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A Survey on Design and Control of Lower Extremity Exoskeletons for Bipedal Walking

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Abstract: Exoskeleton robots are electrically, pneumatically, or hydraulically actuated devices that externally support the bones and cartilage of the human body while trying to mimic the human movement capabilities and augment muscle power. The lower extremity exoskeleton device may support specific human joints such as hip, knee, and ankle, or provide support to carry and balance the weight of the full upper body. Their assistive functionality for physically-abled and disabled humans is demanded in medical, industrial, military, safety applications, and other related fields. The vision of humans walking with an exoskeleton without external support is the prospect of the robotics and artificial intelligence working groups. This paper presents a survey on the design and control of lower extremity exoskeletons for bipedal walking. First, a historical view on the development of walking exoskeletons is presented and various lower body exoskeleton designs are categorized in different application areas. Then, these designs are studied from design, modeling, and control viewpoints. Finally, a discussion on future research directions is provided.

Keywords: lower extremity exoskeleton; bipedal walking; wearable exoskeletons; healthcare devices; design; modeling tools; control; motion generation

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1. Introduction

The Lower Extremity Exoskeleton (LEE) is an orthosis device that can be attached to the lower limbs, which artificially supports one or more of the three joints (hip, knee, and ankle) of the human leg. The goal of the artificial supportive device is to assist humans in the rehabilitation of gait by enhancing locomotion strength, power augmentation in industrial and military applications, safety in security operations, and other related fields. Bipedal walking is a form of locomotion using two legs to stand upright and walk. It enables hominids to use their hands for other tool handling tasks while walking with their feet. They can stand with two legs, sit, and walk in parallel, supporting the weight above their torso. Thus, humans are habitual bipedal walkers. Animals like penguins, baboons, chimps, and other two-legged animals also exhibit bipedal walking patterns. Exoskeleton robots for bipedal walking are devices designed to either mimic the biological structure of the human walking gait or as devices strapped on the human body to support the joints of the limbs. The exoskeleton robots developed today for different application domains are either wearable or platform-based designs (see Figure 1). The wearable exoskeletons (Figure 1a) are robotic devices strapped on the human body to either actively or passively support the lower limbs. A majority of the wearable exoskeleton robots developed today are widely used for industrial logistics [1,2], clinical gait training [3,4], military operations [5,6], and other application domains. The platform-based exoskeletons (Figure 1b) are devices that are placed on a level ground surface and allow for gait training. They are either used for rehabilitation or exercises on a treadmill.

(a) (b)

Figure 1. Wearable and platform-based exoskeleton. (**a**) ReWalk™ Personal 6.0: (copyright credits: ReWalk Robotics GmbH). (**b**) ReoAmbulator (photo: courtesy of Motorika Ltd., Mount Laurel, NJ, USA).

1.1. Contribution

Overall, 170 references are considered in this survey, with 125 of the reviewed papers' focal points being on wearable LEE for bipedal walking. This survey paper provides the current state of the art relative to the design and control methods employed on the modular LEE joints and LEE leg. The achievements, challenges, and drawbacks in the existing designs are pointed-out in detail. Additionally, we addressed the actuator design selection and control approaches currently applied to the exoskeleton robots further represented. Finally, we provided a summary of future research directions for biped exoskeleton robots.

1.2. Organization

The paper is organized as follows: Section 2 gives the history of exoskeleton robots for bipedal walking and the challenges faced in the existing designs of biped exoskeleton robots. Section 3 discusses the classification of wearable exoskeletons according to the application domain and highlights their differences. Section 4 presents the state of art on LEE(s) with regards to the human biological lower extremity in the perspectives of actuator design, exoskeleton design concepts, modeling tools, and control methods. Section 5 discusses the significance of improving the existing designs in reducing costs and enhancing safety to the wearer. It also discusses the control methods already successful in the exoskeleton domain and those not currently applied in an exoskeleton while highlighting the theoretical challenges and adopted solution approaches as a future research direction. Section 5 concludes the paper.

2. History of Bipedal Walking Exoskeleton

This section provides a brief history of the bipedal walking and walking exoskeletons from the earliest design with telescopic legs to a more complex design similar to the human walking pattern. Furthermore, the challenges biped walking exoskeleton robots face are also briefly discussed.

2.1. History of Bipedal Walking and Walking Exoskeletons

In the research history of bipedal walking robots with two telescopic legs way back in 1960, there have been designs, but these were limited to two dimensions (2D) [7]. In 1992, the Massachusetts Institute of Technology (MIT) laboratory-developed and controlled a three dimensional (3D) biped robot walking and running on grass and flat surfaces performing somersaults [8]. Subsequently, a more complex design called the Meltran

V [9] bears an interesting similarity to the 3D biped robot with a prismatic joint at the knee. The M2V2 [10] is also a 3D bipedal walking robot designed to walk on rough terrain. Recently, the Oregon State University unveiled CASSIE robot [11], a bipedal walking robot that could transverse 5 km outdoor terrain in less than an hour.

The earliest types of bipedal walking robots were designed to imitate the human anatomical structure and walking pattern. The modernized form of these bipedal walking robots is called a humanoid robot. They are either designed for entertainment, logistics, collaborative maintenance in the industries, and also teleoperation [12–17]. To this end, researchers have taken motivation from 2D designs, 3D bipedal robots, and humanoid robots to design exoskeleton robots for bipedal walking. The development of exoskeleton robots for bipedal walking began in the second half of the 20th century. Around 1965, General Electric began the development of Hardiman [18], a giant full-body exoskeleton for lifting heavy objects, which turned out to be unsuccessful. The first exoskeleton for gait assistance was developed towards the end of the 1960 and the early 1970s in Mihajlo Pupin Institute Serbia [19] and similarly at the University of Wisconsin-Madison USA [20] respectively, but due to their technical limitations, no evidence of clinical support, and lack of experience and knowledge, it took several decades until the technology became matured and available to the market community.

