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# Recent Development of Unpowered Exoskeletons for Lower Extremity: A Survey

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**ABSTRACT** Unpowered exoskeletons (UEs) have attracted extensive research attentions for their portability, handleability and simplicity. However, designing exoskeletons without any active actuators is a great challenge because essential criteria such as performance enhancement, low impedance, and comfort must be met. This paper reviews the UEs researches from three aspects including modeling for understanding gait pattern, mechanical designs, and validation methods, which are main considerations of designing UEs. This review is based on the reported works in the past two decades and underlines some practical opportunities and challenges. Statistical data analysis and critical reviews are stated to understand human gait patterns, designing of UEs, and ergonomic validation. This review is trying to inspire a common understanding about passive exoskeletons for lower extremity and promote discussion among researchers, developers, or robotic practitioners.

**INDEX TERMS** Biomechanics, exoskeletons, ergonomics, robotics, unpowered and passive assistance.

## I. INTRODUCTION

Human lower limbs are capable of many different motion patterns, which help human adapt to complex terrains for safe and effective fulfillment of various tasks. Exoskeletons are used to enhance human abilities such as speed, strength, and endurance [1], [2]. Powered exoskeletons (PEs) are systems that transfer electric, pneumatic, or hydraulic energy to mechanical power through active actuators regulated by designed control strategies. The technical implementation of PEs can be divided into five aspects: design, modeling, sensing, actuation, and control. Unpowered exoskeletons (UEs) are simpler than PEs as UEs do not need any active drivers or actuators and complex motion control algorithms, generally. UEs have been studied since 1890 [3] and have drawn increasing attention in recent years, as shown in figure 1. However, there are still significant challenges in UEs designs to meet requirements in terms of performance enhancement, low impedance, and comfort [4]. To fully understand the efforts on UEs, this paper reviews the published works on UEs from 2001 to June 2021 in Web of Science database [5] and aims to provide guidance for future research.

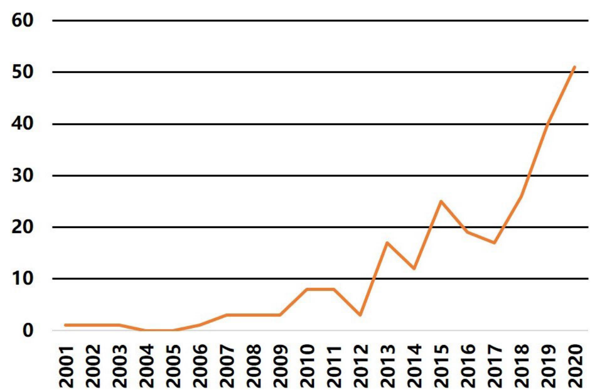


**FIGURE 1.** Statistical results about UEs. The increasing trend of reported works about UEs in the past two decades, given by the number of Web of Science papers in each year.

When the papers were reviewed, keywords "unpowered exoskeleton" or "passive exoskeleton" are combined with "human assistance" to search and collect the published literatures. The keywords search generated more than

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230 journal and conference papers related to human passive assistance. Based on their contents, the research focuses of these papers can be categorized into three aspects: modeling methods for designing, prototype design of UEs, and validation methods.

The exoskeletons mentioned in the surveyed articles all focus on one single or several human body parts of lower extremities. Figure 2 shows the target body parts that are most habitually used in daily activities such as eating, standing, and walking. The category "Others" in figure 2 refers to devices that are used in integrated assistance (e.g., tilt table for respiratory rehabilitation [6], crutches for balancing or navigating [7] etc.). The figure shows there are considerable research interests in lower limbs especially pelvis, hip, knee, ankle, and full leg. It shows that knee and ankle have the most and comparable percentage. Passive exoskeletons studied in the references cover human activities of daily living such as sit-to-stand [8], walking [9], running [10], [11], and even rehabilitation [12]. There are still great needs of more sophisticated UEs for efficient assistance of multiple functions.

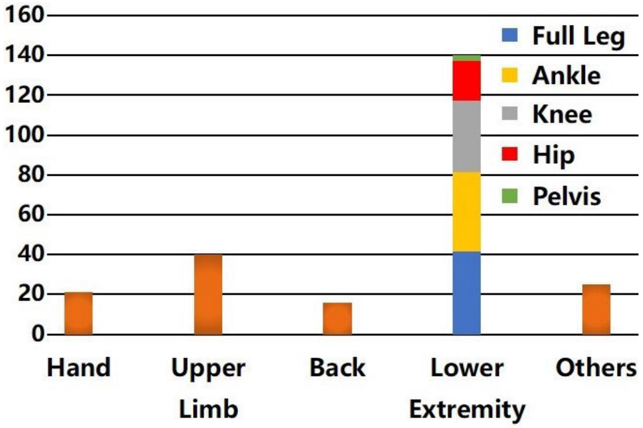


**FIGURE 2.** UEs' target body parts researched in published papers from 2001 to 2020 given by histogram. Distribution diagram of parts in lower limbs.

Human hip, knee, and ankle play different roles during walking. From the perspective of doing mechanical work, hip joint mainly produces positive work, which is about five times negative work [13]. And the efficiency of converting metabolic energy into positive mechanical work of the lower extremity during walking is 61%, 24%, and 24% for hip, knee, and ankle joint respectively [14]. The knee joint mainly produces negative work, which means the direction of net muscle force is opposite to the joint moment and absorbs the shock from ground. The ankle joint mainly produces positive work. From the perspective of the composition of muscle tissue, hip joint is driven by long muscle fiber and a few long compliant tendons with low tendon elasticity. Knee joint is driven by long muscle fiber with low elasticity. But ankle joint is driven by short muscle fibers and long compliant tendons with high tendon elasticity. The tendon functions like a spring that can be stretched at swing phase and recoiled at the end of stance phase.

In this paper, we reviewed the development of UEs for lower extremities including exoskeletons for single joints of lower extremity, exoskeletons for multiple joints of lower extremity, and exoskeletons attached to lower extremities. These UEs mostly provide assistance for walking, running, cycling, standing, and supporting. This review is stated from three levels: modeling methods for designing, prototype design of UEs, and validation methods. Modeling is used for human motion analysis, motion prediction, or designing UEs and it helps researchers understand human gait pattern. The structure contains the most important components to mechanical design of UEs. Validation methods use kinematics, kinetics, or biometric measurements to identify the effectiveness of the modeling and design. The limitation of the existing UEs and inspiration from different application fields are discussed. Details and relationships of the three aspects are also discussed along with the three criteria of performance enhancement, low impedance, and comfort. In the review of each aspect, some discussions of limitations and improvements are provided for future reference. This paper contributes to the UEs research by providing a critical review of existing works in terms of the three categories, proposing some statistical analysis, and promoting future research in modeling and design.

## II. MODELING FOR UNDERSTANDING GAIT PATTERN

Understanding human gait pattern is critical to realize human augmentation with either PEs or UEs. Modeling for lower extremity is widely used for human motion simulation such as motion analysis, robotic control, motion prediction, and product prototype design. For the UEs, modeling can be used for performance prediction, structure design, and motion analysis. Modeling methods for UEs can be divided into physical-based models and bionic models. According to their complexity, physical-based models can be classified into three groups as center of gravity (COG) models, joint models, and musculoskeletal models. Bionic models transform biological characteristics into mathematical forms by uncovering the quantitative feature of morphology. Human and animals provide natural references, such as biological structures and tissue configurations, which guide high-efficient UEs design.

