system parameters such as the stiffness of the elastic element, the damping coefficient and the walking speed of human would be the most important ones. It was found that a lower stiffness of the suspended backpack could only reduce the metabolic cost and dynamic load acceleration when the walking speed is low, otherwise, it would increase the metabolic cost and load acceleration instead [33]. An excitation model [34] was investigated to theoretically demonstrate the relationship between the dynamic load acceleration and the

passive suspended backpack parameters. The effects of different stiffnesses, walking speed, and load mass on the dynamic load acceleration force of the backpack are obtained through the model analysis. It is found that the dynamic load acceleration at a given walking speed can be minimized when the backpack stiffness is designed to be less than half the resonance stiffness. For the relationship between damping, load, and walking speed, a two-degree-of-freedom two-mass spring damping model [35] was proposed. By approximating the energy consumption of humans walking under a suspended load, it is found that the suspended backpack reduces the energetic cost of walking more effectively with low damping, a high load mass and a high walking speed.

However, the mentioned models only consider the motion and force in the vertical direction and ignore the efficiency of the muscle performing mechanical work which inevitably results in an inaccurate energy consumption prediction, and the result could only be treated as a qualitative change trend. To quantitatively analyse the effects of backpack parameters on human metabolic expenditure, Li et al. [36] used a single-degree-of-freedom model to evaluate the effects of the suspension backpack stiffness and load mass on human energetics. A comparison with experimental data showed that the prediction error of the model was less than 10%.

The above researches indicate that the performance of the passive suspended backpack depends on the physical properties of the system and the step frequency of the walking. However, the walking speed and the weight of loads keep varying all the time due to the actual needs of the complex environments, and the passive suspended backpack cannot adapt to the changes because of the settled system parameters. In this regard, scholars have optimized the system structure to further improve the load-carrying capabilities by introducing semi-active suspended backpacks which could control the system parameters such as damping coefficient and stiffness.

Changing the damping coefficient of the suspended backpack can adjust the phase difference between the load motion and human body motion, so that the suspended

backpack would then be capable of adapting to different application scenarios and people. Studies [24] shown in Figure 1(b) have successfully controlled the damping of a suspension backpack system using controllable air dampers to improve the adaptability of the backpack [37]. Through the sliding-mode control method, the tracking error of the load is eliminated, the inertial acceleration of the load is reduced, and the impact of the load on the human body is reduced. An adjustable damping suspension backpack could also dynamically adjust the damping of the system by switching between the electromagnetic generation mode of the motor and the active motor mode, making it optimal for specific situations with the best assistance [38].

In addition to the damping coefficient, stiffness is another important parameter affecting the performance of the suspended backpack. To make sure the device could work with an appropriate stiffness, reducing the load acceleration of the backpack with different load masses and walking speeds, the stretch ratio of the elastic component can be adjusted through mechanical structure designs to change the system stiffness whenever needed [39]. Besides the way of mechanical structure design, the stiffness could also be adjusted by changing the effective number of turns of the spring [25] shown in Figure 1(c). A system consisting of two symmetrical motors arranged on the left and right of the suspended backpack was developed based on this theory to adjust the load to the best suspension state and ensure that the backpack could have better performance at different walking speeds and load masses.

The adjustment of parameters by the abovementioned suspended backpacks can be classified as a semi-active method, which makes it possible to change the parameters as needed. However, the change cannot actively adapt to the user's gait behaviours in real time, and cannot interact well with the human body. Moreover, the adjustment of the load is not precise. Therefore, to ensure the suspension backpack and human body have better interaction, many researchers began to explore the human body's response to different loads, trying to actively adjust to the actual needs.

According to the human body response, active control was introduced to better regulate the load, and to further improve the efficiency and adaptability of the suspension backpack. As there are many control variables in the active system, different optimization principles were developed according to corresponding optimization objectives. Minimization-of-inertia principle [26] is designed to reduce the maximum acceleration force acting on the carrier during the double-support phase of the human body when walking with a load shown in Figure 1(d). The results show that the load acceleration is reduced by 98.5% under a load of 19.4 kg, and the metabolic consumption of the human body is reduced by 11.0%. Yang et al. [40] simplified the method of controlling the human walking process to the optimal problem of minimizing the energy consumption per step and used a vertical dual-mass coupled oscillator model to predict the load motion and energy consumption to improve the energy efficiency and adaptability of a hover-pack. The bipedal energy estimation model is applied to predict the response of the human body to different load motions [41] and provide high-level control objectives for the actively suspended backpack. A brief summary comparing representative suspended backpacks in terms of actuation mode, structures, metabolic reductions and load-bearing capabilities is listed in Table 1.

Although various load suspension techniques have been proposed to dynamically control the load motion, owing to the limitations of the understanding of human biomechanics, the suspended backpack could only reduce the effect of the load on the human body during walking and does not reduce the load force felt by the biological limbs which transfer the gravity of the load and the backpack to the ground or elsewhere. As a result, for the method of reducing the metabolic cost through the load motion relative to the human torso, the average force during the gait cycle is always equal to the load gravitational force, regardless of the load acceleration waveform. By further investigating the mechanism of load-

Table 1 Load suspended backpack

Study	Metabolic reduction (%)	PA/PF reduction (%)	Type	Task	Speed (km/h)	Structure	Exoskeleton's weight (kg)	Load (kg)
Rome et al. [23]	6.2	−82 PA −33 PF	Passive	Walk	5.6	Rubber bands	8.66	27
Foissac et al. [33]	3.8	−22 PA	Passive	Walk	3.7	Leaf spring	–	16
Leng et al. [25]	–	−46.64 PF	Quasi-passive	Walk	5.5	Spring, adjustable stiffness	–	14.5
Zhang et al. [37]	–	−80 PA	Quasi-passive	Walk	5.3	Spring, adjustable dampers	3.4	25.4
Yang et al. [38]	–	–	Quasi-passive	Walk	–	Spring, adjustable dampers	–	40
He et al. [26]	11.0	−98.5 PA	Active	Walk	5.0	Elastic cord, IMU, motor, pulley, linear guide	5.3	19.4
Yang et al. [41]	15.9	–	Active	Walk	4.5	Motor, battery, cable-driven system	1.5	16.7

human interaction to obtain better theoretical guidance for the control strategy of the backpack, there is potential to better optimize the motion pattern of the load.