The 21st century is motivated by human walking robots. This has led to the progressive development of exoskeleton designs, which have attracted the interest of the market. One of these designs is BLEEX [21]. BLEEX is the first functional energetically autonomous exoskeleton designed for the United States army. The first generation of Raytheon XOS exoskeleton [6] was used for a military operation to support locomotion, and the wearer's backpack was unveiled in 2008. In medical applications, there have been quite a few exciting designs. Lokomat [22] was released in 2001 for gait rehabilitation on a treadmill. A leading-edge design in cybernetics evolved in 2007 with the development of the robot suit HAL (hybrid assistive limb), used to improve support to human locomotion ability, as reported in [23]. ReWalk company develops powered solutions that provide gait training and mobility support to lower limb disability patients with crutches. In 2012, the safety and tolerance of ReWalk exoskeleton on people with spinal cord injuries (SCI) was evaluated in [24], with prospects channeled towards walking disabilities.

Walk Again [25] is a consortium project. A team of researchers from the consortia tested their first robotic exoskeleton controlled by brain-machine interaction. The Symbitron exoskeleton is a modular lower limb exoskeleton recently developed by Delft University of Technology, and the University of Twente (The Netherlands). The control effect on the designed Symbitron exoskeleton is evaluated on patients to discern differences between partial and complete SCI and can also fit different disabilities [26]. REX Bionics is an exoskeleton company in New Zealand. In 2016, REX clinical analysis evaluation for Food and Drug Administration (FDA) approval in the USA was conducted on its two variant designs; the REX exoskeleton for clinical and personal use [27]. In 2017, the German Research Center for Artificial Intelligence (DFKI) at its Robotics Innovation Center Bremen developed the Recupera-Reha [28] full-body exoskeleton. It is a modular and self-supporting system for the robot-assisted upper body rehabilitation of neurological diseases. Meanwhile, Wandercraft introduced its first hands-free exoskeleton for lower limb ATALANTE [29]. It allows a paraplegic person to walk without crutches or additional stabilization tools.

In contrast to medical applications, industrial application exoskeleton development has progressed in the past decade as well. In 2019, the Guardian XO Alpha [1] was unveiled as a powered exoskeleton used in the industry for physically demanding tasks, most essentially in industrial logistics. In 2017, Ekso Bionics company launched the evolution of EksoEvo, EksoVest, and EksoZeroG [2]. The EksoVest is an upper-body suit strapped to enhance power and relieve pain in industrially motivated tasks. The latter variant is the EksoZeroG, and it helps construction workers in automobile industries to work faster and reduce fatigue while lifting and working with heavy weight tools. Hyundai company from South Korea unveiled its chairless exoskeleton (H-CEX) in 2017, which reduced musculoskeletal injuries due to pressure exerted on the body, especially the knee joint. H-CEX has a seat plate that relieves construction workers' pain in tasks that demand frequent squatting [30].

2.2. Challenges in Biped Walking Exoskeleton Robots

Bipedal walking is a really challenging control problem and despite recent progress with various humanoid robots, it is still not yet fully understood. Walking exoskeletons should provide assistance to the human in an optimal way while taking care of the under-actuated dynamics of the combined human + exoskeleton system. Further, the exoskeleton device may not be precisely aligned with the human joint complex. Hence, the structure may not be sufficient to support the human torso in providing an efficient, stable gait [31]. Stability is a feature of maintaining balance and posture. The earliest study of bipedal robots focused on achieving stability as a challenging factor. So far, they have achieved static and dynamic walking, jumping, and running [7,32]. However, in tedious industrial applications, maintaining balance and posture while multi-tasking with an exoskeleton device strapped on the legs and navigating through demanding terrain is a challenging problem that can be difficult to achieve. On the other hand, safety concerns and meeting legal requirements to the rehabilitation of gait without crutches support are still lagging for clinical purposes. Stability is not guaranteed for a bipedal walking exoskeleton. We can visualize a human standing on a slope spreading the feet by a small displacement and probably falling over. The spreading of the feet places the human's center of gravity to fall under its polygon of support to maintain balance. Stability in humans is achieved through active control of the nerves, tendons, and muscles, which occurs intuitively. Humans utilize body compliance supported by the active muscles to maintain balance. While in motion, the flexion and extension of the muscles can change the movement pattern.

With regards to control, safety, stability, and human-motion intentions are crucial in achieving efficient control. The zero moment point (ZMP) criteria have been employed in the control of biped humanoid robots [7,33], while the center of pressure (CoP) or center of mass (CoM) criteria have been applied to exoskeletons for translation of the center of gravity [34]. The existing reviews on bipedal walking exoskeletons have been performed for medical applications. A majority of the researchers in the last decade focused on modular rehabilitation of the ankle or knee joints [35–38] while some selected articles reviewed the leg composition, but with an additional supportive device [39–44]. There have been reviews, designs, and clinical gait evaluations in the last few decades, but no specific meta-analysis has been made combining several analyses, evaluations, design, and control methods to validate a model as a proof of concept for developing efficient, affordable, and safety-wise bipedal walking exoskeleton robots that require no additional crutches support. To motivate the need for this survey, a feasible solution to the technological gap, challenges faced in the design, modeling, and control of exoskeletons for bipedal walking will be discussed and addressed in the remaining sections, and, e.g., cost and safety concerns will be brought to light.

