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TOPICAL REVIEW

Review of Lower-Limb (Quasi-)Passive Exoskeletons for Human Augmentation

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ABSTRACT Researchers have been trying to develop lower-limb exoskeletons to reduce the metabolic cost for human augmentation. The research on (quasi-)passive exoskeletons has gained more widespread attention since the first passive ankle exoskeleton was demonstrated to reduce the metabolic cost of human walking in 2015. Here, we reviewed studies on lower-limb (quasi-)passive exoskeletons for human performance augmentation in the past decade and highlighted key innovations and techniques to enable some of these exoskeletons to achieve the goal of reducing metabolic cost. We reviewed the (quasi-)passive exoskeleton research from three aspects including biological fundamentals for exoskeleton design, assistive principle and mechanical design of exoskeleton, which are the primary considerations of designing and evaluating (quasi-)passive exoskeletons. Lastly, we underlined some practical challenges and emerging trends of (quasi-)passive exoskeleton technology for further enhancing human mobility performance in the future.

INDEX TERMS Wearable robotic exoskeleton, assistive device, lower limb, metabolic cost, walk, run, sit-to-stand, energetic, economy, augmentation.

I. INTRODUCTION

The lower limbs of the human body have a high degree of flexibility, and people can independently and flexibly switch between various gaits and locomotion speeds to adapt to different terrains and accomplish a variety of mobility tasks [1], [2], [3], [4]. Since the early 2000s, researchers have been trying to develop robotic exoskeletons to comply with human lower limbs to complete various movements and provide effective assistance in the process of movement, with the goal of enhancing human locomotor performance [5], [6]. The augmented Lower-limb exoskeletons are designed to enhance human abilities such as locomotion speed, loaded capacity, and endurance [7]. For this type of exoskeleton, the ability to reduce the metabolic cost of human is the gold standard to assess the assistive effect [5], [8]. The powered [9] and passive [10] lower-limb exoskeletons first broke the 'metabolic energy barrier' in 2013 and 2015 respectively. After that, the development of exoskeletons for human augmentation has received increasingly widespread attention over the past decade [11]. The powered exoskeletons can transform the external energy of power resources into mechanical work to assist the human lower-limb muscle groups in driving joint movement, characterized by high adaptability and high-power assistance [12], [13], [14]. However, the assistive duration limitation of energy resources and the metabolic penalty caused by bulky energy resources and actuator units somewhat limit their applications and the effectiveness of the assistance [5]. As an alternative, the (quasi-)passive exoskeletons, which only exploit passive elastic elements and lightweight mechanical/electrical controllers, show lightweight and compliant characteristics [13], [15]. To fully understand the current research status of (quasi-)passive exoskeletons for human augment over the past decade, we conducted this review with the expectation that it will provide guidance for subsequent research on quasi-passive exoskeletons.

To highlight the recent development of (quasi-)passive exoskeleton technology, we compiled peer-reviewed publications that reported the design and evaluation of quasi-passive

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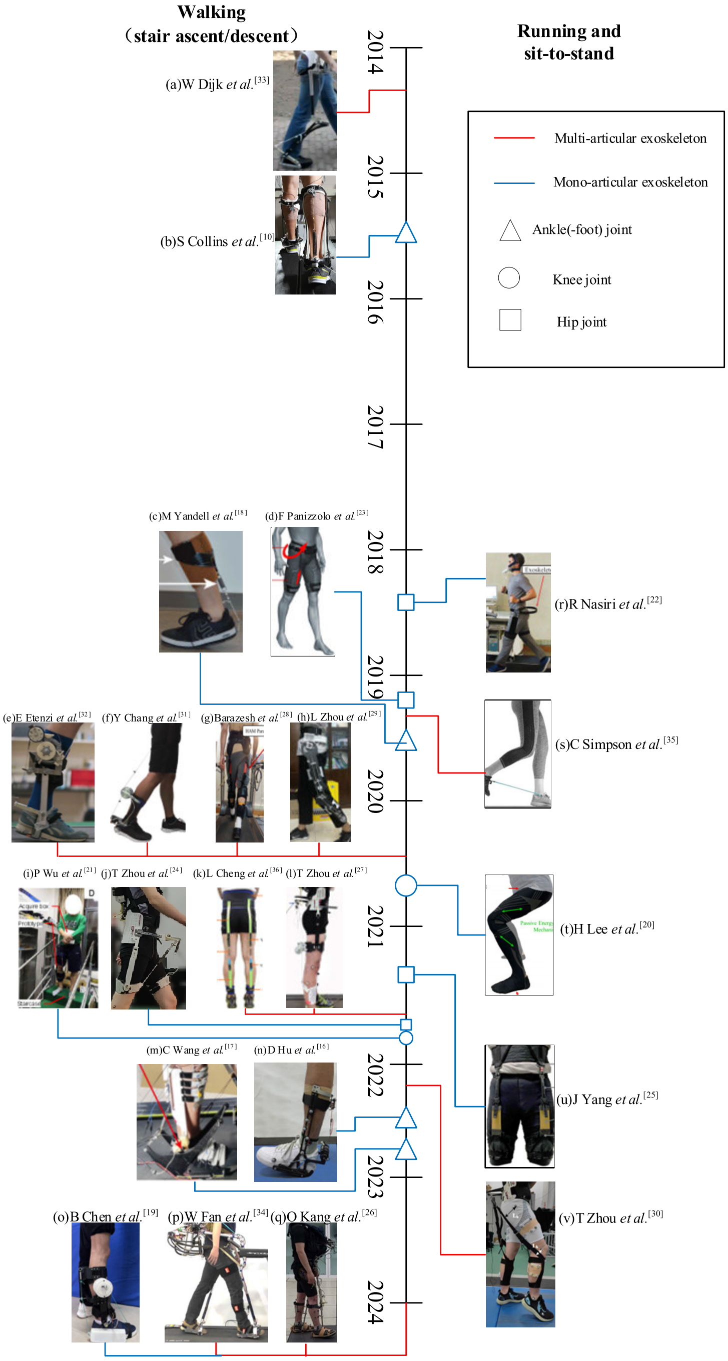