### A. PHYSICAL-BASED MODELING

#### 1) COG MODEL

The inverted pendulum model (IPM) is the most classic COG model for walking simulation [15]. It describes abstract gait information by focusing on the trajectories of the COG and modeling legs as an elastic link with variable length and stiffness. It can be used to predict energy consumption and the ground reaction force (GRF) for walking and generate the trajectory of the COG, which is related to rehabilitation assessment. There are several classic IPMs as illustrated in figure 3, in which (a)-(c) are passive models, (d)-(e) are driven by impact, and (f) is an active model. Cavana *et al.* [16], [18] proposed the first IPM to express human gait. Double support (DS) phase and Single support (SS) phase are proposed to describe the transition between gravitational potential energy of COG and the horizontal kinetic energy (figure 3(a)). DS phase and SS phase are important signals to control the timing of releasing the external energy.

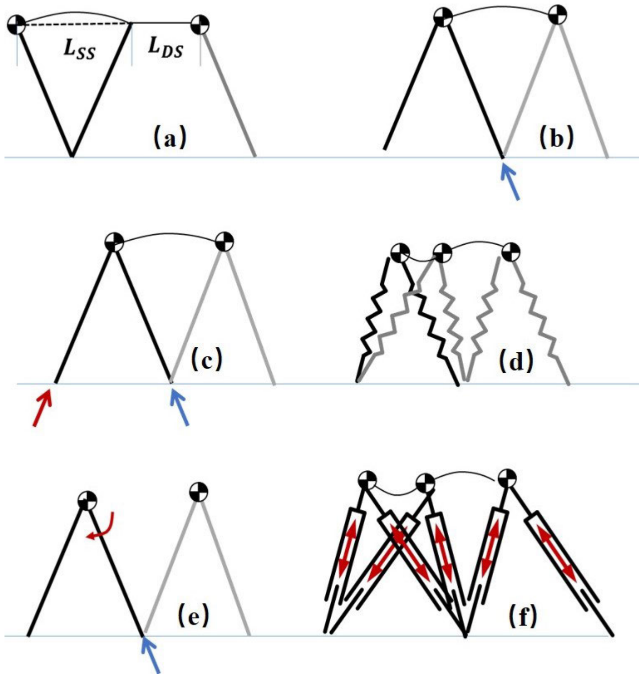


**FIGURE 3.** **Simplified schematic of planar inverted pendulum.**

Garcia *et al.* [18] proposed a simplified gait model that considers DS phase as instant impact and discussed the model stability. Simulation verified that the simplified model can walk steadily and continuously on the downward slope, as shown in figure 3(b). Mcgeer [19] developed a toy realizing periodic walking on downward slope without consuming external energy and control. Spring load inverted pendulum model (SLIPM) (figure 3(c)) was proposed to study human running. Mcmahon and Cheng [20] extended SLIPM to biped model to describe walking gait. Different walking patterns can be obtained by adjusting the spring coefficient and impact angle.

Kuo [21] added the impulse of push-off to realize periodic walking on level ground based on the simplified model and proposed a more economic and similar walking pattern [22], as shown in figure 3(d)(e). Srinivasan and Ruina [23] proposed an active biped model in which the two legs are driven by linear actuators (figure 3(f)). Walking simulation is achieved by optimizing the mechanical work.

Many other enhanced IPMs were also proposed based on different considerations. An angular-momentum-including IPM was proposed by introducing the angular momentum into walking pattern simulation [24], [26], which makes the transition between the single support phase and the double support phase much smoother. To produce more stable and accurate walking patterns, the gravity effect was introduced by the gravity-compensated IPM [27]. The model contains two different masses. One mass is for the leg and the other one is for the trunk. However, the model failed to consider the inertia effect that is generated by the passive dynamics. To address this problem, a multiple-mass IPM was proposed to integrate the passive dynamics with the gravity effect [25], [28], and the model has demonstrated the improvement in stability.

### 2) JOINT MODEL

Joint model introduces detailed limbs and different drive modes (passive, impact, and active) based on COG models. Human upper limbs and lower limbs can be simplified into linkages that rarely interfere normal gait. But the structure of human foot is complex and it interfere normal gait greatly. Foot is treated as a point in simplified models [18].

The way of feet contacting the ground is a key parameter to guarantee position and posture of feet. Adamczyk *et al.* [29] proposed a rolling foot model in human walking, in which the rolling foot rolls over the ground that is analogous to a wheel as shown in figure 4. An optimal radius is then established based on a minimum metabolic cost function. The rolling action offers energetic benefits by reducing the mechanical work for gait transitions.

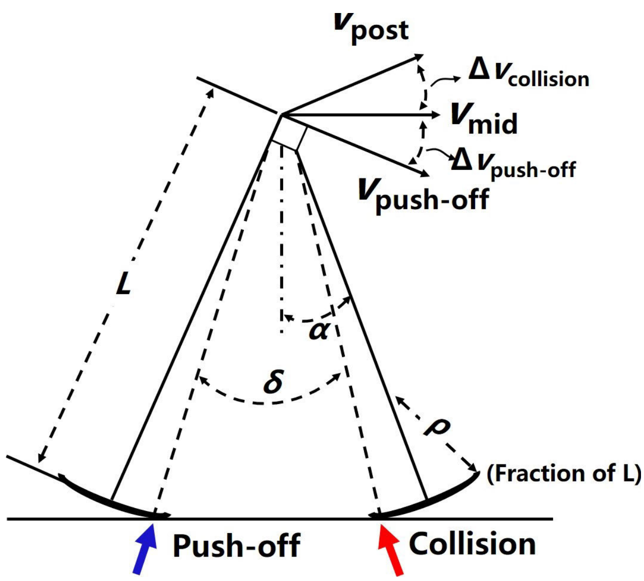


**FIGURE 4.** **Rolling foot model for walking, where $\Delta v_{push\text{-}off}$ and $\Delta v_{collision}$ are changes of push-off and collision velocity, respectively. These leg actions redirect the pre-transition COG velocity ($v_{pre}$) to post-transition velocity ($v_{post}$) and $v_{mid} = v_{pre} + \Delta v_{push\text{-}off}$ [29].**

The rolling model can be simplified as:

$$\begin{cases} \tan\dfrac{\delta}{2} = \dfrac{(1-\rho)\sin\alpha}{\rho + (1-\rho)\cos\alpha} \\ W^{-} = \dfrac{1}{2}Mv_{\text{mid}}^2 - \dfrac{1}{2}Mv_{\text{post}}^2 \end{cases} \tag{1}$$

where $W^-$ is the negative work performed by the collision of the swing leg on the COG, $\rho$ is the curvature of the rolling foot, $\alpha$ is the transition angle of the leg, $M$ is the body mass, and $\delta$ is the angular change that is positively related to the stride. With small values of $\alpha$, $v_{\mathrm{mid}}$ and $v_{\mathrm{post}}$, Eq. (1) can be simplified as:

$$\begin{cases} \tan\frac{\delta}{2} \approx \alpha(1-\rho) \\ W^- = \frac{1}{2}Mv_{\mathrm{post}}^2\alpha^2(1-\rho)^2 \end{cases} \tag{2}$$

Moreover, for constant step length and constant walking speed, $\alpha$ and $v_{\mathrm{post}}$ are constants. It means that $\delta$ and $W^-$ are negatively related to $(1-\rho)$ and $W^-$ is the likelihood of metabolic cost. The model of the rolling foot indicates that the more prominent curvature of rolling, the lower the metabolic cost. Based on the above models, Collins and Kuo [30] designed a prosthesis foot with a curved sole corresponding to the rolling foot and a pushing-off tiptoe. The paper showed that the ankle push-off can reduce the metabolic cost by 14%.