3. Classification of Wearable LEEs on Application Domain

The classification of LEEs based on the application domain is presented in this section. The LEE robots for bipedal walking are classified into three applications: medical, industrial, and military. Additionally, the variations among the application domain with regards to dominance in the existing designs are highlighted.

The medical application LEEs are designed to assist humans with lower limb disabilities towards enhancing locomotion and gait training while physically reducing demanding tasks by therapists. It will enable older humans with weaker muscles and also the disabled to regain locomotion and walk again [3,23]. It also focuses on mobility compensation for paralyzed and aged persons, and it is used in the healthcare facility to enhance the physical performance of the wearer and augment strength to stroke patients, SCI, and other forms of paralysis of the lower limb. The medical application is further categorized into three areas:

rehabilitation, paraplegic assistance, and power augmentation. In an industrial application, LEE(s) are used for power augmentation, i.e., to enhance the human muscle strength in tasks that require more energy in manipulation at a faster rate or for carrying heavy loads in factories [1]. Military application exoskeleton robots play a pivotal role as a tactical and operational tool for military armed forces [5], e.g., for carrying heavy loads on the war field.

3.1. Medical Application of LEE

Accidents, aging, and diseases related to the nervous system such as stroke, SCI, and osteoarthritis (OA) can lead to weak muscles and total loss of the lower limb parts. There has not been massive progress in reducing the number of road traffic incidents, leading to SCI and loss of limbs in many low-income countries between 2013 and 2016, according to the World Health Organization [45]. Over time, the anatomy and physiology of the human body becomes weak, as growth depreciates. It is a natural phenomenon where the tissues, cartilages, and muscles are too weak to support the body joints actively, and locomotion becomes difficult. Stroke and SCI are significant causes of paralysis, leading to impairment in the motor or sensory function of the limbs. OA is a disease that affects the human body joints. The foot is the most used part of the human body, especially in locomotion; therefore, the ankle and the knee joint are majorly affected by OA, resulting in breakdown of the joint cartilage and underlying bone over time. In addition, strenuous exercises and high-impact sports such as basketball, rugby, squash, and outdoor cycling can also cause OA.

The authors of [46] suggest that athletes are more prone to this disease than the general population, while most former footballers suffer chronic knee joint damages, unlike running, cycling at the gym, and swimming, which is less risky for joint injuries. In addition, medical application exoskeletons have been developed for rehabilitation to assist patients with limb impairments due to neurological disorders like SCI. The walking assistance of the HAL exoskeleton has been evaluated for safety with support on a treadmill for therapy training [47]. Furthermore, the Bergmannsheil University Hospital in Bochum has intensified its cooperation with the Japanese robotics company Cyberdyne using HAL for robot-assisted therapy procedures.

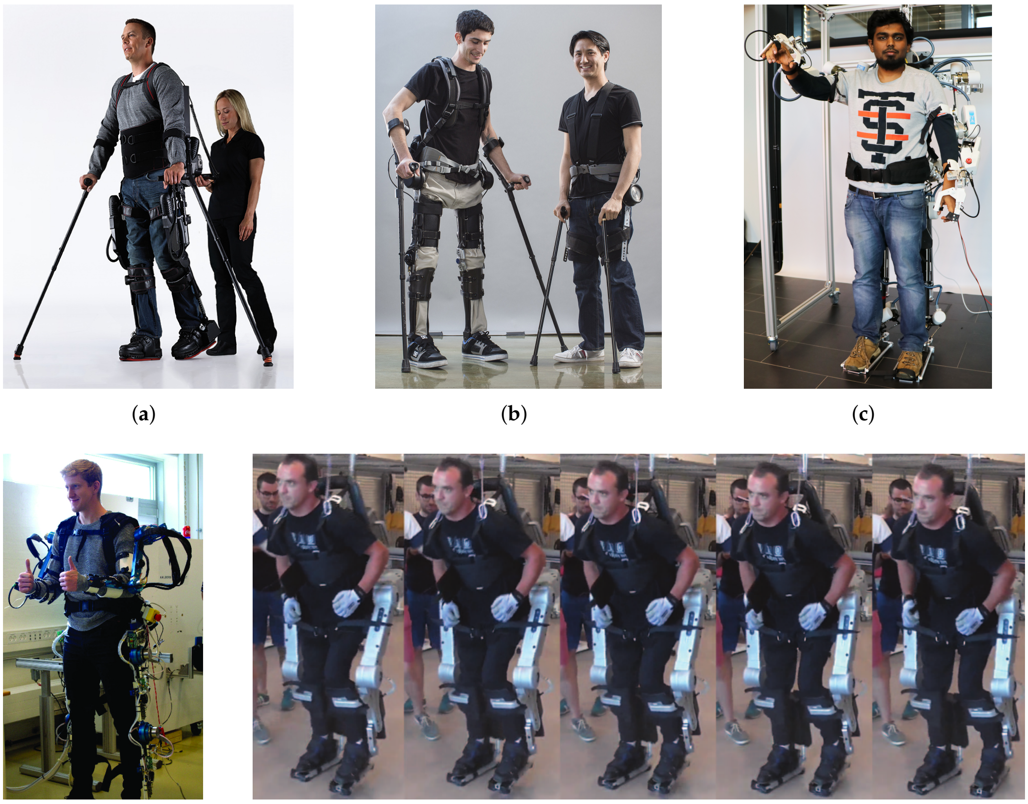
With EksoGT [48] (formerly eLEGS) (Figure 2a), various analysis evaluations and training for the lower limb in neurorehabilitation on paraplegic subjects [48–50] were carried out, using the active powered exoskeleton as a test bench. The clinical trials yielded positive results that are safe, practical, and with minimal risk to secondary injuries and patients with incomplete SCI. However, a limitation of the design is the lack of experimental methods for demonstrating the relative effectiveness of the exoskeleton in comparison with other rehabilitative techniques and technologies. An improved version of the EksoGT is the EksoNR [51], which assists in regaining natural gait patterns by re-teaching the human brain and muscles how to walk again after healing. It means the variant has been integrated with sensors to monitor the movement intent of the leg continuously.