3 Exoskeletons providing joint torques

Lower-limb exoskeletons that directly provide joint torques through actuators or passive components can be used to augment the human locomotion ability [11]. The assistive principle is to offer energy to lower-limb joints to directly reduce the related muscle activations and the resultant energy consumption. As the load can be considered as part of the body mass and this kind of exoskeleton could effectively help people with walking by reducing biological joint torques, studies [12,42–46] have demonstrated that it could augment the human load-carrying capacity.

As the external torque would be directly applied to the lower limb joints, the selection of the assisted joint would significantly affect the exoskeleton performance.

Physiologically, the ankle is an effective choice for the application of assistance because, during normal walking, the ankle produces a larger burst of power and performs more positive work than any other joint of the lower limb. Meanwhile, studies [47] have shown that biological energy is transmitted between the hip and ankle, and the torque of the hip joint decreases when assisting the ankle. Therefore, many exoskeletons [43,48–50] assisting the ankle joint are developed, expecting to improve the human load-bearing capacity. Representative ankle exoskeletons [51,52] are shown in Figure 2(a) and (b) with experiments [49] showing that metabolic cost reduction could be achieved under various loading conditions.

However, the exoskeleton assisting the ankle would increase the distal inertia inevitably, and a load acting far from the centre of mass would significantly increase the metabolic consumption [53]. To avoid this disadvantage, exoskeletons assisting the knee joint [54–56] or the hip joint [12,57–59] was developed which are shown in Figure 2(c) and (d). The primary function of the knee is to support the body weight both in the single-support and double-support phases, and to increase foot clearance, avoiding obstacles in the swing phase by bending [56]. The design of a knee exoskeleton thus focuses on how to reproduce the rotation of the knee and aid with the extra load in the support phase. For example, Kim et al. [60] used a linkage structure to provide an instantaneous rotation which is similar to that of human knee joint during bending. However, because the knee is neither anchored to the ground nor the body centre of mass, there would always be a kinematic mismatch between the exoskeleton joint and the biological joint, resulting in a misalignment of the assistive torque. This misalignment will then generate resistance to the human natural motion, resulting in muscle

fatigue and even damage to the joint [61]. In contrast, the assistance of the hip joint would minimize the obstruction and does not require precise alignment with the biological joint [57,59]. Meanwhile, as the hip-assistive device approaches the centre of gravity, it has been proved to have the ability to further reduce metabolic costs [62].

Besides only assisting one lower limb joint, multi-joint exoskeletons are designed to further improve the load-carrying performance. The strategy of assisting the hip and ankle was simultaneously proposed by Walsh et al. at Harvard University. This strategy was biologically inspired [13,14,63,64] and applied to an exosuit which is depicted in Figure 2(e). The hip joint and ankle joint contribute approximately 80% of the positive work during walking [14] which means assisting both the hip and ankle can therefore maximize the assistance to human walking. It is noteworthy that the exosuit uses textiles to generate tension parallel to the muscles which mimics the ligaments and tendons, passively generates power through human movements, and it is thus able to be lightweight without limiting the wearer's kinematics. Experiments show that the proposed exoskeleton can both reduce the metabolic cost and biological joint positive work effectively.

The multi-joint exoskeleton is considered to be of greater value in load-bearing not only because it could be applied to more joints, but it also allows more diverse assistance strategies. This point of view also has physiological bases as there are massive biarticular muscles in the lower limbs which play important roles in locomotion. Studies [14,42] have shown that the hip-knee-ankle exoskeleton may be more effective than single-joint and double-joint exoskeletons which makes the development of a full-leg exoskeleton the ultimate solution for improving the load-carrying capacity. Collins's team designed a hip-knee-ankle exoskeleton emulator [42] that can apply a strong torque and high power with a powerful actuation platform to drive the 13.5 kg exoskeleton worn by the user, as depicted in Figure 2(f). In load-carrying experiments, participants walking with a load 30% of their body weight showed a 43% reduction in the metabolic cost with the assistance of the exoskeleton which demonstrates the potential of full-leg exoskeletons in carrying loads. However, to provide an explosive torque for the whole lower-limb joint, studies on load-carrying exoskeletons often adopt an off-board power platform, including a heavy actuator, reducer, and complex control system which significantly limits the potential application scenarios with autonomy requirements.