### 3) MUSCULOSKELETAL MODEL

Musculoskeletal models replace joint moment with muscles in joint models. Hill *et al.* proposed a three-element muscle model containing contract element, series elastic element, and parallel elastic element. Vab de Bogert [31] proposed a muscle model with fixed lever length and Miller [32] omitted the parallel elastic element for simplicity. Chou and Hannaford [33] proposed a liner model to describe the relationship between dynamic tension and the elastic element length. Besides, ligamentous tissue generally plays a protective role for joints and muscles as it restricts excessive flexion and extension. The ligamentous tissue can be represented in the model by springs [34].

Although musculoskeletal models are more complicated ones, they are more anatomically similar to the human body. These complex models have more DOFs (degree of freedom) to provide more valuable information and generate more natural gait like human. However, the computing cost increases when conducting model optimization because of the ''curse of dimensionality'' [35]. Luckily, efficient numerical methods and open-source software for musculoskeleton models have become available, which made it feasible to address the questions about the neuro-mechanics of gait that require complex models and are hard to study only based on data.

Musculoskeletal modeling consist of contact model of muscle-skeleton, static model of muscle-tendon, and dynamic model of muscle-tendon, as illustrated in figure 5. The most popular simulation environment (OpenSim) is a solver of forward dynamics, which implements inverse dynamics by combining data filter and forward dynamics.

The musculoskeletal modeling provides an obvious illustration of the distribution of muscles and bones, which guides the design of the distribution of the exoskeleton. And make sure that the UEs can assist human body without hindering natural motion and discomfort.

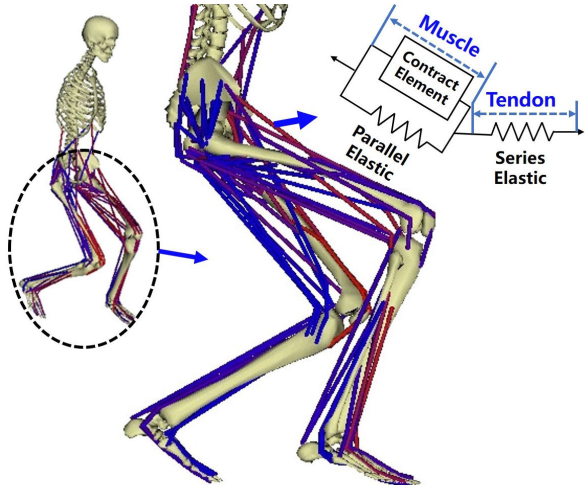


**FIGURE 5.** Musculoskeleton model of lower extremity in OpenSim.

### 4) LOAD CARRIAGE MODEL

Load carriage has great impacts on pattern analysis and modeling. Asian people use compliant poles (CPs) as a low-cost, ingenious, and effective means of load carriage. They are experienced in adjusting their walking speed, and body fluctuation frequency to accommodate the impact of the loads and the stiffness of the CPs. It is noted that the oscillation amplitude of the load to the ground is smaller than that to the human body. In other words, the CPs decouple the loads from the human body.

Base on this idea, Schroeder *et al.* [36] developed a mass-spring-damper model to analyze the characteristics between the resonance frequency and CP properties. The model provides a scientific way to predict the resonance frequency by adjusting different materials of CPs for good load-human interaction. Potwar *et al.* [37] synthesized another predictive model for CPs selection by minimizing the impact on shoulders to avoid muscle fatigue. Both methods focus on calculating the optimal parameters of CPs by optimizing different targets.

Similarly, Rome *et al.* [38] proposed an elastically-suspended backpack (ESB) by using elastic bungee cords. The backpack can follow the up-and-down movement of the human body and reduce the impact on the shoulders by up to 80%. Essentially, an ESB shares a similar function with the CPs and the oscillation amplitude, which is determined by the stiffness of the elastic rubber, the gait, and the loads. Li *et al.* [39] established a predictive biped model, which is extended from IPM, to analyze the load-human interaction, as shown in figure 6. The predictive biped model predicts human walking patterns by minimizing the energy consumption. The relative motion between human and load were modelled with unpowered mode or a powered mode. Comparative experiments of the two modes proved that the powered mode had a better performance than unpowered mode at the same level of peak interaction force. These results showed that unpowered ESB or CP are promising and economic (compared to powered devices) UEs for load carriage.

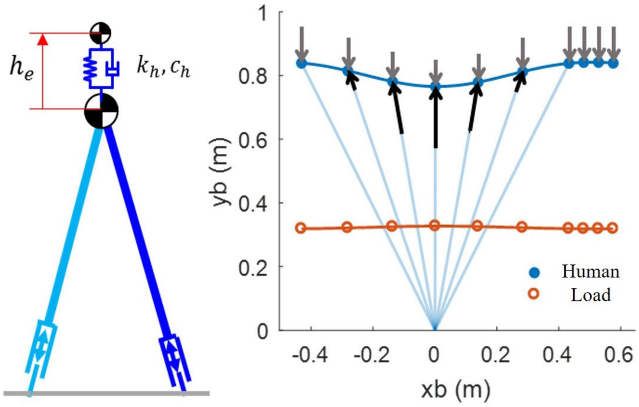


**FIGURE 6.** Analysis of suspension between human and load. Simulation shows that the suspension decouple human and load and it seems that the load is hovering in the air [39].

### B. BIONIC MODELS

Passive walking models describe the passive patterns of the human motions [40]. Collins also established a passive dynamic model with free swing arms to study dynamic arm swing during walking [41]. Four experiments (normal swinging, swing arms opposite to normal, bound arms, and held arms) were conducted and compared in terms of the GRF and metabolic cost. Experimental results showed that swing patterns have influences on the GRF and natural arm swing can reduce the GRF and the metabolic cost.

Ishikawa *et al.* [42] studied the usage of muscle-tendon interaction and elastic energy during human walking. They used an ultrasound apparatus to record the lengths of the gastrocnemius (MG) and the soleus muscle (Sol), and fiberoptic transducers to record the stress of the Achilles tendon as shown in figure 7. Tendinous tissues in the MG and Sol stretched slowly and recoiled rapidly. Nucklos *et al.* [43] highlighted the link between muscle neuromechanics and exoskeleton performance by using ultrasound imaging to record the catapult action of muscle contractile dynamics. The catapult action [1] is also demonstrated in insects jumping [44]. The power impulse is observed at the end of the walking phase, which means that tendinous tissues in MG and Sol strengthen the muscle power during walking. Based on this catapult mechanism, some UEs are designed to use linear springs and clutches [13], [45], [46].

Sutrisno and Braun [11] developed a catapult-like running shoe inspired by the catapult action of ankle. It has proved that human running speed has been increased by 50% which approaches cycling [47]. Haldane *et al.* [44] designed a bionic jumping robot with a single leg. It was inspired by galagos, also known as bush babies (the animal with the highest vertical jumping agility). Galagos uses a power-modulating mechanism that keeps their body close to the ground as much as possible to store energy, and then releases the stored energy instantaneously. By applying the power-modulating mechanism, the jumping robot can jump 10 times its height vertically [49].