FIGURE 1. **Timeline illustrating the advancement of (quasi-)passive exoskeleton technology. Multi-articular (quasi-)passive exoskeletons (red) and Mono-articular (quasi-)passive exoskeletons (blue) assisting ankle-foot (triangle), knee (cycle), and hip (square) joint during walking (left), stair descent (left), running (right) and sit-to-stand (right) are shown.**

exoskeletons for human augmentation through October 2024. We indexed Web of Science for articles in the English language that included the following topics: (unpowered exoskeleton or unpowered exosuit or passive exoskeleton or passive exosuit or quasi-passive exoskeleton or quasi-passive exosuit or exotendon or quasi-passive device or unpowered device) and (metabolic or energetic or economy) and (walking or running or walk or run or sit-to-stand or stair ascent/descent). We set the time constraint from 2014 to 2024. The keywords search generated 203 journal and conference papers related to the development and evaluation of (quasi-)passive exoskeletons. Among these search results, we did not limit the studies that were demonstrated to reduce the metabolic cost with the exoskeleton assistance but also encompass the exoskeletons that provide effective assistance on local muscle groups or joint levels. In total, 22 publications

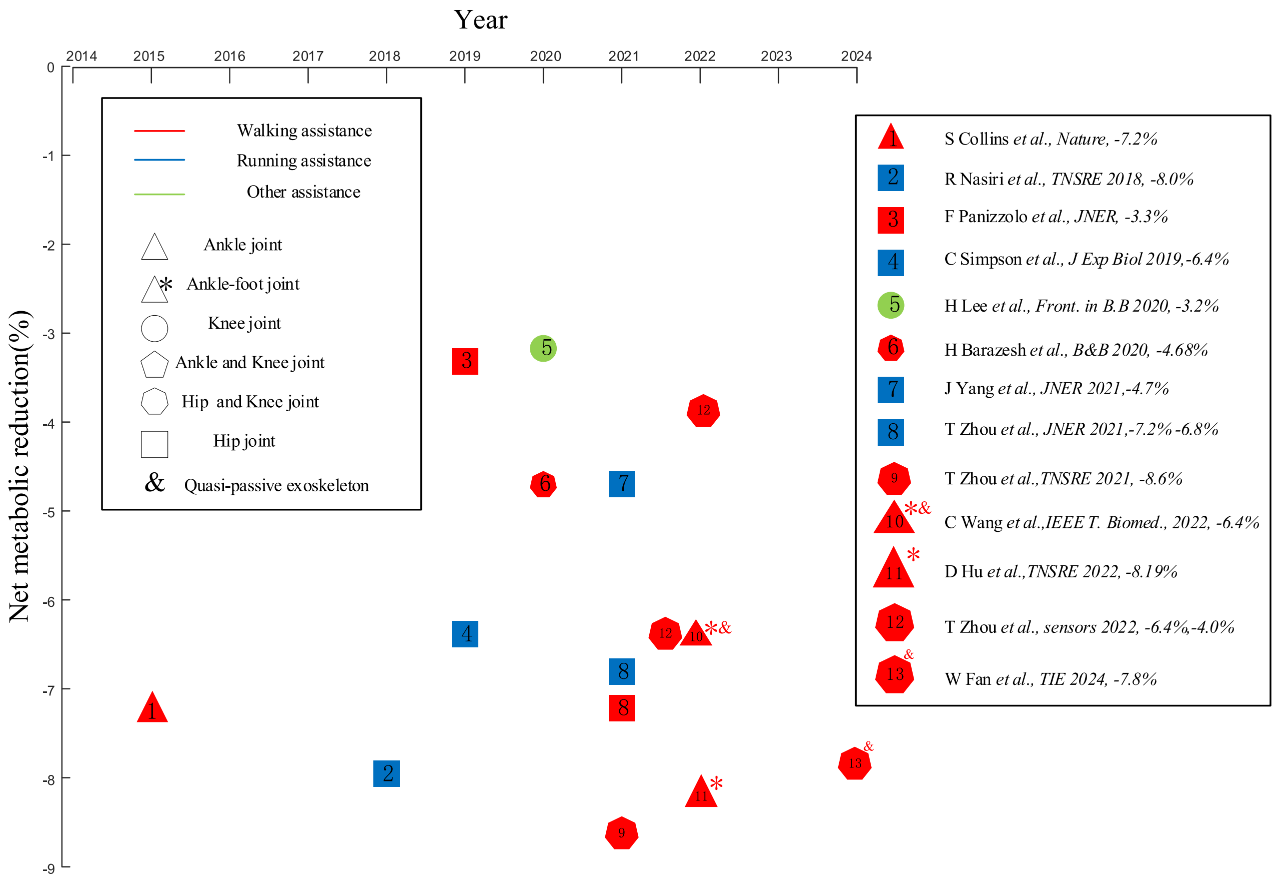

FIGURE 2. The time that each (quasi-)passive exoskeleton research was published versus the change in net metabolic cost versus walking or running or sit-to-stand without using the respective exoskeleton. Red indicates exoskeletons for walking assistance, blue indicates exoskeletons for running assistance and green indicates exoskeletons for sit-to-stand assistance. Different symbols indicate the leg joint(s) that each device directly targets. & indicates special case and cross indicates a passive exoskeleton.

satisfied our criteria (Fig. 1): 12 publications presented the research on mono-articular (quasi-)passive exoskeletons, such as ankle-foot exoskeletons [10], [16], [17], [18], [19], knee exoskeleton [20], [21] and hip exoskeletons [22], [23], [24], [25], [26]; 10 publications present the studies on multi-articular exoskeletons, such as hip-knee exoskeletons [27], [28], [29], [30], knee-ankle exoskeletons [31], [32] and whole lower-limb exoskeletons [33], [34], [35]. 13 publications presented reduced metabolic cost during human walking, running and sit-to-stand with the assistance of an exoskeleton versus without using a device: 8 exoskeletons reduced metabolic cost of walking [10], [16], [17], [23], [27], [28], [30], [34], 5 exoskeletons reduced metabolic cost of running [22], [24], [25], [30], [35], one exoskeleton reduced the metabolic cost of sit-to-stand [20] and two exoskeletons [24], [30] reduced the metabolic cost of both walking and running compared to using no device. These studies demonstrate that net metabolic cost during walking and running can be reduced by 3.3-8.6% and 4.0-8.0% versus using no device (Fig. 2). In other studies, although there were no metabolic energy experiments or the exoskeletons were unable to reduce energy cost, the studies explored a way to provide effective assistance at the joint level [29], [31], [32], [33] and the muscle level [19], [21], [36], such as reducing the specific muscle effort or joint mechanical power.