Many studies have proposed solutions to solve the autonomy problems from perspectives such as structural design and power source. From the structural aspect, one solution is to use a "slow storage and quick release" strategy with clutches. For example, a study [48] presented a fully autonomous ankle exoskeleton that can accumulate energy
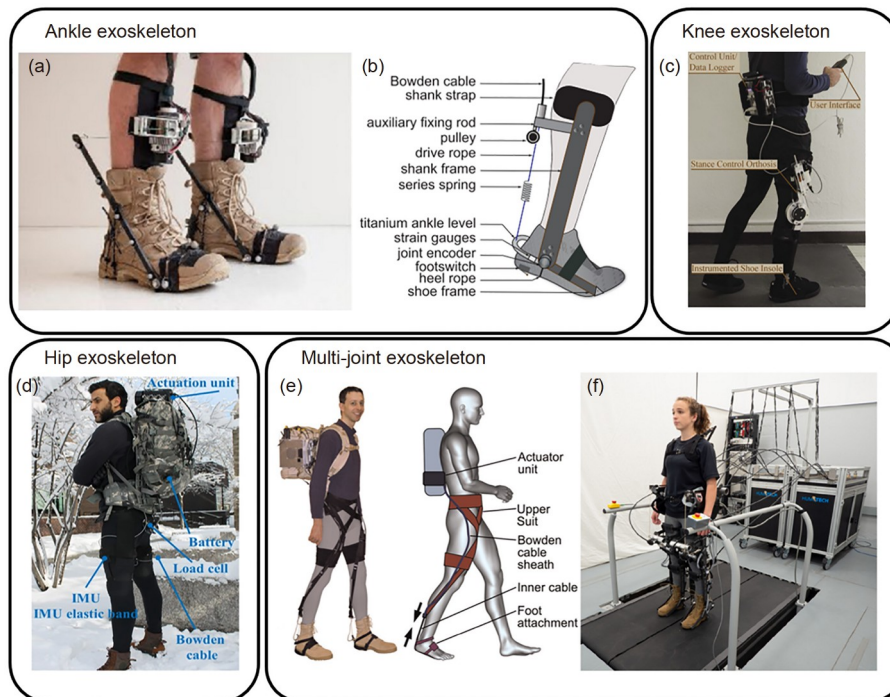
Figure 2   (Color online) Lower-limb exoskeletons providing joint torques. (a) Autonomous ankle exoskeleton [51]; (b) ankle exoskeleton with off-board motors [52]; (c) quasi-passive knee exoskeleton [56]; (d) autonomous hip exoskeleton [59]; (e) autonomous multi-joint soft exosuit [13]; (f) hip-knee-ankle exoskeleton emulator [42].

during the swing phases and most of the standing phases, and then release it quickly during push-off to achieve full autonomy. Another solution is to simplify the exoskeleton structure, intending to reduce the distal mass to achieve autonomy. For single-joint exoskeletons, the structure is often simplified by optimizing the geometric layout and mass of the strut components [10,51,65]. For the multi-joint exoskeletons, the human-machine system static analysis method [66] can be used to reduce the use of unnecessary struts, skeletonize the panels while ensuring reliability, and reduce the number of drive units by under-actuation to simplify the structure. In terms of power source, challenges can be solved by optimizing the driving mode. The load-carrying exoskeleton that directly input energy to the motion system can be called an active exoskeleton, while the exoskeleton that enhances the load-carrying capacity by reasonably adjusting the energy distribution through the elastic element is called a passive exoskeleton. For the active exoskeleton, the actuator directly affects the performance. At present, actuators used in active exoskeletons mainly include hydraulic actuators [67], electrical motors [68], and pneumatic muscle actuators [69]. Hydraulic actuators are smaller in size, deliver great power and can absorb high impact loads. However, it is difficult to maintain the stability of motion. To solve this problem, the combination of hydraulic drive technology [70] and sensor data estimation strategy was proposed to ensure the correct synchronization of the exoskeleton with the user and improve the stability of the device.

Compared with a hydraulic drive, a motor-driven system for exoskeleton is more preferred by researchers owing to its wide range of speed and torque, easy control, no need for maintenance and simplicity. However, the actuation system will be too heavy if a combination of a DC motor and harmonic reducer that provides strong torque is used for assistance. In developing a lightweight system, Bowden cables that can provide strong torque are often used despite the efficiency may be low, and the compliant human-machine interaction often cannot be realized. To overcome these problems, a series elastic actuator [71] is proposed due to its passive compliance, low impedance, and impact resistance. The series elastic module can improve the flexibility of the actuator to meet the requirements of different motion stages and change the range of output force, although it cannot avoid the oscillation phenomenon.

Compared with hydraulic actuators and electrical motors, the use of a pneumatic muscle actuator structure is simple, convenient, inexpensive, and flexible. Wang et al. [72] proposed a modular soft-rigid pneumatic lower limb exoskeleton driven by curl pneumatic artificial muscles that is light weight, has excellent compliance and a high force-to-power ratio. However, pneumatic muscle has the disadvantages of time delay and nonlinearity, and the joint position control is difficult.

Other than active exoskeletons, passive exoskeletons [11,73] are also favoured by researchers due to their lightweight and autonomy derived from the absence of the power

source and corresponding electronics. The key characteristic is that they can passively store elastic energy when biological joints do negative work and release the stored energy when the biological joints do positive work. To achieve the alternation, it is common for passive exoskeletons to adopt clutches such as a ratchet mechanism to collect and release energy in different gait phases.

Due to the lack of external power, passive devices cannot provide sufficient power and the performance in reducing muscle activity and metabolic cost is compromised compared with the active ones. For example, in a study [74] of a passive exoskeleton designed to carry loads, the average median oxygen consumption decreased by only 9.45% in an experiment where a mass of 15 kg was lifted 10 times to a height of 1.5 m. Table 2 gives an overview of lower limb exoskeleton providing joint torques addressing the metabolic reduction performance [10,12–14,42,53,59,63,64,68,70,74,75].

Although a series of studies have been carried out to address the problems afflicting lower-limb exoskeletons providing joint torques, and many solutions have been proposed, owing to the limitation of current material technologies and corresponding design principles, there is no perfect solution to overcome all the problems. However, studies have shown new trends.

First, although rigid structures have been widely used in existing studies, exoskeletons comprising flexible materials will gradually replace the rigid ones in the pursuit of a safe and comfortable human-machine interactive experience. The use of soft materials can greatly simplify the structural complexity and reduce the difficulty of design. Meanwhile, flexible materials can be tightly fitted to the wearer, minimizing obstruction to movement. Moreover, the use of soft