In published works, bionic models mostly focus on one single characteristic of human or animals. These models

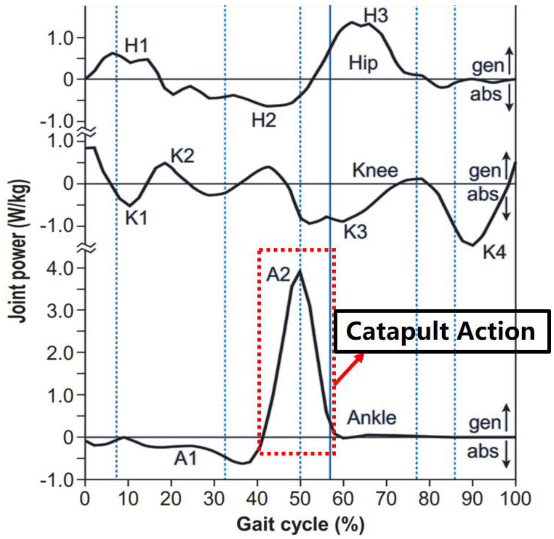


**FIGURE 7.** Catapult action of ankle joint power [36].

uncover the relationship between parameters of human or animal structures and modeling targets, such as minimizing energy consumption, reducing impact force, reducing GRF. Therefore, modeling targets are critical and are often used to assess the effectiveness of the design of UEs.

## III. MECHANICAL DESIGN OF UEs

There are four considerations for designing a passive assistant device conforming to ergonomics: energy storage module, mechanical control, mechanical transmission, and coupling methods with human [1], [13]. The energy storage module is mostly constructed by elastic components. The components can be linear springs, torsion springs, gas springs, dampers, leaf springs, inflated pneumatic muscles (PMs), or any other recoverable elements determined based on the models discussed in Section II. The energy conversion during human locomotion is controlled by mechanical switches. UEs transfer forces through specified transmission mechanism such as tethers [50], levers [30], or other mechanical structures. It is worth mentioning that these systems should either be wearable [46], riding type [51], or in parallel with human bodies [1].

### A. SINGLE JOINT EXOSKELETONS

#### 1) PASSIVE ANKLE EXOSKELETONS

Collins *et al.* [1] developed an unpowered ankle exoskeleton to reduce the energy cost of human walking. It is completely unpowered and consists of a shank frame, a linear spring, a clutch, and an ankle joint, as shown in figure 8(a). The mechanism is set in parallel with human gastrocnemius and soleus fascicles. In the system, a spring functions like an Achilles tendon and stores energy.

The tendinous tissues in the calf muscle extend slowly in the swing phase and retract rapidly in the stance phase. The working mechanism of the Achilles tendon suggests that

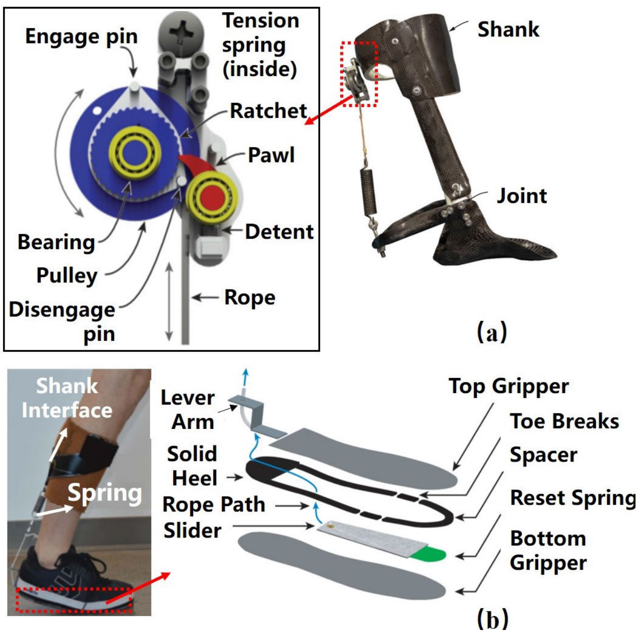


**FIGURE 8.** (a) Unpowered ankle exoskeleton controlled by mechanical clutch [35]. (b) Unpowered ankle exoskeleton controlled by sliding clutch [40].

the elastic contraction should not be a spring but a catapult that can generate a power pulse, as illustrated in figure 7. This bionic characteristic functions like a clutch that engages when the foot is on the ground, disengages when the leg is swung, and controls the releasing of the stored energy at the proper time during walking. The clutch contains a ratchet, timing pins, and a pawl [13]. The rotation of the ankle joint is transferred to the rotation of the ratchet by linear springs and tether linkage according to the walking gait. Timing pins are used to determine the best control time and set the engaging and disengaging positions. However, since exoskeletons are customized, it is hard to accommodate individuals with different walking speeds.

Yandell *et al.* extended the design in [13] and developed a lightweight, unobtrusive, and adaptive ankle exoskeleton [46]. The design placed a new clutch underneath the foot, which can be located above the insole, below the outsole, or integrated into the shoe. The exoskeleton contains a reset spring, a slider, a top gripper, and a spacer, as shown in figure 8(b). It is clutched during the stance phase and unclutched during the swing phase. The experimental results showed that the exoskeleton leads to 5%-17% reduction in soleus electromyography (EMG) activity. The exoskeleton makes good use of the friction under the feet and body weight during gait cycle. Since it does not need accurate position of the cultch, it can be adapted to different individuals and can accommodate different walking speeds.

Researchers also tried to integrate PMs with ankle assistance [52]–[55]. The ankle exoskeletons are actuated by PMs, which are treated as springs with variable stiffness by tuning the inner pressure. PMs are bionic actuators that function like human muscles; they have excellent bionic characteristics such as muscle-like contraction, variable stiffness, and lightweight. PMs are usually set in parallel with the calf and replace some functions of the gastrocnemius, soleus, and Achilles tendon. However, the sealed PMs have limited contraction in the axial direction, which restricts the normal rotation of the ankles. For unpowered ankle exoskeletons, PMs can be part of ankle orthoses that allow slight motions.

The ankle UEs set an exciting example that pure mechanism attached to human body can achieve high efficacy. The ankle UEs optimize musculoskeletal structure of ankle joint through utilizing energy recycling and converting by introducing extracorporeal compensation.

### 2) PASSIVE KNEE EXOSKELETONS

Biologically, the human knee joints have non-constant rotation axes [56]. Knee movements include rolling and sliding. The flexion-extension DOF and rotary DOF are in different planes. The trajectory of the rotary center has a "J" shape [57] as shown in figure 9(a). The knee exoskeletons can be divided into two categories according to the rotary axis: fixed one and variable one. Kim *et al.* [58] implemented a movable instantaneous center of rotation linkage to realize the non-constant rotation axes of the knee exoskeleton. The wearability and augmentation of the exoskeleton were confirmed.

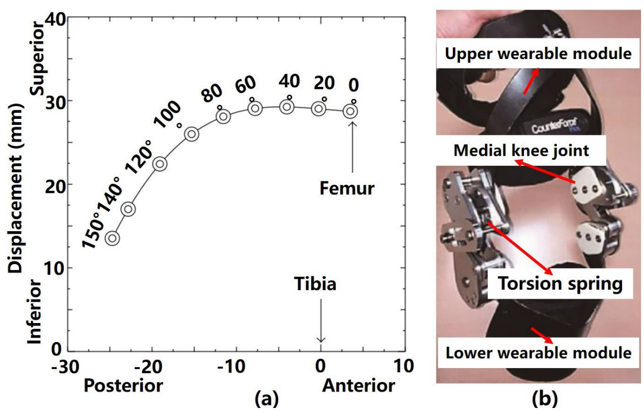


**FIGURE 9.** (a) Trajectory of the center of the femur in the sagittal plane [50]. (b) Unpowered knee exoskeleton reduces quadriceps activity during cycling [52].