In this paper, we reviewed the development of lower-limb (quasi-)passive exoskeletons, including mono-articular exoskeletons and multi-articular exoskeletons, which provide assistance for different gaits, such as walking, running, standing, sit-to-stand and stair descent. This review is stated on biological fundamentals for exoskeleton design, mechanical implementation of exoskeleton structure and biomechanical evaluation results. The limitations of the existing (quasi-)passive exoskeletons and future directions for the (quasi-)passive exoskeleton are discussed. This paper contributes to the research on (quasi-)passive exoskeletons by critically reviewing the current state of existing works and development trends to promote future research in design and evaluation.

II. DEVELOPMENT OF (QUASI-)PASSIVE EXOSKELETONS: INSIGHTS AND TRENDS

In the past decade, breakthroughs have been made in both mono-articular (quasi-)passive exoskeletons and multi-articular exoskeletons to reduce the muscle efforts or the metabolic cost during locomotion (detailed device

TABLE 1. Detailed device specifications of (quasi-)exoskeletons for human augmentation.

Number	Leader author	Year	Target joint(s)	Motor pattern	Speed (m/s)	Mode	Exo. mass(kg)	Metabolic reduction(%)	note
1	W Dijk	2014	Ankle, knee, hip	Walk	1.0	Level ground	6.91	N/A	
2	S Collins[	2015	Ankle	Walk	1.25	Level ground	0.91	7.2	
3	R Nasiri	2018	Hip	Run	2.5	Level ground	1.8	8.0	
4	F Panizzolo	2019	Hip	Walk	1.1	Level ground	0.65	3.3	elderly
5	C Simpson	2019	N/A	Run	2.67	Level ground	N/A	6.4	Ankle Attachment
6	M Yandell	2019	Ankle	Walk	1.25	Level ground	0.459	N/A	
7	H Barazesh	2020	Hip, knee	Walk	1.3	Level ground	1.8	4.68	
8	L Zhou	2020	Hip, knee	Stand, Walk	N/A	Level ground	2.2(single leg)	N/A	Gravity compensation
9	Y Chang	2020	Ankle, knee	Walk	1.3	Level ground	0.832	N/A	Quasi-passive
10	E Etenzi[	2020	Ankle, knee	Walk	1.25	Level ground	2.8	N/A	
11	H Lee	2020	Knee	Sit-to-stand	N/A	N/A	0.3	3.2	
12	P Wu	2021	Knee	Walk	self-selected speeds	Stair descent	0.8	N/A	
13	T Zhou	2021	Hip	Walk and run	1.5(walk) 2.5(run)	Level ground	1.3	7.2(walk) 6.8(run)	
14	J Yang	2021	Hip	Run	2.5	Level ground	0.6	4.7	
15	L Cheng	2021	Hip, knee	Walk	1.4	Level ground	0.4	N/A	
16	T Zhou	2021	Hip, knee	Walk	1.5	Level ground	1.86	8.6	
17	D Hu	2022	Ankle-foot	Walk	1.25	Level ground	1.31	8.19	
18	T Zhou	2022	Hip, knee	Walk and run	1.5(walk) 2.5(run)	Level ground	0.55	6.2%(walk) 4.0%(run)	
19	C Wang	2022	Ankle	Walk	1.25	incline and decline slope	1.67	6.4	Quasi-passive, 15%,10%, -10% and -15% grades
20	W Fan	2024	Hip, knee, ankle	Walk	1.1	Level ground	13.87	7.8	30 kg loaded walking
21	O Kang	2024	Hip	Walk	0.14	Level ground	9.8	N/A	12 kgf loaded walking
22	B Chen	2024	Ankle-foot	Walk	1.25	Level ground	0.8	N/A	drop-foot prevention

specifications of (quasi-)exoskeletons are present in table 1). In this paper, we reviewed the development of the (quasi-)passive exoskeletons from the two aspects:

A. FROM MONO-ARTICULAR ASSISTANCE TO MULTI-ARTICULAR ASSISTANCE

Walking is the most common means of locomotion in human daily life, and the first breakthrough in the 'metabolic cost barrier' was made on the passive ankle exoskeleton for walking assistance. In 2015, Collins et al. proposed an ankle passive exoskeleton, which exploited a clutch-spring mechanism to mimic the biological structure of gastrocnemius-tendon, to assist ankle push-off during walking [10](Fig. 1(b) and Table 1). The mechanical clutch, consisting of a ratchet paw and a ratchet wheel(Fig. 3(a)), controls the assistive process based on the ankle joint angle during walking. During ankle dorsiflexion, the clutch engages and the spring is passively stretched. Then, the clutch disengages to make the spring recoil and release energy for ankle plantarflexion. The isometric contraction force of the gastrocnemius muscle and

FIGURE 3. Ankle-foot (quasi-)passive exoskeletons and their specific structures. (a) ankle passive exoskeleton and its clutchspring mechanism [10] (b) ankle passive exoskeleton [18], (c) anklefoot passive exoskeleton and its mechanical controller [16] (d) quasipassive ankle-foot exoskeleton [17] (e) ankle-foot exoskeleton with propulsion module and drop-foot prevention module [19].

the peak positive power of the ankle joint are reduced with the assistance. By passively modulating ankle energy with the exoskeleton, the net energy cost of walking was reduced by 7.2% compared to walking without the exoskeleton. This was the first passive exoskeleton demonstrated to reduce the energy cost during walking. Based on this assistive principle, Yandell et al. developed an adaptive passive ankle exoskeleton, which makes good use of friction under the feet and body weight to fulfill the function of a mechanical controller [18] (Fig. 1(c) and Fig. 3(b)). This new clutch makes the exoskeleton more adaptive for different individuals and allows for a broader range of walking speeds. Although the result of metabolic test was not reported, the soleus muscle activities were reduced by 5-17% with the assistance of this new-type ankle passive exoskeleton.