Table 2 An overview of lower limb exoskeleton providing joint torque

Study	Year	Structure	Drive	Joint	Exo mass (kg)	Load (kg)	Features
Mooney et al. [10]	2014	Rigid Each boot had a medial and lateral fiberglass strut pinned to the front of the boot	Unidirectional actuator	Ankle	3.963	23	8% reduction in metabolism
Yu et al. [70]	2015	Rigid A flexible hyper carbon structure in ankle joint	Hydraulic actuator	Hip & knee & ankle	–	40	Muscle strength decreased by 49.5% when walking horizontally, and decreased by 21.1% when walking up stairs
Asbeck et al. [13,14]	2016	Soft Two load paths	Bowden cable-driven actuators	Hip & ankle	6.6	30% of the body mass	Reduced metabolism by 7.3%±5.0% Reduced joint positive work by 0.16 J/kg
Ding et al. [12]	2016	Soft Textile components	a programmable multi-joint actuation platform	Hip	0.695	23	8.5% reduction in metabolism
Malcolm et al. [63]	2017	Soft A single load path	Off-board actuation platform	Hip & ankle	6.5	23	Both negative work and positive work are provided; 11%–15% reduction in metabolism
Lee et al. [64]	2018	Soft Two load paths	Bowden cable-driven actuators	Hip & ankle	9.3	6.9	14.88% reduction in metabolism
Cha and Kim [68]	2019	Rigid A rigid link matches between the spine of the driver and the exoskeleton	4 DC motors at each knee and hip joint	Hip & knee	21.5	20	Average muscle activity: rectus femoris decreased by 67.1%, gastrocnemius decreased by 68.3%, and abdominal muscle decreased by 68.0%
Panizzolo et al. [59]	2019	Soft A spandex base layer, a waist belt and a waist belt liner, two thigh braces	Bowden cable-driven actuators	Hip	5.4	20.4	Metabolic cost decreased 10.5%±4.5%
Cao et al. [75]	2020	Soft A waist belt and two thigh wraps	Bowden cable-driven actuators	Hip	4	15	Net metabolism decreased up to 13.05%
Collins's group [42,53]	2021	Rigid Four carbon fiber shoulder struts	Bowden cable-driven actuators	Hip & knee & ankle	13.5	30% of the weight	Metabolic cost decreased 43%
Li et al. [74]	2021	Rigid The spring and wire rope in series used for assistance	Hydraulic actuator	Hip & knee	6.8	15	Oxygen consumption fell by an average of 9.45%

tethers to connect multiple joints, such as the hip and ankle, can promote the transmission of energy between joints [47], despite the metabolic reduction performance is still far behind that of the rigid exoskeleton owing to the current flexible material development. Therefore, there remain many difficulties to overcome in the development of flexible exoskeletons. The soft materials used should not be limited to textiles, which are prone to displacement and shear forces, but shift to solid fabrics with customizable properties to increase the surface area and limit displacement. Basic scientific questions such as how to apply greater forces through soft materials and how those forces affect the musculoskeletal system also need to be answered.

Second, we note that the method of designing an exoskeleton is changing, from the overall design to modular design. For example, Wang et al. [72] introduced a design method for a new modular exoskeleton. The exoskeleton comprises three flexible hinges and three rigid links. Each rigid link and the flexible hinge below it form an independent module, and each module can be used independently or in combination to assist multiple joints. Because of its good motion reliability and flexible auxiliary strategy, this design method shows great potential in assisting load-carrying walking.

Finally, the strategy for the lower-limb exoskeleton providing joint torques differs across studies, and the method of evaluating performance becomes very important. At present, most studies use the metabolic cost as the physiological goal of minimization to optimize the control strategy of the exoskeleton [76], but the metabolic cost requires a long-term experimental evaluation. To solve this problem, Han et al. [52] used a particle-swarm optimization algorithm to select muscle weight combinations in constructing objective functions based on muscle activity to evaluate the performance of the exoskeleton. The results not only validate the effectiveness of the evaluation method but also provide guidance for the development of new evaluation methods for exoskeletons. Recent studies even have used ultrasound to assess the assistance strategies according to muscle dynamics [77]. In the future, it may be possible to optimize the exoskeleton assistance in a simple gait test.

4 Exoskeletons transferring load to the ground

Exoskeletons that augment the load capacity have been designed in various forms, among which the rigid support exoskeleton, which improves the maximum load capacity of the human body by transferring the load to the ground through rigid lower-limb structures, is the earliest type in terms of origin. The principle is to provide additional load transfer paths to the ground so that the human body is only directly subjected to a weak load force. Depending on the load transfer paths to the ground, these exoskeletons can be

classified into two types, known as anthropomorphic limbs and non-anthropomorphic or supernumerary robotic limbs (SRLs). The former refers to the exoskeletons with similar structures to human legs, which can transfer load through rigid structures parallel to the legs. And the latter refers to extra legs independent from the human body. In terms of power source, they fall into two categories, namely active and unpowered.

Early designs of rigid support exoskeletons are mostly anthropomorphic, expecting to transfer large loads to the ground to enhance human load capacity while walking or squatting. Active exoskeletons were the very first to be studied due to their ability to provide large assistive forces. Examples are Berkeley lower limb exoskeleton (BLEEX) shown in Figure 3(a) [7] and HULC exoskeletons [8]. These exoskeletons are hydraulically actuated and can provide a large assist force, but the efficiency performance is another story because the hydraulic system has to maintain pressure even when the system is not moving. Moreover, the systems have complex structures, large sizes and considerable masses. Although they are possible to increase the load capacity and ensure partial locomotion, the cost is an increase in the energy consumption of human body.

To reduce the metabolic penalty of the exoskeleton, researchers began investigating exoskeletons with other actuation methods and developed exoskeletons actuated by electric motors, e.g., Body-extender [78], HEXAR [79], Kawasaki power assist [3]. Other types of lightweight electric rotary actuators have also been introduced in different designs to address the shortcoming of huge mass [43,80–82]. However, these electric actuators aim at generating joint torque other than transmitting the load to the ground. Therefore, the load-carrying capacity is still limited. Thus, electric parallel-driven mechanisms with high load capacity have been introduced into the design [83]. Besides the actuators, improvements have also been made to the arrangement of actuators to solve the increase of metabolic cost caused by the weight of exoskeletons. Studies [82,84] tried to put the power source inside a backpack or at the hip joint to reduce the distance from the center of mass of the body to reduce the metabolic penalty.