Wang *et al.* designed an adaptive knee joint and proved the effectiveness of the dynamic model of the knee joint [56]. The bionic joint adopts a riding-type design and works with kinematic components, including pins, sliders, and cams. The energy storage elements are placed into the upper and lower links. The riding-type design provides a convenient connection with human, which makes it easy to take on and take off. It decouples the human gait into the swing phase and the stance phase. Moreover, it transfers the body weight to the ground in the stance phase and frees the leg in the swing phase.

Sakai *et al.* [57] designed a simple knee joint inspired by human knees and an adaptive torque mechanism. A PM is used as a recovery source by adjusting the inner pressure.

Experimental result shows that the sliding mechanism can fit the subject's flexion-extension motion and shows 30%-63% reduction in EMG signal.

Similarly, a laterally placed leaf spring is used in a knee exoskeleton for squat lifting [59]. The assistant force and the leg's motion are in different planes, which are both in parallel with the human sagittal plane. This design hinders human walking and, therefore, is not suitable for practical use. To make it practice, the leaf spring can be placed behind the knee to make the assistance force and leg's motion in the same plane.

Chaichaowarat *et al.* [60] designed an unpowered knee exoskeleton for cycling as shown in figure 9(b). It contains an upper wearable module, medial knee joint, torsion spring, and a lower wearable module. Results show that it relieves the quadriceps activity and does not deliver positive mechanical work. It is a promising potential passive exoskeleton for cycling. Grabowski and Herr designed a hopping help device that is attached to human knee in which springs are laterally placed to thigh and calf [61]. The lateral position of this device has similar shortcomings, which could be improved by reducing the lateral displacement.

#### 3) PASSIVE HIP EXOSKELETONS

The hips, knees, and ankles coordinate with different roles during human walking. The hip joint connects the trunk with the lower limb by supporting the upper body for balancing and swings the whole leg for locomotion. The hip joint mainly produces positive work, which is about five times the negative work. The mechanical work mechanism is a reference for designing an exoskeleton.

Nasiri *et al.* [62] proposed an unpowered hip exoskeleton to compensate hip moment when running. It contains lower frame, revolute joint, upper frame, bent-leaf-spring, swivel-eye-bolt, belt and wedding ribbon. The bent-leaf-spring functions like a torsion spring to apply torques for hip assistance. The exoskeleton transfers free swing motion of legs in running by lower frame to torsional deformation of bent-leaf-spring. Inertial energy is recovered and converted to elastic energy. The conversion occurs two times in one gait cycle.

Chen *et al.* [63] designed a passive elastic exoskeleton (peEXO) to provide hip assistance for walking. The peEXO contains an upper frame, linear spring, and lower frame. The muscle-tendon-exoskeleton model is used to explore the biological mechanics and energy conversion mechanism. Experimental results demonstrate the effectiveness of the model and the reduction of metabolic cost. Haufe *et al.* [64] proposed a passive hip exoskeleton that can store and return energy during walking. EMG and oxygen consumption are recorded. Experiment showed that human hip power reduced 23% for the cyclic walking.

The most attractive features and advantages of UEs are that they do not include bulky energy source and actuators, which makes them light-weight, durable, and flexible. Several successful UEs examples of single joint and synthetic exoskeletons are discussed in this section to illustrate their design ideas and provide general guidance for UEs design.

### B. SYNTHETIC PASSIVE EXOSKELETONS

This section discusses exoskeletons through which target synthetic locomotion can be generated by combining multiple joints with human body parts. Different from the UEs for single joints, the synthetic UEs can transfer significant assistance while minimizing contraints or user discomfort. Bogert [65] proposed a concept of exotendon for human locomotion in 2003. The exotendon contains long elastic cords attached to an exoskeleton and pulleys placed at the joint. Simulation results show that the exotendon can reduce the total joint torques by about 46%. Zhou *et al.* [66] proposed a multiarticular UE both for hip and knee joint that enhanced the energy efficiency by reducing 8.6% metabolic cost.

Inspired by the exotendon, Dijk *et al.* [67] designed a passive exoskeleton with artificial tendons, XPED2. The exotendon uses a Dyneema cable to connect a lever from the pelvis to a leaf spring at the foot. It stretches and stores elastic energy during the swing phase and releases the stored energy during stance phase. Experimental results showed that XPED2 can reduce the total joint torque by 27.3%. Note that there are also some powered designs inspired by the extracorporeal tendon [68], [69].

In 2007, MIT developed a quasi-passive exoskeleton to enhance load-carrying capacities during walking [70]. It manages energy management through springs, clutches, and variable dampers. Springs are placed in the backpack payload and hip joint. A damper is placed in the knee joint. The clutches work based on the human walking gait from which springs store energy during the swing phase and release energy during the stance phase. This exoskeleton shows a 10% metabolic benefit for carrying the payload. Grabowski *et al.* [61] proposed a device for hopping that is effective in reducing metabolic cost. It consists of a rigid frame, stunt harness, leaf springs, and nylon cord. Exoskeletons with a multiple leaf (MLE) scheme and a single leaf scheme can reduce metabolic cost by 6% and 24%, respectively.

There are also some passive exoskeletons for supporting and balancing. ES-EXO [71] was designed for spinal cord injured patients. It looks like a crutch with four legs. Yan *et al.* [72] designed an unpowered load-carrying lower limb exoskeleton. Granados et at. [73] and Lee *et al.* [74] designed a sit-to-stand device for elderly and spinal-injured people by combining gait trainers and partial weight-bearing lifters. There are also reported works of passive upper limb supporters for sanding operation [75], pneumatic muscle-actuating arms [9], arm supporters [76], walking protection [77] and other exoskeletons [78]. These practical tools were all designed for specific motions.

Spinal exoskeleton robot (SPEXOR) is very practical for repetitive lifting that is a common motion in industrial or daily life. Spinal UEs can be divided into two categories according to the energy elements: (1) composite materials and elastic bands, and (2) air or metal springs [79].

Baltrusch *et al.* developed a SPEXOR to decrease metabolic cost [80] and muscle activity for repetitive lifting or bending tasks [81]. It has proved that 18% reduction in metabolic cost and 16% reduction in muscle activity. In addition, passive back or spinal exoskeletons were designed for upper trunk support or reducing back pain. Koopman *et al.* [82] designed a pure mechanical exoskeleton to reduce low back pain during lifting. It can reduce back muscle activity by 10%-40%. Madinei *et al.* [83] proposed two passive back-support exoskeletons to assess EMG, energy consumption, joint power, and subjective response. Comparative experiments showed that two back exoskeletons significantly reduced peak levels of EMG by 9–20% and reduced energy consumption by 8–14%. It is worth noting that SPEXORs may hinder other activities such as walking or running, and make it more demanding when conducting multiple activities.

In 2015, Australian Government Department of Defense launched a novel wearable exoskeleton OX, which can transfer two thirds of the pressure borne by soldiers' shoulder, spine, and legs to the ground [84]. It is a synthetic UEs that makes good use of the Bowden cable, which can transfer tension and thrust and is placed on the surface of human body, as illustrated in figure 10. Mawashi Co. presented UPRISE that can transfer 50%-80% of the pressure (about 54.4 kilograms) borne by soldiers' shoulder to the ground without interfering normal motion [85]. UPRISE is constructed by using high-strength titanium alloy. Niudi Co., LTD from China proposed a modularized UE that can withstand 70 kilograms but weighs only 6 kilograms [86]. The exoskeleton is constructed by using high-strength nylon through 3D print technology. The above three UEs are able to transfer the pressure borne by human shoulder, back, and legs to the ground. And they are all well-bionic designed and constructed by using novel materials, dexterous structure, or advanced manufacturing technology. Considering this, the UEs may not be cheaper than PEs.