Although the passive ankle exoskeleton mentioned above showed the ability to reduce the metabolic cost, the activation of antagonistic muscles was increased when the exoskeleton stored energy during dorsiflexion, which may offset part of the assistance effect. Recent biomechanical studies showed that the structures beneath the hindfoot absorb substantial energy during heel strikes in the early stance phase of walking [37], [38]. Ulike the joint motions, the heel strike motion has no specific antagonistic muscles, making it a promising energy resource for the exoskeleton to avoid antagonistic co-contraction [39], [40]. With a further understanding of the biomechanics of the ankle-foot complex during walking, Hu et al. and Wang et al. proposed the passive ankle-foot exoskeleton. [16] (Fig. 1(n)) and a quasi-passive ankle exoskeleton [17] (Fig. 1(m)) respectively, which not only assist gastrocnemius-tendon in recycling energy during dorsiflexion but also recycle the collision energy during heel strike to assist ankle plantarflexion during push-off. The passive ankle-foot exoskeleton proposed by Hu et al. utilized the mechanical clutch, torsion spring, and strike-recipient mechanism(Fig. 3(c)) to realize the assistive process of energy storage from heel strike, energy retention, and energy release to ankle push-off. The whole process is controlled by the ratchet-pawl-trigger mechanism of the mechanical clutch. The muscle activation of target ankle plantarflexors decreased significantly without added effort for the antagonistic muscle under the assistance, leading to an 8.19% metabolic reduction [17] (Fig. 2). Wang et al. recycle the heel-strike energy loss to assist ankle push-off more adaptively by developing a quasi-passive exoskeleton. The assistive process was controlled by an electrical clutch based on the pressure signal of the forefoot(Fig. 3(d)), making it available to use in different terrains, such as incline/decline slopes. Level-ground experimental results showed that the metabolic cost can be reduced by 6.4% compared to normal walking [17] (Fig. 2). As the passive exoskeletons show lightweight characteristics, there is more room for versatile mechanical design with low a metabolic penalty. Chen et al. proposed a portable passive ankle-foot orthosis(AFO) for both walking propulsion and drop-foot prevention [19]. The AFO consists of a propulsion module and a drop-foot prevention module (Fig. 3(e)). The propulsion module recycles the negative mechanical work during dorsiflexion by spring-A and releases the stored energy to assist propulsion with the control of the clutch-A mechanism. During the energy-releasing phase of spring-A, spring-B stores part of the released energy and provides ankle with dorsiflexion torque to raise wear's foot. During the swing phase, the clutch-B mechanism engages and prevents foot drop. The experimental results demonstrate that during a gait cycle, reductions of 7.74%, 6.72%, and 16.36% of the average muscle activities of the gastrocnemius, soleus, and tibialis anterior are observed, respectively.

During human walking, the apparent efficiency of hip musculature in converting metabolic energy to positive mechanical work is only 24%, which is lower than that of ankle musculature(61%) [41]. The previous studies showed that elevated energy cost is a hallmark feature of gait in elderly individuals and is most likely caused by multiple factors, including changes in neuromuscular and gait mechanics [42]. Aging causes an increased reliance on the hip rather than on the ankle to power walking [43], [44]. To enhance the energy efficiency of hip musculature, Panizzolo et al proposed a hip passive exoskeleton [23] (Fig. 1(d)) for hip flexion assistance, which utilizes an elastic band(Exoband)(Fig. 4(a)) in parallel with the hip flexors to passively store energy with hip extension and release the stored energy to assist hip flexion. The experimental results showed that the metabolic rate of the elderly can be reduced by 3.3% with the hip flexion assistance.

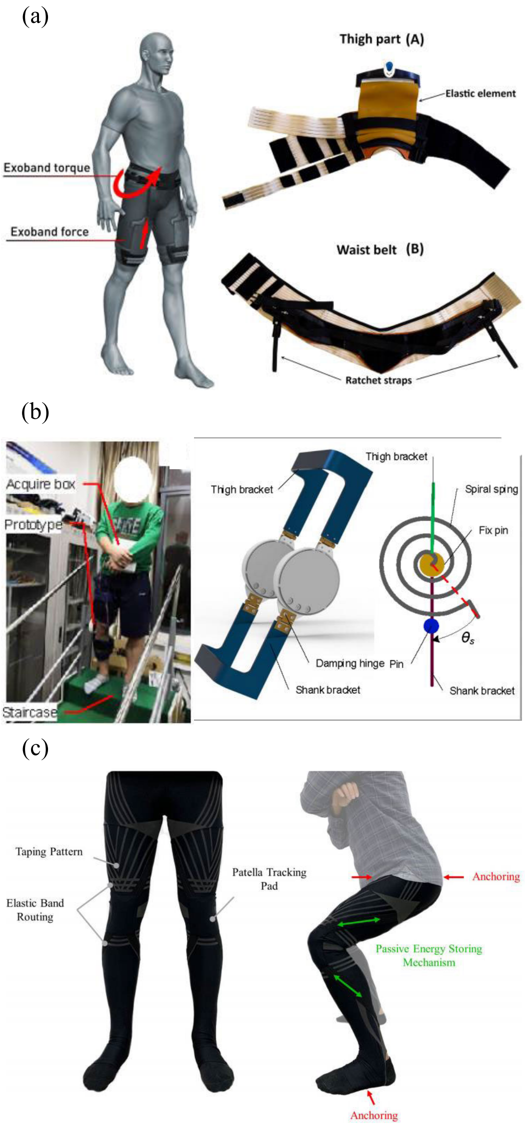

FIGURE 4. Hip and knee passive exoskeletons for walking, stairdescent and sit-to-stand assistance and their structures. (a) hip exosuit providing hip-flexion assistance for old adults [23], (b) knee passive exoskeleton for stair-descent assistance [21], (c) knee passive exosuit for sit-to-stand assistance [20].