Although, active parallel exoskeletons are possible to provide larger assistive force and they are relatively more controllable, the problems of the large mass of the drive system and the short working duration still exist. Therefore, more and more researchers have put their efforts into unpowered exoskeletons. Without the demand for an external power source, they are usually lightweight and can work for a long period of time.

Unpowered rigid support exoskeletons have gradually developed into passive and quasi-passive forms to augment the load-carrying ability of the human body. If the exoskeleton is able to control the presence or absence of assistive
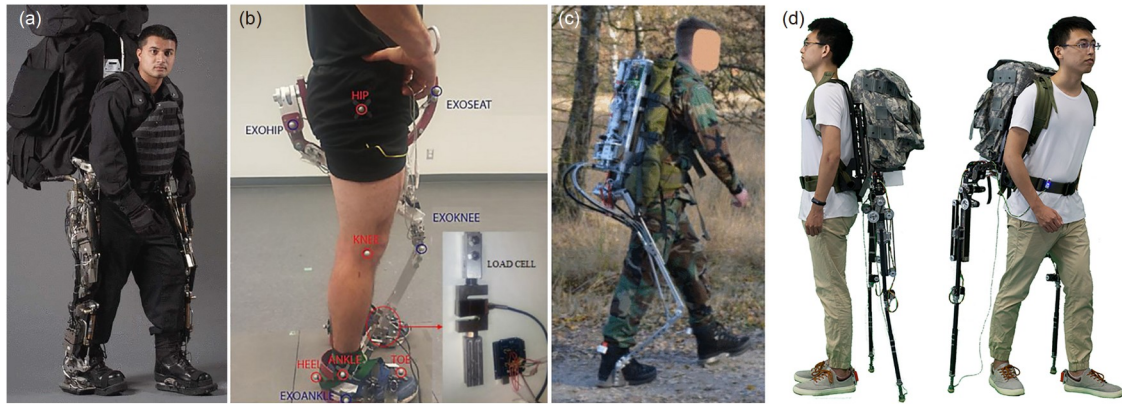
Figure 3 (Color online) Rigid support exoskeleton. (a) Berkeley lower extremity exoskeleton (BLEEX) [7]; (b) a passive exoskeleton with a seat mechanic [85]; (c) a non-anthropomorphic quasi-passive exoskeleton for load carrying [92]; (d) a supernumerary robotic limbs to assist human walking with load [44].

forces through low-power components, it is quasi-passive. Otherwise, it is passive. For passive exoskeletons, a variable stiffness is critically important. A variable stiffness allows the exoskeletons to transfer the load to the ground in the stance phase and to follow the movement of the body in the swing phase and avoid the disturbance of exoskeletons to normal gait when walking. A variable-stiffness can be realized through mechanism design (e.g., compliant knee joints based on wire control [85] or cam-spring control [86]) or based on a novel smart material (shear-thickening gel (STG)) [87]. Moreover, this approach has the advantage of not requiring the design of complex locking mechanisms. Passive exoskeletons that don't need to consider variable stiffness are also possible. In these designs, a seat mechanism shown in Figure 3(b) has been introduced at the pelvis of the human body to support the body weight during walking [85,86]. In response to the need for assistance in long-term squatting, a number of exoskeletons that transfer the body weight to the ground through a rigid frame that can be locked at different angles have been designed to reduce the load acting on the lower limbs. The locking mechanisms include ratchet mechanisms [88] and crank-slider mechanisms [89] and so on. These mechanisms effectively reduce muscle activity, plantar pressure during squatting and the activity of leg muscle during squatting, and ultimately, increase the endurance time.

Although, passive exoskeletons are lightweight, stable, reliable and can solve the problems of active exoskeletons in terms of working duration, they have the problem of limiting user movement in tasks that do not require assistance [90]. Therefore, more controllable quasi-passive exoskeletons are necessary.

Quasi-passive mechanisms are usually implemented through variable dampers to control the presence of assistive forces. Magnetorheological variable dampers [91], placed at the knee joint, and hydraulic variable dampers [92] placed at

the leg shown in Figure 3(c), have been introduced to the design. Both provide damping in the stance phase to prevent knee flexion and unlock at the end of the stance phase so as not to impede human motion. The difference between them is that the former uses a battery for a low-power supply, whereas the latter controls the damper with the energy absorbed from the body.

The anthropomorphic exoskeletons mentioned above have similar structures to human legs, so they require precise alignment with biological joints. Therefore, the problem of mismatch between the center of rotation of biological joints and the exoskeleton, resulting in obstructed motion, still exists. The above problem may arise for various reasons, such as size differences between the exoskeleton and wearer [93], misjudgment of the human joint rotation axis [94], and the incorrect wearing of the exoskeleton [95]. This may lead to excessive restraint of the exoskeleton on the person during movement, resulting in physical injury or even related joint diseases [96]. To solve this problem, Shafiei and Behzadipour [97] proposed a backlash control method in the connecting elements, which improves the matching of the exoskeleton to human motion, and has been proven to be effective regardless of the complicated control algorithm.

As the anthropomorphic load transfer path has encountered so many challenges, supernumerary robotic limbs as a whole new concept was proposed. SRLs can perform multiple functions as an additional leg or arm, support the human body in different operations, and most importantly, are capable of effectively transferring loads to the ground. These SRLs are kinematically independent of the human body and provide support without limiting the natural limb movement, avoiding the difficulties of joint alignment [98]. Based on the above concepts, robotic limb designed with a wheel-leg [99] and other types of SRL robot which are capable of following the human gait to provide support [44], shown in Figure 3(d), have been developed. In addition to carrying additional loads

while walking, other functions of SRL exoskeletons have also been explored, which allow such exoskeletons to be used in wider applications, such as providing support during loaded squatting and crawling [100] and supporting body weight while completing fatiguing postures such as hunching and hanging from the ceiling [101,102].