**FIGURE 10.** Three synthetic UEs products.

UEs with rigid structures often contain rigid links, rotary pivots, springs and attachment components [87]. The rigid links can support body by transferring the force to the ground and therefore helping to enhance capacity of load carrying. They help to balance by making good use of the powerful limbs. To achieve the low impedance target, more degree of freedoms (DOFs) should be designed, which can be realized by using different rotary pivots. The springs are the energy storage elements that can store the elastic energy transferred from human motions. They are practical for sit-to-stand or stand-to-sit assistance because the motion ranges of these motions are wider than those of with walking or running. The attachment components affect the efficiency and comfort of force transmission, of human bodies with the equipment.

UEs with soft structures usually have simpler designs than those with rigid structures. Compliant rubber tube and cloth-like outline are often adopted. They are light and can be hidden in daily clothes. The elastic rubber contracts like exotendon along the curve of the body so that the friction between body appearance and exotendon should be considered. UEs with soft structures can be used to enhance strength of muscle and often are used for fitness, traveling, rehabilitation, etc.

## IV. VALIDATION METHODS

Human kinematics studies human motions and kinetics studies the causes of motions. Section II discusses the inverse dynamics that bridges kinematics and kinetics. The validation methods for UEs focuses on sensors used for biomechanics and energetics measurements. Sensors commonly used in passive exoskeletons can be divided into three groups: kinematic and dynamic measurement, metabolic cost measurement, and muscle activity measurement. In general, kinematic and dynamic measurement is used to evaluate the flexibility of the UEs and predicts energy expenditure indirectly. Metabolic cost measurement represents how much energy was saved by the UEs, which can be estimated by models indirectly and measured by devices directly. Muscle activity measurement indicates the fatigue of muscles, which is evaluated by EMG signals.

### A. KINEMATICS AND KINETICS MEASUREMENT

Kinematics describes the changes of displacement in linear or angular position and their derivatives, such as linear velocity, linear acceleration, angular velocity, and angular acceleration. The displacement of human body can be captured by sensors. In the past, human motion study was challenging because the trajectories of the body had to be manually extracted. The development of motion capture system greatly advances researches through automatic trajectory processing and extraction. Camera-based motion capture systems [1] have become the standard measurement devices. Camera-based motion capture systems often contain several high-speed cameras and one or more data processing systems. The cameras can capture the reflective markers pasted on a human body and then obtain the body trajectories. The accuracy of the trajectory is determined by the resolution and the number of cameras.

Human motion trajectory can also be obtained by wearable sensors. Liu *et al.* [88] developed a wearable sensor combining gyroscopes, accelerometers, with thermometers, which is attached to the body to collect motion signals. The signals are processed by the established human kinematics model to obtain the motion trajectory. The wearable motion capture systems are used for gait analysis, posture resolution analysis, and model verification. Harvard Bio-design Lab designed a sensor skin [89] that can be used for real-time joint angle analysis.

Kinetics aims to study forces that affect human motions [90]. These forces can change the linear or angular motions. Force data can be obtained directly by using force and torque sensors. GRF is the representation of the human body's impact on the ground measured by force plates, which can be used to analyze the force provided by exoskeletons. Torque sensors are able to measure linear force from X, Y, and Z directions, and rotary moment from the three directions. These torque sensors are also widely used in robotic compliant control. Moreover, force can also be obtained through indirect means. For example, Collins [1] used inverse dynamics to estimate the human joint performance by subtracting the exoskeleton torque or power from the total ankle joint moment or power.

### B. METABOLIC COST MEASUREMENT

The energy for human life comes essentially from the conversion of chemical energy. Figure 11 shows a simplified schematic of the energy flow. Some energy is used for mechanical work whereas other energy is dissipated as heat by the skin or breath. The energy for human motion mostly refers to external energy, which contains potential energy and kinetic energy. It is therefore feasible to estimate the transition mechanism by studying potential energy and kinetic energy. The overall effectiveness of the exoskeletons can be evaluated. Theoretically, the potential energy and kinetic energy can be calculated by the IPMs. The models explain the trajectory of COG in X, Y and Z directions. The displacement and its differential can be used to calculation the potential energy and kinetic energy, respectively. Metabolic cost can be directly measured by calorimetry devices. The most popular one is the COSMED produced by an Italian company [1]. The devices evaluate the cardiorespiratory fitness to high intensity training of athletes or soldiers and help doctors evaluate the state of patients. It is designed to record more than thirty physiological parameters, including oxygen consumption, carbon dioxide production, heart rate, and gas flow.

Evidence have proved that exoskeletons can reduce the metabolic cost both for the UEs [91] and PEs [92]. The reduction of metabolic cost for several single-joint exoskeletons are shown in figure 12. The chart demonstrates the macroscopic benefits for human assistance by single-joint exoskeletons. Exoskeletons 1-5 are for unpowered ankle assistance [1], [13], [67], [90], [93], 6 for is powered ankle assistance [52], 7-8 are for unpowered hip assistance [62], [63] and 9 is for powered hip assistance [50]. Figure 12 shows that the PEs have greater reduction in metabolic cost. However, it does not indicate that the PEs are more practical than UEs. PEs achieve greater metabolic benefits by sacrificing the portability and the endurance, which means that they can be only used for limited scenarios. For instance, PEs are more suitable for complete specific tasks that are time-constrained and with high power input. On the contrary, UEs are promising solutions with advantages of light-weight, long endurance, and considerable assistance.

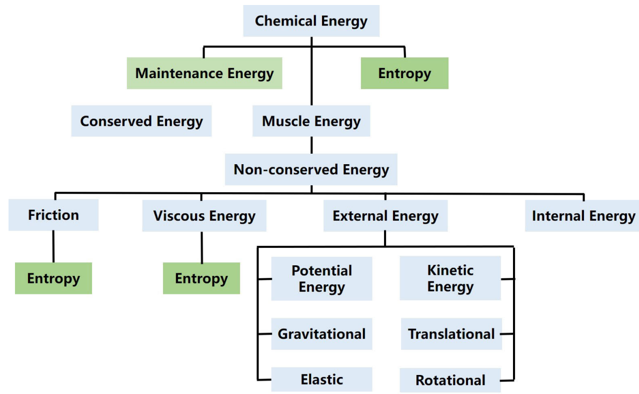


**FIGURE 11.** **Energy flow through body to the environment. Maintenance energy contains energy to tissues including skeleton muscle. Entropy is the dissipated energy which heats the environment or creates turbulence. Conserved energy flows among the human body parts [48].**

It is foreseeable that PEs can reduce more metabolic cost because of the input of external energy that is generated by electric, pneumatic, or hydraulic energy. Meanwhile, the external energy should be supported by extra module such as battery, driver, and control unit, which make PEs heavier and inflexible. On the contrary, UEs have great portability for omitting power units. The instantaneous work pulse mechanism of human Achilles tendon, as shown in figure 7, promotes many researches in passive ankle exoskeletons. However, their performances of these UEs in terms of metabolic cost reduction vary a lot. It is a knack to select a matching spring in the mechanical clutch with the energy storage element. Most joint passive exoskeletons benefit from improvements in materials and advanced manufacturing techniques but few UEs consider the longevity and robustness of devices. Evidences show that powered assistance in general performed marginally better than passive assistance [34]. In our surveyed literatures, the minimal difference of reduction of metabolic cost between PE and UE is around 4%, and the maximal difference of reduction of metabolic cost is around 12%, as shown in figure 12. UEs with higher performance in metabolic reduction are well-designed ones with specific modeling, advanced materials, and ergonomic designs. With development of modeling, simulation methods, materials, and ergonomics, the difference of metabolic reduction between PEs and UEs can be further reduced.