Although the knee musculature mainly produces negative mechanical work during locomotion to decelerate motion, it may be effective for exoskeletons to assist in performing negative mechanical work to reduce muscle efforts. Wu et al. proposed a passive knee exoskeleton to assist stair descent [21]. The custom-built spiral spring of the exoskeleton (Fig. 4(b)) assists knee extensors in performing negative mechanical work during knee flexion and then releasing the stored energy to assist knee extension. In this way, the exoskeleton enhanced the efficiency of converting gravitational potential energy to mechanical work during stair descent. The experimental result showed that the average muscle activity of the rectus femoris reduced by 6.12%-13.54% with the assistance. However, the muscle activity of biceps femoris increased by 1.6%-8.99%. So, further experiments on metabolic cost should be conducted to verify the effectiveness of the exoskeleton assistance.

Sit-to-stand is also recognized as one of the most challenging activities of daily living due to the high knee torque required, especially for old adults with poor knee extensor strength. Lee et al. developed a fully soft and passive exosuit(X-tights) to assist knee extension during sit-to-stand [20]. The total weight of the X-tights exosuit, which uses only soft and passive components, is merely 300 grams. The X-tights routed the elastic bands across the front of the knee to stretch and store energy when sitting and then return it when standing to assist the sit-to-stand (Fig. 4(c)). The stiffness of the elastic band was determined at 470 N/m based on the waistband threshold pressure and coefficient of friction to prevent slipping and ensure comfortable wear. The experimental results showed that the metabolic rate of sit-to-stand can be reduced by 3.2% with assistance compared to sit-to-stand without exosuit.

Although it has been found that metabolic cost can be reduced by passively modulating mono-articular energy with an ankle, hip or knee passive exoskeleton, how to modulate multiarticular energy remains a challenging problem in early studies. First, the effects of assistance are more likely to be offset by the misalignment between exoskeleton structure and biological joint [32], [45], [46], [47], [48] and metabolic penalty caused by the complex structure of the multiarticular exoskeleton [49], [50]. The mechanical structure of a multiarticular exoskeleton is more complex than that of a monoarticular exoskeleton. Moreover, it will cost human more energy to produce positive and negative mechanical work to accelerate and decelerate lower limbs when the mass of the multiarticular exoskeleton is added to human lower limbs during locomotion. In addition, multi-articular assistance is more likely to interfere with the natural biomechanics of the lower limbs during human walking [33]. Early studies on multi-articular passive exoskeletons mainly focused on the energy recycling function [28], [33], [36]. Dijk et al. proposed a multi-articular passive exoskeleton (XPED 2) [33] (Fig. 1(a)) based on the concept of exotendon [51], which exploited a multi-articular exotendon to assist hip flexion and ankle plantarflexion during walking in a coupled manner (Fig. 5(a)). The high-strength rope (Dyneema cable) of the exoskeleton extends from the lever of the pelvis through a knee pulley to a leaf spring at the foot. The leaf spring will be stretched to store energy during hip extension and ankle dorsiflexion, then release the stored energy to assist hip flexion and ankle push-off. Although the experimental results show that the average torque of the three joints was reduced by 12.1% with the assistance, the metabolic rate increased by 27% compared to walking without the exoskeleton. The authors attributed the reason to the fact that the coupled assistance of the exoskeleton may interfere with the natural energy recycling of the tendons and energy transfer of bi-articular muscles. Inspired by the balance maintenance function of biarticular muscles, Barazesh et al. proposed a biarticular passive soft exosuit [28] (Fig. 1(g)), which utilizes two bi-articular exotendons to work in parallel to the rectus femoris and hamstring muscles(Fig. 5(b)), respectively, to enhance balance control during walking. Although the experimental result showed that the metabolic cost of walking by 4.7%±4.24%with the assistance(Fig. 2), the high standard error indicated a high variance among different individuals. Cheng et al. proposed a portable exosuit [34](Fig. 1(k)), which utilizes biarticular exotendons to work in parallel with the hamstring muscle group to decelerate the leg swing at the end of the swing phase(Fig. 5(c)). And they found that the exoskeleton reduces the peak muscle activity of the semitendinosus during walking. Although the assistance of the multi-articular exotendons has been proven to be effective at the muscle and joint levels, multi-articular assistance in a coupled manner was not ideal for metabolic reduction.

The human lower limbs not only utilize tendons to recycle energy and improve the energy efficiency of single-joint musculature [52], [53], [54], [55], but also improve the overall work efficiency of the whole lower-limb musculature by transferring energy between joints through lower limb body segments and bi-articular muscles [56], [57], [58], [59], [60], [61]. Recent studies on multi-articular passive exoskeletons have gradually focused on the energy transfer function of the exoskeleton. Etenzi et al. and Chang et al. proposed the assistive principle of recycling the kinetic energy of the knee joint during the late swing phase to assist ankle push-off by a quasi-passive knee-ankle exoskeleton [31] (Fig. 1(e)) and passive knee-ankle exoskeleton [32] (Fig. 1(f)) respectively. The major difference between the two exoskeletons is the controller. The passive knee-ankle exoskeleton proposed by Etenzi et al. utilized a mechanism of ratchets and pawls to recycle elastic energy through compression and release of metal springs that act in parallel with the knee and ankle, respectively (Fig. 5(d)). The quasi-passive exoskeleton proposed by Chang et al. utilized an electronic clutch, which consists of a motor, ratchet mechanism (Fig. 5(e)), and torsion spring to control the assistive process. The preliminary experimental results showed reduced negative biological work at the knee joint during late swing and at the ankle joint during mid stance with assistance, which demonstrated the effectiveness of the exoskeleton at the joint level. Inspired by the double actuation and energy transfer function of biarticular muscle, Zhou et al. proposed a hip-knee passive exoskeleton [27] (Fig. 1(l) and Fig. 5(f)), which assists hamstrings in recycling part of kinetic energy from the knee joint during the late swing phase and releases the stored energy to assist hip extensors to produce positive mechanical work during stance phase. The metabolic cost can be reduced by 8.6% compared to walking with no exoskeleton(Fig. 2). This research also demonstrated that the passive exoskeleton can enhance the walking economy by adding a complementary loop for efficient energy recycling and energy transfer.