Table 3 compared 18 representative exoskeletons in terms of the type, design method, mass, load, and other important features.

Although SRLs avoid the problem of kinematic mismatch, they have obvious drawbacks, i.e., they are not anchored to the human body like other exoskeletons which makes the motions of SRLs not completely controllable and predictable, leading to dissonance with natural human movement. Moreover, SRLs interact with the external environment through constant interference, which may disrupt the normal human locomotion by the force exerted on the loads, e.g., there may be accidental collisions between SRLs and human torso. In addition, SRLs face problems such as low adaptability to complex terrain, which places higher demands on the accuracy of the control systems to compensate the disturbances [83].

5 Exoskeletons transferring load between body segments

In addition to the load transfer to the ground, based on the fact that different parts of the body have different load-bearing abilities, the use of particularly designed exoskeleton that can build extra force pathways outside the body to construct external load transfer channels between body segments is a new solution to increase the load-carrying capacity.

In load-carrying operations, the force often acts on the spine to bend it. However, although the spine can bear a certain amount of positive pressure, the excessive bending force would inevitably harm the spine structure, which makes it the most vulnerable part. Therefore, most exoskeletons based on the principle of transferring loads between body segments are dedicated to protecting the spine. Such exoskeletons tend to transfer the force from the spine down to the lower back, hips, legs and feet which have better load bearing capabilities [102,105–110]. By investigating the power source, these exoskeletons can also be divided into active, passive and semi-active ones. In addition, in some special work scenarios, it is necessary to maintain the posture of the upper limb for a long time under load, which requires the design of specific load transfer paths between specific joints.

The musculoskeletal principle underlying the spine protection approach is that when a person bends over to lift weights, the spine flexes, the erector spinae muscles become active, the musculature near the lumbar spine is stretched to provide an abduction moment, the load on the ligaments approaches the failure tolerance limit [111,112], and the body's centre of mass moves out of the body to the detriment of normal spinal force production. As it is found that the load-bearing capacity of the lower back and the lower extremities is greater than that of the spine and upper extremities [113–115], it becomes reasonable to construct load transfer pathways parallel to the spine through which loads can be transferred from the spine to the lower back or even the lower extremities, reducing the chance of potential damage to the spine.

In terms of the load-transfer exoskeleton to protect the spine, a primitive solution is similar to the current fitness belt shown in Figure 4(a), which always fits the human spine and lower back, forming a parallel external pathway [107]. When the human body is doing load-carrying movements such as lifting and squats, the belt can help the user to keep the spine upright to a certain extent, transfer the load to the lower back, and reduce the bending force acting on the spine. An improved version on this basis was then further developed [116] which can reduce the deformation of lumbar components, preventing excessive spinal strain and lumbar intervertebral disc problems. However, simply transferring the load from the spine to the lower back can lead to lower back pain after prolonged working. Since the load-bearing capacity of the hip is stronger than that of the lower back, a divided band was developed [117] to address this problem by transferring the load from the spine to the hips. This split band is made up of four active extensions that limit excess curvature of the spine and actively adapt to the movement of the body. When the load is shifted further down, we can find more advantages due to better stability. On the one hand, the load is transferred to the lower extremity through the connection of the hip belt or the leg strap, and the transfer path is through the hip joint where the force-transmitting component can assist the hip extension. Since the gluteus maximus is the extensor of the hip, it can promote the participation of the gluteus maximus in load-bearing exercise and enhance the carrying capacity of the human body. On the other hand, weight-bearing work is often accompanied by a squatting movement of the body, during which the body's gravitational potential energy can be stored in the elastic elements of the lower limb exoskeletons, which makes it possible to further assist the load-carrying abilities. For example, an exoskeleton has been developed that transfers loads to the feet. The device connects the shoulders, upper back, legs and feet. It works by imitating the hold-waist action when the back is in pain. When standing under load or when there is a tendency to bend over, the elastic belt connecting the spine and the soles of the feet is elongated, and the elastic potential energy is transferred to the cams and other components located around the spine, so that the upper back of the human body is

Table 3   Exoskeletons transferring load to the ground

Study	Type	Design method	Task	Exo mass (kg)	Max load (kg)	Load transferring	Features
Zoss et al. [7]	Active	Linear hydraulic actuator	Walk	–	75 (weight + payload)	–	Can walk at 1.3 m/s; Autonomous
Gregorczyk et al. [8]	Active	Hydraulic actuator	Walk	24	90	–	Can walk at 1.34 m/s; Lead to the alternation of users' gait biomechanics compared; Autonomous; 2 h battery life
Wang et al. [83]	Active	Underactuated, PEA	Squat/walk	27.8	66 (squat) 45 (walk)	–	Good loading performance; Good wearing comfortableness; Height adaptability (160–190 cm); Can walk at 7 km/h
Fontana et al. [78]	Active	DC brushed electric motor	Walk	160	100	–	22 DOF; Acts as a load augmentation device; Battery powered
Kim et al. [79]	Active	DC brushless motors	Walk	21	35	–	Can walk at 6 km/h; 7 DOF for each leg; Battery powered
Fan et al. [87]	Passive	Passive variable stiffness joint based on STG	Walk	–	–	45% on average	Variable stiffness material; Stimulated
Zhou et al. [103]	Passive	Clutch composed of gear, rack and unidirectional damper	Stand & walk	63.5	15.8	68.0% (stand) 24.6% (walk)	Simple and passive structure design; High robustness and flexibility
Lovrenovic and Doumit [85]	Passive	Unpowered seat mechanism	Stand & walk	5.68	Body mass of 82	–	Upward stance force between 9.41% and 26.18% of body weight; Upward peak walking force between 14.02% and 27.52% of body weight
Wang et al. [86]	Passive	Seat mechanism, translational hip spring for energy harvesting	Walk	1	Body mass	–	6 DOF; Can be operated without being fastened to body; Reduction in compressive load in the knee
Yan et al. [88]	Passive	Locking mechanism based on ratchet structure	Squat	2	Body mass (68 kg)	–	44.8%–71.5% reduction of EMG; 58.5%–64.2% reduction of plantar pressure; Increase in endurance time from 2.76 to 13.58 min
Zhu et al. [89]	Passive	Locking mechanism based on crank-slider mechanism	Squat	2	Body mass	–	Easy-to-wear; Can reduce the leg muscle activity; Can improve the comfort of squatting operation
Walsh et al. [91]	Quasi-passive	Variable damper	Walk	11.7	36	80%	Requires 2 W of electrical power during loaded walking; Can walk at 0.92 m/s
Van Dijk et al. [92]	Quasi-passive	Variable damper, non-anthropomorphic	Walk	21.8	40	On average 30%, 53% max	Can walk at 1.25–1.47 m/s; Powered by little energy drawn from body
Collo et al. [104]	Quasi-passive	Locking mechanism based on solenoid-controlled pawl and gear	Walk	9	Body mass (65 kg)	–	Low power requirement; Low cost; Low weight
Hao et al. [44]	Active	SRL, hybrid control strategy	Walk	6.5	15	85.7%	4 DOF each robotic limb; Can walk at 0.7 m/s; Can follow the human gait
Leng et al. [99]	Passive	Wheel-legged robotic limb	Walk	1.77	22.18	–	Reduces the vertical load force on the human; Reduces the vertical GRF; Reduces the metabolic power
Gonzalez et al. [100]	Active	SRL, differential mechanism	Walk, squat, crawl	–	–	–	Helps to carry a heavy payload; Helps to reach and maintain difficult postures; Allows high-bandwidth force control