Phoenix (Figure 2b) is the world's lightest wearable powered LEE developed by SuitX. It is designed to assist people with impairment disabilities and has enabled many individuals to stand upright and walk around. It is adjustable for different sized users with only two actuators at the hip joint. In addition, the knee joints are designed to allow support with a pair of crutches during stance and ground clearance during swing [3].

The Recupera-Reha (Figure 2c) is a modular designed full-body exoskeleton for health-care applications [28,52,53]. The upper body is used to assist and rehabilitate weak upper limbs, while the lower body has two modes; sitting and standing. The goal of Recupera-Reha is to develop an innovative and mobile whole-body exoskeleton that combines online evaluation of electroencephalography (EEG) and electromyography (EMG) signals [54,55], to enable an assessment of the condition of the operator and multi-level support via embedded multimodal multisensor interfaces [56–58]. However, the prototype requires optimization towards application as a full-body exoskeleton for rehabilitation of gait [28].

Recently, a modular full-body exoskeleton for physical assistance called AXO-SUIT (Figure 2d) is designed for medical applications to assist elderly persons. The exoskeleton enhances full-body motions such as walking, standing, and bending, as well as performing lifting and carrying tasks to assist older users to perform tasks of daily living [59]. ATALANTE is a lower limb exoskeleton that allows stable walking for paraplegic people without any additional stabilization tools, such as crutches. The mechanical design supports the entire weight of the patient, with the exoskeleton firmly strapped from the feet to the abdomen. Experimental results on paraplegic patients presented in [29] show a slow gait of 0.1 m/s (Figure 2e) and a simulated stable gait of 0.4 m/s.

The medical application of exoskeletons for bipedal walking is further sub-categorized into rehabilitation, paraplegic assistance, and power augmentation. The first category, for rehabilitation or recovery from injuries like fracture, joint sprain, OA, SCI, stroke, surgery, and other accidents, may require physical therapy to strengthen and heal the injured leg towards normal locomotion activities. The second category is assistive, and this is mainly offered to mentally healthy and aged individuals whose lower limb muscles are too weak to stand alone and actively walk without support. They require some aid, which could improve the quality of their lives by removing crutches and wheelchairs that serve as external support to enhance walking. A third category is a form of full power augmentation offered to completely paralyzed patients and amputees who are completely physically disabled. The exoskeletons are further categorized into: partial support (minimal force exerted by the exoskeleton) and full support (all the force exerted by the exoskeleton) types. In Table 1, various LEEs developed for medical applications are summarized and categorized from the last two decades.



(**a**) (**b**) (**c**)

(**d**) (**e**)

Figure 2. Medical application exoskeletons. (**a**) EksoGT™by©Ekso Bionics. (**b**) Phoenix (photo credit: SuitX). (**c**) Recupera-Reha (photo credit: Meltem Fischer, DFKI). (**d**) AXO-SUIT (copyright credit: Shaoping Bai, Aalborg University). (**e**) The ATALANTE lower limb exoskeleton with free hands during walking experiments with a paraplegic patient (photo credit: Wandercraft).

Table 1. Overview of medically-based biped exoskeleton robots (for rehabilitation, assistance, and power augmentation).

Name/ Institution	Sub-Category	Exoskeleton Type	Partial/Full Support
ReWalk Personal 6.0, (2015) [60]	Rehabilitation	Wearable	Partial
University of Goce Delcev, Macedonia, (2013) [61]	"	Platform	"
Vrije University Brussel, (2009) [62]	"	Platform	"
eLEGS, (2010) [4]	"	Wearable	"
H-MEX, (2017) [63]	"	Wearable	"
WalkBot, (2020) [64]	"	Platform	"
LOKOMAT, (2013) [22]	"	Platform	"
Recupera-Reha (2018) [28,52]	"	Wearable	"
KEEOGO, (2017) [65]	Assistive	Wearable	Full
HAL, (2017) [66]	"	Platform	"
University of Elect. Sci. and Tech., China, (2015) [67]	"	Wearable	"
Korea Adv. Inst. of Sci. and Tech. (KAIST),(2021) [68]	"	Wearable	"
Istituto Italiano di Tecnologia, Genoa, Italy, (2020) [69]	"	Wearable	"
Exosuit, (2013) [70]	"	Wearable	Partial
Axo-Suit, (2019) [71]	"	Wearable	Full
EksoGT (2015) [48]	Full power augment.	Wearable	"
Yonsei University China, (2013) [72]	"	Wearable	"
Phoenix, (2018) [3]	"	Wearable	"
ATALANTE, (2018) [73]	"	Wearable	"
MINDWALKER, (2014) [74]	"	Wearable	"

3.2. Industrial Application of LEE

Exoskeletons have widely been used in industrial applications and are still in progressive development. They are used to enhance human power during locomotion and transportation of heavy loads.

The Guardian Alpha XO in (Figure 3a) is an industrial application full-body exoskeleton used for logistics. It represents the cutting edge of physical human augmentation and wearable robots to enhance power [1]. It is designed and operated to perform manual handling tasks with four limbs simultaneously, and the two exoskeleton limbs can suspend the weight of an object to themselves while the human upper limbs are stationary. Thus, during locomotion, the wearer feels little or no weight that restricts movements with the lower limbs.