As the passive exoskeletons store energy from human motion, assistive torque for the target muscle group may lead to antagonistic co-contraction [10]. The ankle-foot exoskeletons avoid the antagonistic co-contraction by recycling the energy in the heel strike motion instead of ankle dorsiflexion.

While ankle-foot exoskeletons can avoid antagonistic co-contraction, the hip-knee passive exoskeletons also found ways to avoid co-contraction. As mentioned above, In [27], [28], [36], they proposed hip-knee passive exoskeletons to provide both hip and knee joints with assistive torque during human walking. The experimental results showed that direct utilization of exotendon working in parallel to the biarticular muscle group, such as hamstrings, may lead to antagonistic co-contraction with varying degrees. It may be an effective way to choose a suitable stiffness of exotendon to avoid a significant increase in antagonistic co-contraction. As both Cheng and Barazesh chose suitable stiffness of exotendon, the increase of antagonistic muscle activation was insignificant. Zhou et al. proposed a hip-knee exoskeleton that utilizes biarticular exotendon and mechanical clutch to realize phased energy modulation. In the late swing phase, the biarticular exotendon assists hamstrings in storing part of mechanical energy of swing leg while providing both hip extension and knee flexion torque. In the following stance phase, the exotendons only provide hip extension torque with the control of mechanical clutch. In this way of energy modulation, the activation of rectus femoris (major knee extensor) did not show a significant increase, which means the assistive torque of exoskeleton did not result in significant antagonistic co-contraction. This way of phased energy modulation by exoskeleton is another way to avoid significant antagonistic co-contraction.

B. FROM ASSISTANCE FOR SINGLE GAIT TO ASSISTANCE FOR MULTIPLE GAITS

Along with the breakthroughs in research on exoskeletons for walking assistance, researchers are also exploring how to develop exoskeletons to reduce the metabolic cost of running. Running is an inefficient form of locomotion, as it will cost human more metabolic energy to run than walking or swimming the same distance. With the increase in locomotion speed, people will spontaneously switch from walking gait [4], [62] to running gait [63], [64], and the average positive joint power in running gait is significantly higher than that of walking [65], [66], [67], [68]. The proportions of ankle, knee, and hip mechanical work produced by lower-limb musculature also differ from that of walking [68], [69]. It has been found that 65 - 82% of metabolic energy is used to accelerate and decelerate the body's center of mass in the vertical and horizontal directions, and about 7% of the energy is used to swing the legs [70]. Metabolic penalty caused by the mass of the exoskeleton is another critical factor affecting the effectiveness of exoskeleton assistance, especially in running. The metabolic penalty coefficiency [71] of adding mass to human lower limb during running is 1.4-4.4 times that of walking [72], [73], [74].

Nasiri et al. from the University of Tehran developed a passive exoskeleton based on the biomechanics of running at the hip joint [22] (Fig. 1(r)), which utilizes a torsion spring to

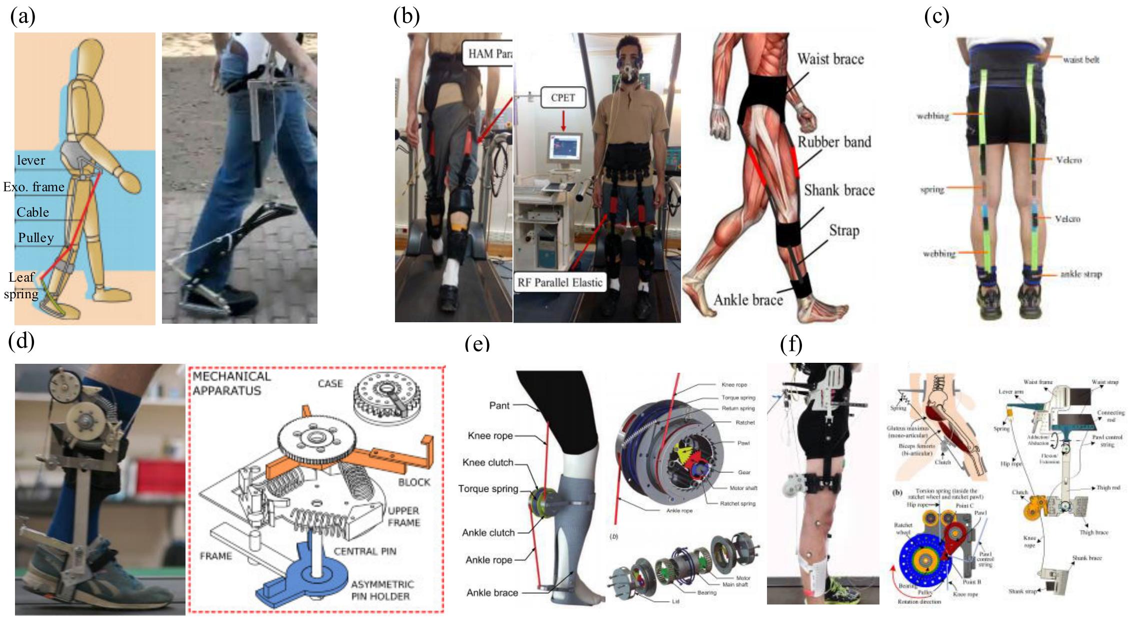

FIGURE 5. **Multi-articular (quasi-)passive exoskeletons and their mechanical structures. (a) XPED2 [33] (b) hip-knee passive exoskeleton for balance assistance [28] (c) hip-knee exosuit for hamstrings assistance [36] (d) knee-ankle passive exoskeleton and its mechanical controller [32] (e) quasi-passive knee ankle exoskeleton and its mechatronic controller [31] (f) hip-knee passive exoskeleton and its mechanical controller [27].**