extended and the spine would be kept upright [106,118]. In general, considering the structural complexity of different exoskeletons and the corresponding fitness to the human body, it is necessary to select a suitable transfer pathway
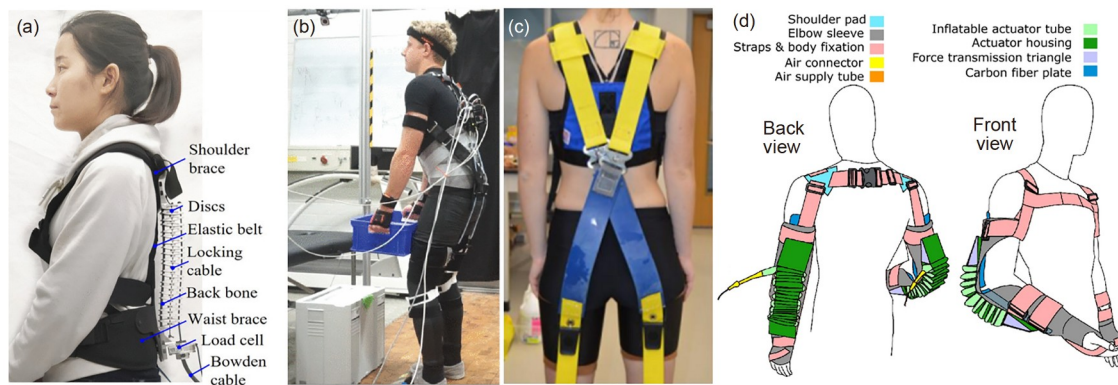
Figure 4   (Color online) Load transfers between body segments. (a) Spine-inspired continuum soft exoskeleton [107]; (b) active exoskeleton with a soft drive [119]; (c) X-shaped passive exoskeleton [120]; (d) pneumatic soft elbow exoskeleton [121].

according to the actual working situation to construct an exoskeleton that transfers loads from the spine to the back, the hips and even the lower limbs to achieve an ideal assisting performance.

In terms of power sources, when external drive sources are involved in the system, the exoskeletons could effectively assist the spine in staying upright and reduce the involvement of back muscles in handling tasks. Therefore, active parallel exoskeleton attracts most attention [107,109,117–124]. Most of these active exoskeletons use rigid actuating elements such as servo motors to transfer the load carried by the spine during handling operations to the lower extremities. A typical example is an active exoskeleton driven by servo motors which are arranged around the waist near the centre of mass of the human body. The tensioned cables connect the waist and shoulders while the waist, knee joints and the soles of the feet are connected through flexible straps. The device is proven to be able to reduce muscle activation in the lumbar rectus by 40% during bending over [109]. However, as the drive element is rigid, the natural movement of the body would be limited to some extent. Therefore, flexible actuators (e.g., artificial pneumatic muscles), shown in Figure 4(b) [119], are proposed to solve this problem. Because of the inherent compliance, it can follow the movement of the body adequately, making the human-machine interaction more friendly. Nevertheless, flexible actuators can only provide limited assistance due to the lack of rigid support elements. The emergence of rigid-flex coupled drives has brought new solutions to these problems. A SEA-based active back support exoskeleton [124] whose actuation element includes support beams and torsion springs beside the DC motor is proposed. This unique design can not only achieve a large torque output up to 81 N m, but also provides lower mechanical output impedance, further improving the assistive capability of the transfer-load-to-the-ground exoskeleton. Although active exoskeletons can significantly reduce the activation of muscles associated with the spine, passive exoskeletons with simple structures and lightweight masses

are also of great importance. Lamers et al. [120] proposed a passive exoskeleton using elastic straps shown in Figure 4(c), which owns the advantages of simple structure and light weight. The elastic band connects the shoulders and thighs in an X shape. During lifting works, the flexion and extension of the lower limbs allow the elastic band to assist in stretching the spine, alleviating the potential injury to the spine and lower back to a certain extent.

There are also semi-active exoskeletons whose power sources are only used for tuning the transfer pathway, expecting to simultaneously possess the advantages of high efficiency of active exoskeletons and lightness and simplicity of passive exoskeletons [118].