The LegX [75] from SuitX company is an industrial application exoskeleton suit strapped below the torso to relieve pain and fatigue while squatting. It can be combined with the earlier variant modules V3 ShoulderX and BackX to perform human movement motions [76]. Task coordination is one of the fundamental activities in industries that require the movement of both production equipment and manufactured products.

The German Bionics company developed the CrayX [77]. It is capable of manual handling tasks and can be integrated into digital logistic workflow devices.

Ottobock industrials, also a German-based company, developed passive exoskeleton (PAEXO) robots to relieve logistic workers from energy-demanding tasks. The six variant design modules are: PaexoBack, PaexoShoulder, PaexoThumb, PaexoWrist, PaexoNeck, and Paexo softback [78], which support individual tasks for the upper-body in the logistic industries, and some modules can be combined. Evaluation tests with the PAEXO exoskeleton strapped to the body in [79] have been carried out in the laboratory and on the field. Overhead tool lifting tasks were performed with whole-body inertial motions of some healthy students. Their reaction force exerted on the ground, oxygen consumption, heart rate, and muscle motions of the upper limbs were captured using EMG sensors. The lab experiment revealed reduced heart rate and oxygen consumption while performing the tasks with the exoskeleton worn on the body, compared to manually handling the tasks without the exoskeleton.

(a)

(b)

Figure 3. Industrial application exoskeleton. (**a**) Guardian® XO Alpha (photo credit: Sarcos Robotics). (**b**) LegX (photo credit: SuitX).

An overview of the industrial-based exoskeleton with full-body and lower-body design configuration is presented in Table 2 in walking assistance, load handling, and relief from pain and fatigue. First, we can discern the difference between the two design configurations. The former has the capabilities of the average human functionalities, while the latter case may have one or more functionalities. It means that designing a full-body exoskeleton device capable of accommodating different functionalities could assist humans in multi-tasking while applying less strength. However, no available table of overview for the military application of exoskeleton in this research work exists, because similar functionalities are exhibited by their industrial counterpart. A majority of the already existing military application exoskeletons enhance muscle power or load handling while walking.

Table 2. Overview on industrially-based biped exoskeleton robots (for walking assistance, load handling, pain or fatigue relief assistance).

Name	Body Part	Walking Assistance	Load Handling	Pain/Fatigue Relief
Guardian Alpha XO, [1]	Full-body	✓	✓	✓
Power Assist Suit (PAS), [80]	"	✓	✓	✓
FORTIS, [81]	"	✓	✓	✓
CrayX, [77]	–	✗	✗	✓
H-CEX, [30]	Lower-body	✗	✗	✓
LegX, [75]	"	✗	✗	✓
Chairless chair, [82]	"	✓	✗	✓
BoostX, [83]	"	✓	✗	✗
ONYX, [84]	"	✗	✓	✓

3.3. *Military Application of LEE*

The military application of biped exoskeleton robots is designed to augment the muscle power of humans during military operations in demanding terrain. The electrically actuated LEE BLEEX (Figure 4a) successfully demonstrated autonomous walking while supporting its weight with an extra payload [5]. The wearable LEE used for military operation focused more on actuator design, each leg with seven DOFs representing three

DOFs each for the hip and ankle joints and a single DOF on the rotary joint of the knee. Apart from grounding its weight, the BLEEX architectural design decreased the complexity of power consumption while clinical gait analysis (CGA) data were obtained to measure approximate torque, motion angles, and power required by the joints to determine actuation selection. On the other hand, not all the joints are aligned in conformity with the human leg. It is not power-efficient, as it cannot actuate all DOF at the same time. Instead, it offers only a substantial positive power to actuate the joints during desired gait movement. Another biomechanical design is a variant of BLEEX powered by linear hydraulic actuators and capable of carrying its weight with an extra payload. Despite approximating the BLEEX kinematics and dynamics similar to the human leg, the motion curves obtained from CGA data did not match the human leg [85].

Other BLEEX military application exoskeletons variants are the ExoHiker for load augmentation on a long-distance mission, ExoClimber carrying heavy loads while ascending/descending stairs/slopes, and Human Universal Load Carrier (HULC). The HULC (Figure 4b) exoskeleton is a third-generation exoskeleton designed to incorporate features of both ExoHiker and ExoClimber, carrying heavy loads on uneven terrain without the wearer applying much strength [86]. The HULC was originally developed by Berkeley Bionics (now Ekso Bionics) in 2008, and in 2009 Lockheed Martin acquired the design license to provide soldiers with a decisive advantage in ground operations.

(**a**) (**b**)

Figure 4. Military application exoskeleton. (**a**) BLEEX (photo credit: Berkeley Bionics). (**b**) HULC (photo credit: Lockheed Martin).

3.4. Distinctions in the Exoskeleton Classifications

The bipedal walking exoskeleton robot design is significant to human life due to daily activities requiring extra strength to perform specific tasks. Over time, aged persons experience weak muscles, while joint disorders such as sprain, OA, and paralysis could be sustained by athletes or even during physically demanding tasks by physically able persons. Though exoskeleton robots for medical purposes have been in geometric progression over the past years, most designs today compensate for mobility loss or lower limb joint disorders. Researchers have focused on kinematic optimization of the exoskeleton [28,87], multimode rehabilitation [54,57,58], and others have evaluated the motion intention of the wearer as evidence of support for general use [88–90], but the designs are still not sustainable safety-wise for personal use.