### C. MUSCLE ACTIVITY MEASUREMENT

The human body is a muscle-tendon-skeleton system. EMG signals record the muscle activities [46], which can be used

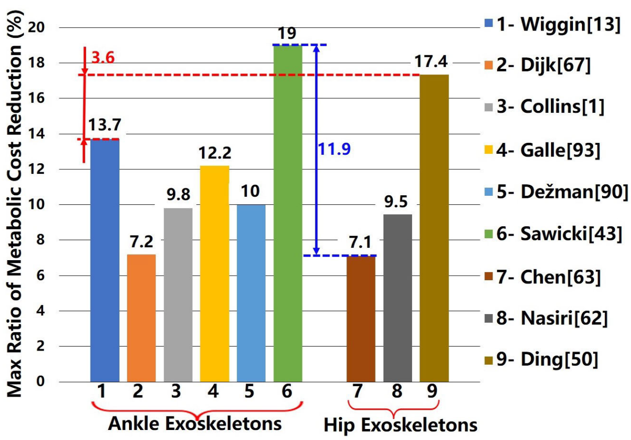


**FIGURE 12.** The histogram of exoskeletons and their reduction of metabolic cost. Each number corresponds to a certain exoskeleton as given by the citation number.

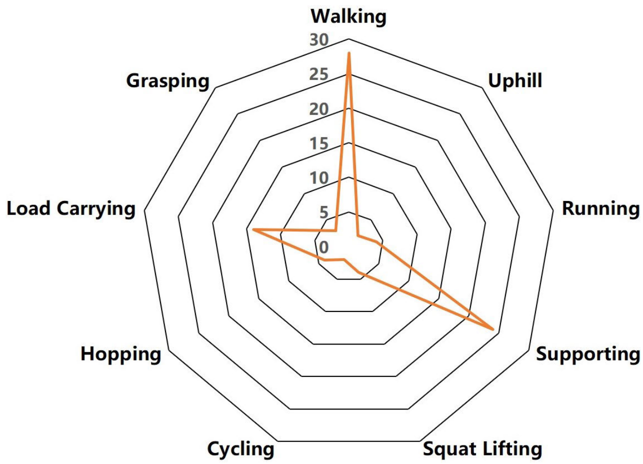


**FIGURE 13.** Radar diagram of the applications of the exoskeleton based on reference statistics.

to qualitatively analyze the assistance of the exoskeleton. The EMG signals are recorded using surface electrodes and data acquisition devices. For $N$ exoskeletons with different sets of parameters, the EMG signal can be calculated as [90]:

$$\begin{cases} E_{\mathrm{ki}} = \dfrac{\int_{T_1}^{T_2} |U_{\mathrm{ki}}(t)|\mathrm{d}t}{\int_{T_1}^{T_2} |U_{\mathrm{kn}}(t)|\mathrm{d}t} 100\% \\ E_{\mathrm{i}} = \dfrac{1}{N} \sum_{k=1}^{N} E_{\mathrm{ki}} \end{cases} \tag{3}$$

where $U_{\mathrm{ki}}(t)$ and $U_{\mathrm{kn}}(t)$ are the EMG voltage, subscript $n$ and $i$ denote normal walking without and with the exoskeleton, respectively, $k$ is the index of the $N$ exoskeletons with different sets of parameters, $E_{\mathrm{ki}}$ is the ratio of effectiveness in the time interval $[T_1, T_2]$, and $E_{\mathrm{i}}$ is the average values of all the $N$ exoskeletons with different parameters. Note that $E_{\mathrm{i}}$ can be used to represent the fatigue of muscles.

## V. DISCUSSION

Passive exoskeletons can enhance many kinds of human motions as shown in figure 13. Our discussion here focuses on walking, load-carrying, and supporting as these motions are mainly associated with industrial [57], healthcare [73], and daily human life [46] application scenarios. Liu *et al.* [75] proposed a passive upper exoskeleton for manual sanding operation. It helps to support a user's upper arm when he or she holds a polisher or a drill in hands and provides effective static posture support. Lockheed Martin proposed an industrial human augmentation systems to connect workers and heavy tools [94]. It can reduce work force injury and eliminating physical fatigue. Ranaweera [95] and Kikuchi [50] developed knee exoskeletons for squat lifting that requires bending knees and standing up with loads.

Exoskeletons are also able to provide dynamic assistance for simple locomotion. Graham *et al.* [96] developed a wearable personal lift-assist device (PLAD) towards the automotive assembly tasks. The device anchored at the feet, pelvis, and shoulders. The PLAD functions like an extracorporeal spine and reduces the force of low back bending or lifting. Experimental results show that the PLAD reduces the activity of thoracic and lumbar muscles. UEs applied to industrial scenarios are used to specific functions such as supporting to upper limbs or lower limbs, assistant torque for single joint or back. It is easy to design such UEs to meet the simple applications. However, it is hard to apply them to more complex scenarios.

In the healthcare field, Piovesan *et al.* [8] designed a seat-to-stand helper for lower-body paralysis. This device helps the users stand up by themselves by using passive actuators and the users' upper body. Similarly, Granados *et al.* [59] proposed an unpowered lower-body exoskeleton with a torsion lifting mechanism for seat-to-stand transition for people with body paralysis and spinal cord injury. Many other applications for rehabilitation that requires torso support have been developed for hemiplegia, and cerebral palsy. For other human body parts, applications of passive rehabilitation exoskeletons include foot orthoses for neurological disability [97], arm exoskeletons for stroke [98], protection of back injury [71], tilt table for patients in intensive care unit [6], and NUEROBike for leading legs manipulation after trauma [99], among others. Different UEs for medical applications take different considerations by focusing on the types of diseases. UEs may be orthosis for injury of legs, back, or spinal cord; and transition tools for people with paralysis, stroke, or hemiplegia. Safety and stability are major considerations.

Different from industrial applications, portability and handleability are major considerations for human daily life. According to the literature review, walking is the most interested motion as it can significantly increase efficacy in industries and improve life quality in medical treatment and human daily life. It is worth noting that most of the UEs considered in this review are laboratory prototypes. It needs advanced design and has a long way to go to achieve large-scale implementation. UEs applied to daily life are used in daily activities such as eating, standing, or walking. Handleability and dexterity are major considerations.

UEs have a great potential to be applied to military, firefighting, rescue, construction, or outdoors. It's important to take high efficiency into consideration [1], [89] for industrial applications, such as power, safety, stability and handleability. UEs with high efficacy are often equipped with storage elements with high-energy density, such as spring with high stiffness, that are able to provide assistance at proper time by transferring the stored energy into kinetic energy. Because UEs interface with human body, it is necessary to guarantee that they cannot hurt human body and should be as comfortable as possible. In order to improve the work efficiency of UEs the stability of UEs structure and handleability should be as higher as possible. All the above considerations determine the synthetic performance of UEs.