Despite the majority scenarios in which protection of the spine is important, there are also some situations require transferring loads between specific body segments. For example, in scenarios where the load should be held for long periods of time (e.g., when raising the arm to drill and firing with a gun), the operator must bear the weight of the tool as well as the reaction forces (e.g., drill reaction force and gun recoil) [102,105], which can cause continuous stress on the human upper extremity and is not conducive to persistent high-precision position retention. As a result, shifting the load from the upper extremity to the waist or other segments can be of great help in operating with high precision and long persistence. In the military, there is a gun-wielding exoskeleton designed specifically for soldiers to fire a gun, where a portion of the gun's weight is transferred from the upper extremity to the waist and hips, reducing the problem of decreased shooting accuracy due to constant upper extremity weight bearing. At the same time, equipment such as shoulder straps can correct the centre of mass of the soldier and the gun, ensuring that the soldier could be stable when moving [125]. Another scenario that needs a special design is load lifting. Except considering protecting the spine, alleviating the strain on the elbow by constructing load transfer pathways between the elbow and the arm or shoulder should be investigated. An elbow-assisting device, shown in Figure

4(d), which adopts a pneumatic drive to provide auxiliary torque was proposed which could achieve reducing muscle fatigue during elbow flexion and muscle activation at the shoulder (trapezius) and wrist (flexor carpi radialis) by transferring the load to the exoskeletal fixation straps at the anterior part of the small arm and the root of the large arm [121]. Table 4 gives the comparison of different exoskeletons that transfer the loads between different body segments.

In general, the transfer of load between body segments can correct the displacement of the body's centre of mass under load to a certain extent, restrain the participation of fragile joints or muscles (protection of the spine is an important implementation), and reduce the chance of potential injuries on the human body [116].

6   Challenges and future trends

It is exciting that with the expanded understanding of human biomechanical principles under loading conditions and the development of the material, driving and control technologies, commercial exoskeleton products with basic assisting abilities have emerged [126–128]. However, the following challenges may need to be overcome to realize large-scale practical applications.

(1) Complete autonomy. To truly accomplish a heavy task in general working condition, exoskeletons must be detached from a fixed platform which provides power to the system and control the motion of the exoskeleton to achieve full autonomy in a complex external environment. However, the conflict between the system autonomy and the output force couldn't be adequately solved by current technology.

(2) Assistive performance and weight penalty. Owing to

the existence of the mass of the exoskeleton itself, the design of the exoskeleton system must maximize the metabolic and assistive benefits obtained while limiting the metabolic loss due to the mass of the exoskeleton to the maximum extent [47].

(3) Transparency. Load-carrying activities will not only increase the human-machine interaction forces but also cause gait variation and increase metabolism if the exoskeleton is not well synchronized with the human body [47]. Therefore, the design of the assistive articular exoskeleton for load-carrying should reduce the interference with the normal movement of human body and improve the wearing comfort [45].

(4) Flexible materials. Biological joints have special properties such as variable stiffness and damping which are obtained from millions of years of evolution to cope with the constantly changing motion needs and the complex environment. Although rigid exoskeleton joints could provide considerable assistive force, it is difficult, if possible, to reproduce these properties and achieve corresponding compliance. Flexible materials which could adequately mimic the biological properties may serve as solutions in the future.

7   Conclusion

In this paper, an overview of existing exoskeletons aiming at improving load-carrying ability is provided. A four-category classification method is proposed according to the different design principles which are mainly concerned with the load transfer pathway and how the load force is alleviated. As the vertical fluctuations of the centre of mass of the body and load system during walking consume a lot of energy while

Table 4   Transfer of loads between body segments

Study	Type	Design methods	Max load capacity (kg)	Exo mass (kg)	Task	Effect joints/segments	Effects type
Ji et al. [113]	Passive	String	20	4.9	Lifting loads	Back	EMG decreased
Kim et al. [105]	Passive	Link	–	6.5	Hand tool work	Upper arm	EMG decreased
Zhang et al. [106]	Passive	Shoulder strap	–	3	Lifting loads	Back muscles	EMG and force decreased
Yang et al. [107]	Active	Elastic elements	–		Lifting loads	Spine	Force decreased
Inose et al. [108]	Passive	Artificial muscle	15	2.9	Lifting loads	Spine	Force decreased
Abdoli-E et al. [109]	Active	Elastic elements	–	–	Lifting loads	Lumbar and thoracic spine	EMG decreased
Näf et al. [110]	Passive	Link	15.7	–	Lifting loads	Spine muscle	Force decreased
Bratic and Noel [117]	Active	Rigid elements	–	–	Lifting loads	Lumbar	EMG decreased
Luo and Yu [118]	Semi-active	String	–	–	Lifting loads	Many muscle	EMG decreased
Muramatsu et al. [122]	Active	Link	30	5.5	Lifting loads	Many muscle	EMG decreased
Lamers et al. [120]	Passive	Elastic bands	12.7	2	Lifting loads	Waist and back	EMG decreased
Nassour et al. [121]	Active	Pneumatic	15	1.85	Lifting loads	Arm joints	Force decreased
von Glinski et al. [123]	Active	Link	12	–	Lifting loads	Back	EMG decreased
Yao et al. [119]	Active	Shoulder strap and string	–	2.4	Lifting loads	Many muscle	EMG decreased

providing no biomechanical benefits, suspended backpack was developed. Lower limb joint torque assistive exoskeleton was proposed for the purpose of reducing the required biological joint torque and corresponding joint pressure. Supernumerary robotic limbs serve as the most intuitive solution which directly transfers the heavy load to the ground while not interfering with the locomotion. The concept of load transfer between different body segments was developed owing to the developing understanding those different segments of the body have various load-bearing abilities. Moreover, in each section, the biomechanics basis, mechanical designs and actuation methods of exoskeletons are discussed in detail. The conflicts between the assistive power and mass penalty, the interference between the exoskeleton and the human body and the autonomy are also investigated to present the challenges and possible future trends of the load-carrying exoskeleton development. Once the obstacles are overcome, advanced load-carrying exoskeleton will be implemented in practical applications and have a concrete impact on society.

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