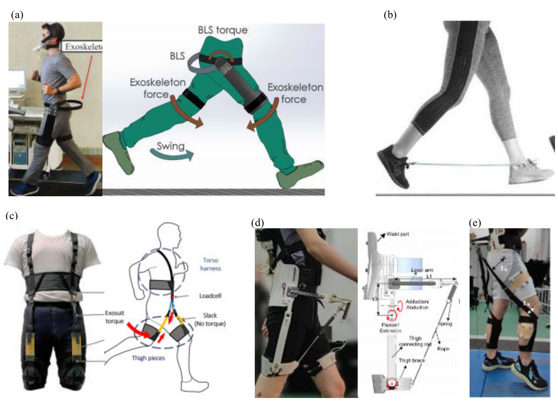

FIGURE 6. **Passive exoskeletons for running or multiple gait assistance and their configerations. (a) hip passive exoskeleton for running assistance [22] (b) exoband for running assistance [35] (c) hip exosuit for running assistance [25] (d) hip exoskeleton for both walking and running assistance [24] (e) hip-kne exosuit for both walking and running assistance [30].**

assist the bilateral hip joints in a coupled manner (Fig. 6(a)). When the bilateral hip joints produce an angular difference, the kinetic energy of one hip joint is recycled to assist the contralateral hip extensors in producing positive work. The metabolic cost was reduced by 8% relative to no exoskeleton (Fig. 2). This is also the first passive exoskeleton capable of reducing the running metabolic rate. Simpson et al. utilized an exotendon [35] to connect the left and right feet (Fig. 1(s)), recycling kinetic energy from the front swing leg while assisting the back leg to swing forward during running (Fig. 6(b)). With the assistance of the exotendon, the stride frequency of running increased. And the higher stride frequency results in shorter stride length, which means that the human body did less mechanical work on the center of mass. In this way, the metabolic rate of running decreased by 6.4% relative to running without the exotendon [35] (Fig. 2). Yang et al. designed a hip passive exosuit, which was fabricated using textile materials and elastic bands (Fig. 6(c)), to assist hip flexion. They also found that the energy cost of both walking and running can be reduced by 4.7% with the hip-flexion assistance.

While the research on exoskeletons assisting a single gait (walking or running or it-to-stand) has made breakthroughs, researchers gradually focus on the versatility of exoskeletons to develop exoskeletons that can simultaneously reduce metabolic energy consumption for multiple gaits [74], [75]. However, biomechanical differences between walking and running gaits are a critical factor influencing the effectiveness of exoskeleton assistance [66], [76]. With increasing locomotion speed, people spontaneously switch from a walking gait similar to an alternating inverted pendulum [4] to a more bouncing running gait [63], [76], [77], with the disappearance of the double-stance phase and the emergence of the double-swing phase, and significant changes in lower limb kinematics, muscle mechanics [65], and joint mechanics [68] occur. Differences in biomechanics between gaits may result in assistive principles, applicable to one gait being inapplicable to another [78]. The optimal magnitude and pattern of exoskeleton assistive moment may also differ between different gaits [78]. As the previous ankle passive was successfully reduced the metabolic cost of walking, Stanford University utilized an exoskeleton simulator [78] to apply this passive assistance to the ankle joint during running. Experimental results showed that the spring-like assistance increased metabolic rate by 11.1% compared to running without the exoskeleton. Similarly, when the passive hip exoskeleton proposed by Nasiri et al. was applied to walking gait, the metabolic cost cannot be reduced, possibly due to the biomechanical difference of hip joint during the late swing phase between the two gaits [22]. In order to reduce the metabolic cost of both walking and running, Zhou et al. developed a passive hip exoskeleton [22] regulating the metabolic energy of hip flexion during the common energy consumption period of the two gaits (Fig. 1(v)). The exotendon acts in front of hip flexors to store energy during hip extension and releases stored energy to assist hip flexors in the initial leg swing(Fig. 6(d)). The metabolic cost of both walking and running can be reduced by 7.2% [24] (Fig. 2). The biarticular exo-tendon of another multi-articular passive exoskeleton [30] proposed by Zhou et al. assists the hamstrings in recycling the kinetic energy of the leg swing while providing hip extension torque in the swing phase (Fig. 6(e)). In the following stance phase, the exo-tendon releases the stored energy to assist the co-contraction of gluteus maximus and rectus femoris for both hip extension and knee extension, thus realizing the phased modulation of hip and knee joint energy. The metabolic rate of both walking (1.5 m/s) and running (2.5 m/s) can be reduced by 6.2% and 4.0% (Fig.2) with the multiarticular energy modulation of a hip–knee passive exoskeleton, compared to that of walking and running without an exoskeleton [30].