### A. MODELING CHALLENGES

Modeling is achieved by focusing on a specific target that is abstracted from application scenarios and studying the relationship between parameters and the target. The target can be represented by minimizing energy consumption, reducing impact force, and reducing GRF. The parameters used in modeling are related to structure design, which include joint angle and trajectory of COG. The target determines the validation parameters such as metabolic cost, EMG signal, peak torque, and GRF.

Many different models of human motion have been developed to provide alternative methods to analyze human motions. To get the minimum cost in terms of the sum of mechanical work and force, multiple methods have been employed. Many models are based on the aim of exploiting the mechanism of specific tasks. Xiang *et al.* [100] designed a model to predict walking transition locomotion. Bogert *et al.* [65] proposed a 2D musculoskeletal model to study the muscle activation performance. Li *et al.* [39] analyzed effective methods to carry loads based on a predictive biped model. Uchida *et al.* [101] simulated energy consumption and muscle activity during human running. The results showed similar effects observed by domain experts. These models provide a theoretical references before designing UEs to reduce its associated cost and time.

The accuracy of natural simulation of motion patterns depends on several factors. Firstly, it is hard to measure accurate anthropometric data, such as the inertia of body segments, COG of body segments, and muscle fatigue and strength. Secondly, these models simplify many mechanical features, such as impact, friction, and reaction forces. Thirdly, these models often consider a single task. Therefore, it is difficult to predict human locomotion and metabolic consumption completely by using simplified parameters in simulation and modeling. Future researches on modeling should consider all these factors to build high fidelity motion models.

### B. MECHANICAL DESIGN CHALLENGES

UEs have been successfully developed for decades. However, their practical use is still limited by many technological challenges. An individual user can gain metabolic benefits by using UEs to reduce the force of muscles attached to a single joint, namely, the hip, knee, or ankle joint. These research efforts combine novel mechanical designs with human natural dynamic characteristics, such as the large angle between the hips when running, the rolling and sliding mechanism in knee joints, and the catapult mechanism in ankle joints. Customized exoskeletons can adapt joint motions for specific tasks (e.g., running at 2.5 m/s, cycling at 30 km/h, walking at 1.25 m/s). Biological joint work is partly replaced by these exoskeletons. These successful developments demonstrate many promising and referable methods for designing practical passive exoskeletons. Nonetheless, it is difficult to use the same exoskeleton for different users or for a user to achieve different speeds of the same motion.

This issue has been addressed by some recent efforts. A clutch embedded into an insole [46] was designed to accommodate a broad range of individuals. The clutch uses the change of friction between the sole and the ground during human gait cycles, and then engages the spring when the foot is on the ground and disengages when the leg is in the air. Similarly, a wearable hip exoskeleton [50] showed that is can be effective for different users by adjusting control parameters automatically through motion pattern recognition. It is desirable to adopt the concept of clothes in designing wearable exoskeletons to make them unobtrusive and adaptable for different users.

Natural bionic characteristics provide inspirations for implementing natural movement and comfort. Human gait appears to use the feet to behave like arcs. The plantar arcs have an optimal radius that can reduce the effort to maintain human balance, decrease the collisions at heel strike, and achieve easy step-to-step transition. Human also tend to swing their arms. A small torque is then needed to drive the swing of arms, which causes direct metabolic cost. However, arm swinging can reduce the GRF. It is a trade-off between consuming little energy to swing the arm and reducing GRF from the ground with arm swinging. The mass distribution of UEs should be correspond with the distribution of human tissues, which guarantees natural motion and comfort.

Single joint assistance is easy to design as it has relatively simple biological structure. It is difficult, however, to design passive exoskeletons for multiple joints or the whole-body. Because the energy conversion mechanism between human body segments and the interactions between joints is still unclear. PEs that wraps around human limbs [1] can achieve whole-body assistance by mimicking the DOFs of human joints. For these applications, motions are determined by active exoskeletons, while users behave like puppets controlled by the exoskeletons equipped with advanced intension recognizing systems. The exotendon [66] and extracorporeal spinal [94] have inspired the design of passive exoskeletons for multiple joints or the whole-body. They use elastic bands, such as bungee cords, rubber bands, nylon cords, or Dyneema cable, attached to the body to achieve synthetical assistance.

The energy storage elements are pivotal components for UEs. These elements are springs (linear, torsion, leaf springs), PMs, dampers or elastic bands. They transfer the kinetic energy of the human motions to potential energy. Since different springs with different stiffness show different metabolic benefits, there exists an optimal stiffness. Determining the most optimal elastic elements for UEs is a great challenge to address the trade-off between comfort and considerable metabolic benefits. In addition, the energy storage elements are mounted on a frame that is worn like a shell or is tied directly to users (e.g., like a coverall suit). The exoskeleton connection ways with the body affect its comfort and metabolic benefits.

### C. VALIDATION CHALLENGES

Theoretically, modeling provides a feasible way to realize accurate analysis of human motions. Since human body is a complex skeletal-muscular-neural system, it is almost impossible to establish an accurate model to express human motion completely. Therefore, it is a challenge to predict human motions and energy consumption through modeling and simulation. The simplification of modeling is established from three levels: COG, joint, and skeleton-muscle. The COG level provides information about the trajectory of center of human mass and the external GRF. Joint level provides the kinetic and dynamic characteristics of joints based on COG level. Skeleton-muscle level provides information of muscular forces and muscle synergy based on joint level. Due to the simplification, model estimations are often used for qualitative analysis while device measurements are more suitable for quantitative analysis.

The max reduction ratios of metabolic cost of UEs are illustrated in figure 12 in which PEs and UEs are compared. Generally, the reduction of metabolic cost of the surveyed PEs is over 17% and that of the surveyed UEs' is below 14%. It proves that UEs play a similar role with PEs in introducing extra energy. However, the reduction of metabolic cost differs among different passive ankle exoskeletons. Different springs with different stiffness are introduced into designing energy element of ankle exoskeletons. Evidence shows that springs with optimal stiffness can achieve the maximal reduction of metabolic cost and it means that increasing or decreasing stiffness may increase the reduction of metabolic cost [1]. Moreover, the peak torque of devices and the EMG activities are affected by the stiffness. The peak torque will double when the stiffness of the spring is doubled. Also, decreasing of 50 mm of the lever arm can double the reduction of the peak torque of the device. Compared to walking without passive ankle exoskeleton, the EMG activities of walking with passive ankle exoskeleton reduce by 5-17% [46]. In addition, it is an increasing trend of the EMG activity reduction with decreasing the spring stiffness. Besides, materials and manufacturing techniques also greatly affect the portability, longevity, and robustness of devices that need much more extensive experiments.

The energy for human motions comes from the chemical energy by digesting food and it flows in three directions: Entropy, Maintenance, and Muscle Energy. The energy of metabolic cost is part of Muscle Energy and it can be measured indirectly by recording respiratory flow, respiratory flow rate, heart rate, muscle activity, and etc. It may be an effective way by combining the modeling and measurement to approaching the actual energy consumption. Actually, it is feasible to compare measurement data (with and without UEs) to assess the efficiency of UEs.

## VI. CONCLUSION

This review paper highlights the fact that UEs have advantages in terms of simplicity, light-weight, reliability, and flexibility, because of ingenious structure and not including bulky energy sources and actuators. There are many potential bionic characteristics, which have evolved over generations, and they can be described by mathematical methods to reveal the mechanism of natural enhancement. The development of novel materials and advanced manufacturing methods make it possible to build dexterous structure with high-strength and to promote UEs from laboratory prototypes to large-scale applications.

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