It can be seen that the adoption of an exoskeleton for bipedal walking has indeed become evident in the last two decades in the three application areas; medical, industrial, and military. The pie-chart representation in Figure 5 shows the percentage variations of exoskeletons designed based on their application in the last two decades. A large proportion of about 50%, which accounts for 60 selected papers either as a modular LEE joint or a LEE leg, has dominated the medical applications design field. These powered exoskeletons can improve the quality of life of people who have lost the active use of their legs by enabling system-assisted walking. However, before they can be commercially available in the United States, the FDA must approve them. In Europe, however, the new Medical Device Regulation (MDR), which replaced the previous regulations; Medical Device Directive (MDD) and Active Implantable Medical Devices Directive (AIMDD) [91] ensures that legal requirements, regulations, and standards are also met before they are commercially accepted. In the industrial application, there has been considerable growth in the designs, with about 35% of exoskeleton robots being used for logistics in factories, the majority of which augment power. Following the industrial exoskeleton, 15 papers focused on locomotion, and 30 papers discussed strength augmentation. The idea is to reduce worker injury and errors due to fatigue and increase muscle strength. In military application, threats to domestic law and order from the misuse of exoskeletons by rogue users and meeting soldiers' requirements have proved challenging. As a result, the military robots have not shown inclined growth, with about 15% corresponding to 15 reviewed papers in the last decade. The designs are still in the research institutes, pending approval, as they need to meet the standard compliance to regulations provided by the International Standard Organisation (ISO) and the International Electro-technical Commission (IEC) to prevent sanctions.

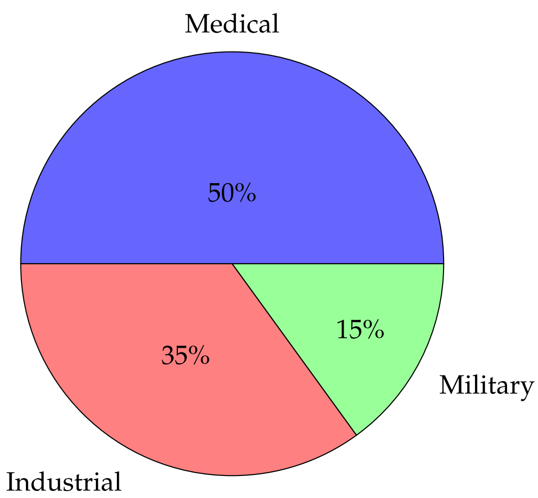


Figure 5. Classification of exoskeleton robots based on applications.

The bar chart in Figure 6 depicts the number of exoskeleton robots that will be considered for meta-analysis in the perspective of design and control of biped robots for human walking. It also corresponds to the percentage ratio that distinguishes the functionality of the three classifications of exoskeleton robots.

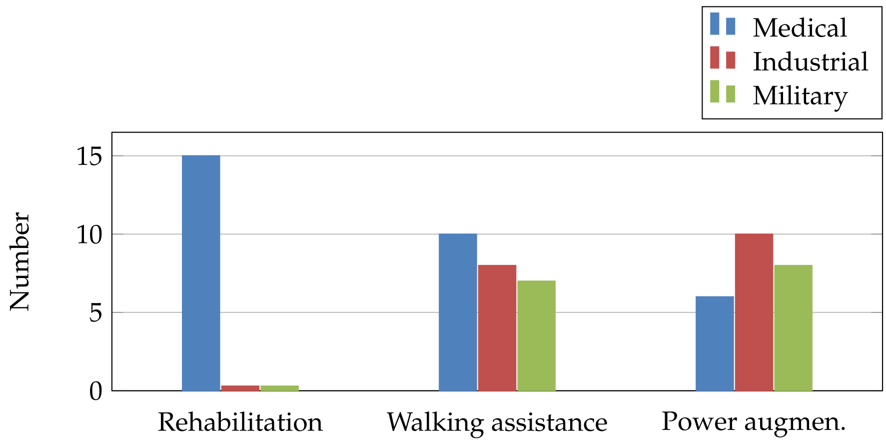


Figure 6. Number of exoskeleton robots according to domain area.

The histogram in Figure 7 depicts the distribution of the reviewed papers by publication year. It corresponds to the number of exoskeletons developed based on application over 60 years. Only some selected articles that are relevant to our work are included. We consider the development year of the exoskeleton designs for the three categories: In 1965, the first gait assistance exoskeleton was developed. In 1972 and 1978, respectively, a new design similar to the first design was developed. There was a dormancy period between the late 1970s and 1980s. A climax period that attracted the market began in the early 2000s, with progressive growth in the designs.

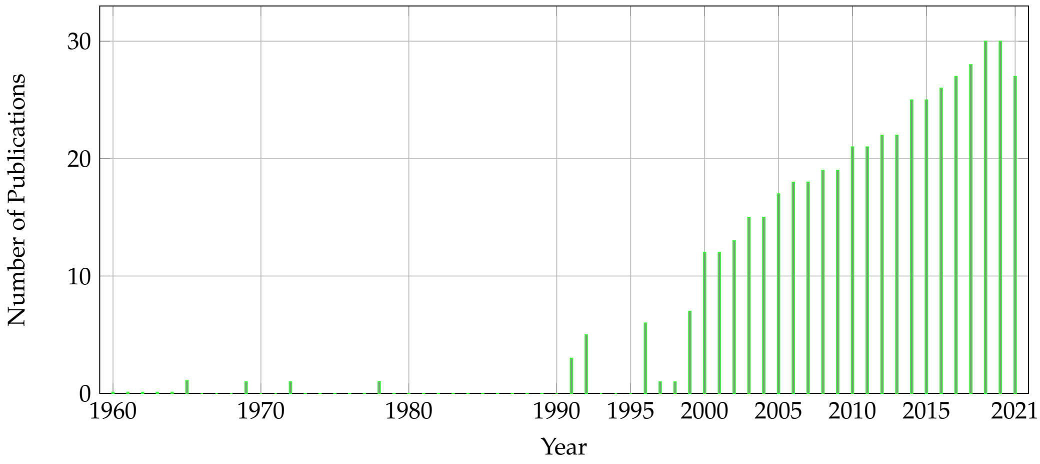


Figure 7. Histogram of the publication years of the considered works.