III. LEADING APPROACHES AND TECHNOLOGIES FOR ADVANCING EXOSKELETONS

A. THE VERSATILE DESIGN OF THE (QUASI-)PASSIVE EXOSKELETON

Most existing passive exoskeletons were only demonstrated to reduce the metabolic cost during a single gait, as most of them were designed based on the biomechanics of the human lower limb during a specific gait [12]. However, how to design the passive exoskeleton to provide effective multi-articular assistance during multiple gaits is still a challenging problem [30]. The kinematics and biomechanics of the lower limb show significant differences among different gaits, such as walking, running, and jumping, which may be the major factors that hinder the existing passive exoskeletons from multiple gait scenarios. The previous study on a passive exoskeleton for hip flexion assistance [24] showed that exploiting the common energy consumption period of walking and running is a valid method to develop an exoskeleton. However, when it comes to multi-articular passive exoskeleton, the mechanical controller, which is designed based on the kinematics of specific gaits, may not be applied in other gaits due to the differences in kinematic range among different gaits. So the passive exoskeleton showed fixed mechanical properties [5], [11]. Suppose we want to expand the versatility of the passive exoskeleton from single gait assistance to multiple gait assistance. In that case, research on more flexible quasi-passive exoskeletons with passive structures and electrical controllers may be an effective technical way [17], [34].

As the metabolic cost is the gold standard for assessing augment exoskeleton performance, most research on lower-limb passive exoskeleton only performs experiments to test whether the metabolic cost can be reduced with assistance. The other indices are also essential for actual use, such as mobility during loaded locomotion, and the maximum load carriage ability during locomotion [79], [80], [81], [82]. The previous study on the hip exoskeleton showed that the kinematics of human walking can be enhanced by applying stiffness to the hip joint [83]. While the passive exoskeleton assists the human lower limb to store and release energy, it also provides human lower-limb joints with passive stiffness, which may enhance human mobility during loaded locomotion [83], [84]. Therefore, innovation of passive assistive principle may be explored, such as phased compensation of multi-articular stiffness, to reduce the metabolic cost while increasing locomotion velocity. Another direction may be the combination of a passive lower-limb exoskeleton with other assistive devices, such as powered backpack, trunk exoskeleton and so on. Previous studies showed that the active control of inertial force of the loads with a powered backpack can reduce metabolic cost of walking [85]. The combination of modulating the inertial force of the loads with powered backpack and lower-limb energy with passive exoskeleton may achieve further metabolic reduction during loaded walking.

B. COMBINATION OF PASSIVE AND ACTIVE EXOSKELETON ASSISTANCE ACCORDING THE BIOMECHANICAL CHARACTERISTICS OF LOWER LIMB JOINTS IN DIFFERENT GAITS

The previous study showed that both passive and powered assistance on the lower limb can reduce the metabolic cost of human locomotion. However, the two types of exoskeleton showed different features [12], [13]. Both powered and passive exoskeletons have their own advantages, and they may be complementary to each other. Powered exoskeletons showed the characteristics of high adaptability and high-power assistance due to advanced control framework [86], powerful motor and quasi-direct drive actuator. These advantages make the powered exoskeletons more effective in reducing the metabolic cost during walking than passive exoskeletons. And they are promising to be applied in the real world. As for passive exoskeletons, they do not need power resources and powerful motors, making them have no limit on the duration of assistance. In addition, the advantages of passive exoskeletons are also reflected in its lightweight and compliant characteristics. As shown in Table 1, the weight of (quasi-)passive exoskeleton ranges from 0.3kg-13.87kg. Most passive exoskeletons have a mass of less than 3 kg. Some passive exoskeletons are only made of soft material, making them great wearability and compliant, such as X-lights proposed by Lee et al. (300 grams) for sit-to-stand assistance. The lightweight characteristic makes it have more room for versatile mechanical designs. For example, the ankle-foot passive exoskeleton not only has the propulsion module for walking assistance, but also has the mechanism for drop-foot prevention function, while achieving the reduction in muscle activities of both plantarflexors and dorsiflexors. Furthermore, the lightweight characteristic makes passive exoskeletons have the advantage of reducing more metabolic penalty during running and achieving more metabolic reduction. The metabolic penalty coefficient of added mass during running is 1.4-4.4 times that of walking [72], [73], [74]. The passive hip exoskeleton proposed by Nasiri et al. can reduce metabolic cost of running by 8.0% compared to wearing no exoskeleton.

Therefore, a new type of pseudo-passive exoskeleton, which combines the complementary features of active and passive exoskeletons, may be a promising future direction for exoskeleton research. It is worth mentioning that the combination of passive and powered assistance should consider the biomechanical characteristics of human joints among different gaits. As the assistive principle, demonstrated to be effective for one gait, may be unavailable to other gaits. The reason may be related to significant changes in biomechanical characteristics when switching gaits [78].

IV. CONCLUSION

This paper reviewed the current state of research and development trends in augmented (quasi-)passive exoskeletons not only for walking and running assistance, but also for other challenging tasks in daily life, such as sit-to-stand and stair ascent/descent, from the aspects of biological fundamentals for exoskeleton design, assistive principle and mechanical design of exoskeleton. We emphasized the consideration of different biological fundamentals between gaits for exoskeleton design, especially for multi-functions of exoskeleton. This review highlighted both the advantages of (quasi-)passive exoskeletons, such as their lightweight and compliant characteristics, and their limitations on fixed mechanical properties that can not provide human with adaptive assistance according to variable conditions. The paper also discussed the future directions for passive exoskeletons based on their characteristics and current state of research. Specifically, the lightweight characteristic of passive exoskeletons makes it have more room for versatile mechanical design, such as assembling both walking assistance and foot-drop prevention on ankle-foot exoskeleton, with less metabolic penalty compared to powered exoskeletons. We also discussed the possible effective technical ways to promote passive exoskeletons from laboratory prototypes to large-scale applications, such as integrating the passive assistive principle and active controller to make the passive exoskeleton more flexible. A new type of pseudo-passive exoskeleton, which combines the complementary features of active and passive exoskeletons, may be a promising future direction for exoskeleton research. This paper contributes to the research on (quasi-)passive exoskeletons by critically reviewing the current state of existing works and development trends, summarizing advantages and limitations and highlighting the possible technical ways to promote future research in design and evaluation.

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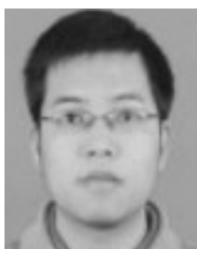

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