Finally, Table 3 shows the list of companies pursuing exoskeleton research based on our proposed classification. This demonstrates a decent interest from the private sector in investing into exoskeleton research.

Table 3. Overview of companies pursuing biped exoskeletons.

Exoskeleton Name (Year)	Company	Weight (kg)
Military Applications		
Hardiman (1965) [18]	General Electric	680
BLEEX (2006) [5,85]	Berkeley Bionics	41
Raytheon XOS 2 (2008) [6]	Raytheon Sarcos	95
HULC (2009) [86]	Lockheed Martin	24
Medical Applications		
HAL (2006) [47]	Cyberdyne	10
LOPES (2007) [92]	TWENTE University	N/A
Indego (2010) [93]	Parker Hannifin	12
ReWalk Personal 6.0 (2015), [60]	ReWalk Robotics GmbH	23.3
Walk Again (2014) [25]	Duke University	20
EksoGT (2015) [2]	Ekso Bionics	20
Phoenix Exo (2016) [3]	SuitX	12.25
REX (2016) [27]	REX Bionics	38
H-MEX (2017) [63]	Hyundai	18
Recupera Wheelchair [28,52]	DFKI	29.7
Symbitron Exo (2018) [26]	TU Delft	37.2
BELK system (2019) [94]	Gogoa Mobility Robots	N/A
EksoNR (2019) [51]	Ekso Bionics	20
ATALANTE (2020) [29]	Wandercraft	75
Exo-H3 (2020) [95]	Technaid	17
Industrial Applications		
Power Assist Suit (2015) [80]	Mitsubishi	39
H-CEX (2017) [30]	Hyundai	1.6
ChairlessChair (2017) [82]	Noonee	2
Guardian XO (2019) [1]	Hyundai	68
LegX (2019) [75]	SuitX	11.7
PAEXO (2019) [78]	Ottobock Industrial	4
CrayX (2020) [77]	German Bionics	7.4

4. State of the Art of LEE

In this section, we present the concept of designing an exoskeleton, taking inspiration from the principles of the biomechanics of the human lower limbs. Section 4.1 describes the biological structure of the human leg. Section 4.2 presents an overview of some actuator designs for exoskeletons. Section 4.3 summarizes the current state of the art using the kinematic abstractions of the human leg from 2D (planar walking) and 3D cases as a bridge in designing exoskeletons for human walking, presented in a tabular form for the modular LEE joints. Section 4.4 reviews the kinematic and dynamic modeling software for dealing with complex mechanical LEE systems. Finally, Section 4.5 describes methods and strategies used in controlling exoskeleton robots that mimic the human walking pattern.

4.1. Human Lower Extremity

Bipedal walking with an exoskeleton without external support is a very challenging problem. However, more than three legs seems much more effortless. The anatomical study of the lower extremity skeletal system of a human (Figure 8a) is a crucial practice to clinical sciences and other health-related studies to mimic the biological design of the human limbs. The function of the human lower limb anatomy in [96] highlights the musculoskeletal function and how the structure is modified by gait or joint disorders. Therefore, it is essential to carefully study the human anatomical structure and function before designing an exoskeleton device that mimics the human gait. The human lower extremity is made up of three joints; hip, knee, and ankle. Each of these joints has an underlying bone that links up to form a single leg, with every joint having a role to play in order to enhance locomotion. The kinematic chain is insufficient to mimic the human joint kinematics and behavior when designing an exoskeleton. The exoskeleton surrounds the body and therefore needs more DOF to allow all human joint movements. The geometry or kinematic open chains of rotary and linear joints form the basis of robot motions from 2D cases like (RRR, RPR, RRP, PPP), representing planar walking in one direction, where the "R" and "P" stand for revolute and prismatic joints. The 3D cases (SRS, SRU, SPU, SPS) provide a realistic strategy as a bridge to the concept of design for the human leg structure. They serve as kinematic abstractions for a two joint (universal joint) or three joints (spherical joint), where the "S" and "U" in the 3D case stands for spherical joint and universal joint. The abstractions of the various human joints as either a series of serial chains or closed-loop parallel chains is discussed in [97,98].

4.1.1. Hip

The hip is a ball and socket joint in the human anatomical system. It connects the pelvic girdle and the thigh, which permits movements in three DOF, also known as the principal motion trajectory, allowing flexion, extension, and rotational movements. They are the dorsiflexion/plantarflexion (DF-PF), eversion/inversion (EV-IN) and adduction/abduction (AD-AB) motions. The hip joint supports the body's weight in both static (standing) and dynamic (walking or running) posture and enhances stability. The skeletal muscle is a soft tissue composed of specialized cells called muscle fibers attached to the bones of the hip, thereby producing force and motion by contraction of the muscles.

4.1.2. Knee

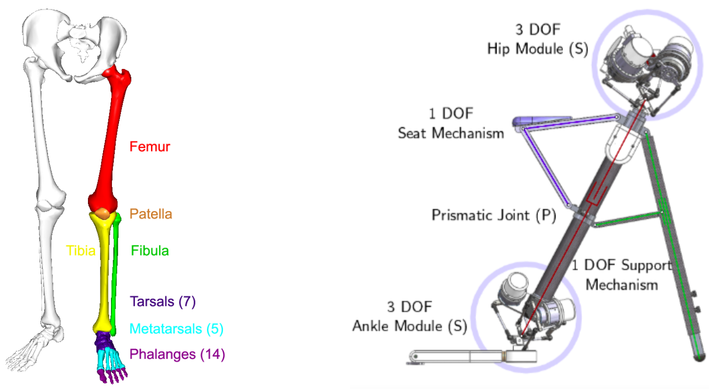
The knee joint is a hinge-type synovial joint formed by articulations between the femur and tibia bones. It permits flexion, extension, and slight internal and external rotation while carrying the body's weight during movements in the horizontal and vertical directions.

4.1.3. Ankle

The ankle joint is a synovial joint located above the foot. It connects the bones of the leg (tibia and fibula) and the foot (talus). Functionally, it is a complex hinge type joint, permitting primarily (DF-PF) of the foot, and (EV-IN) movements are also produced at the subtalar region of the foot. However, slight rotational movement of the foot also occurs as (AD-AB) motion.

4.1.4. Example of Exoskeleton Abstracting Human Leg

The Recupera-Reha LEE in (Figure 8b) is a prototype designed to mimic the anatomy of the human lower extremity. The three joints SPS module corresponds to the three joints (SRS) of the human leg in (Figure 8a). The LEE of Recupera-Reha consists of modules representing hip (S), ankle (S), and a prismatic joint (P) connecting the hip and ankle joints with an extension from the hip, which supports sitting mode [28]. The Recupera-Reha ball and socket joint of the hip and the functional hinge joint of the ankle are both designed and treated as an almost spherical parallel mechanism (ASPM), which was introduced in [99] and later extensively analyzed in [100,101]. Due to its complexity, the placement of the joints at an exact center of the pelvic and foot respectively defines the geometry of the human anatomy as a unique design [28,101]. The motor actuators placed at the joints replace the muscle functionality in humans, while the number of actuators placed at each joint determines the directions of motion.



(**a**) (**b**)

Figure 8. Human and exoskeleton leg. (**a**) Human leg [96]. (**b**) Exoskeleton leg [28].

4.2. Actuator Design for Wearable Exoskeleton

The bio-mechanical exoskeleton devices strapped onto the human body are a vital tool that could fit into the biological structure of the body since they are used in different application domains and try to mimic the natural human gait pattern. Considering the mechanical design perspective, material technology, alignment with the human joint complex, and meeting the requirements for actuation are key to human safety. Therefore, it is essential to evaluate the type of actuator to use before defining the basis for controlling the exoskeleton. Generally, exoskeletons are underactuated, and it is impossible to imitate all the motion trajectories in the human lower extremity, but it is possible to adapt the principal motion's trajectory suitable for the movement patterns in normal daily activities, such as climbing stairs, or in the rehabilitation of gait. The muscles of the human leg enhance movement strength when the muscular motor neurons are too weak to lift the legs of a paralyzed patient or aged person. The actuators on the wearable exoskeleton devices are designed to augment the muscular strength in humans to provide efficient power at the joints. Data evaluations from the CGA have been used in [72,85,102] to measure angular motions, forces, torques, and power to determine the type of actuator to use, while authors in [103] provided an optimal approach for selecting actuator design components for exoskeletons.

As a motivation towards developing wearable exoskeleton devices, the devices are required to have a small size, be lightweight, have good precision, generate torque effectively only when needed, and be safety-minded. Therefore, the actuator design type should meet the following design specifications; affordability and availability in the market, produce less impedance to enable interactive transmission of forces as feedback control, resistance to disturbance, backdrivability, high bandwidth, high power, and be easily controlled. Given these requirements, researchers have developed exoskeletons for human walking primarily from electrical [29,31,52], hydraulic [85], and pneumatic actuated [104] devices.

Electric actuators are electrically driven by direct current (DC) motors, which create the necessary force for linear or rotary motions. They are available in small sizes and are reliable, cheap, have less noise output, and easy sourcing of power, with the risk of electric shock being a drawback. A broad overview of the actuation of the LEE for power augmentation is made in [105]; according to the authors, CGA data are essential factors for determining the power required to actuate an exoskeleton joint. Hence, they provide input data required for an actuator design. The authors in [106] stressed that the advantages electric actuators offer are preferential, in contrast to their hydraulic and pneumatic actuated counterparts, which are bulky in size. According to them, it is impractical to have each modular exoskeleton part designed with independent power units. Stiffness between the actuators and the material of which the exoskeleton frame is made is a common approach to exoskeleton design. Therefore, the authors in [107,108] suggested that a serial elastic actuator (SEA) could be used to provide accurate torque delivery, disturbance rejection, transparency, repeatability, and compliance to force control. Although, SEAs are effective actuators that could enhance the backdrivability they are still not good enough for high bandwidth control loops, which is an important factor for designing walking exoskeletons or legged locomotion in general. Quasi-direct drives encompass most of the requirements of actuation for legged locomotion due to being lightweight, have efficient backdrivability, high control bandwidth, low inertia and stiffness, and better torque control. The application of quasi-direct drive actuation was used in [109] as a low-cost compliant robot capable of force controlled manipulation, and recently in [110] to drive the hip of an exoskeleton. Results from the experiment produced a high control accuracy in the nominal torque, bandwidth, and backdrivability perspective.

Hydraulic actuators are often used for driving high-powered machines, mostly in industrial domains using hydraulic fluids. They deliver good work density, high power and forces, and are easily controlled, producing linear and rotary motions. The disadvantages are safety problems with regards to leakages and their flammability [111].

Pneumatic actuators work in principle similar to hydraulic actuators by converting compressed air to mechanical energy in the form of linear and angular motions. They have good work densities, but not as high as hydraulic actuators, are easy to control, and have the ability to work at higher temperatures. However, they exhibit energy loss due to heat transfer, noise, and higher leakages. They are not often used in high force transmission or precise position control. Instead, they are used for fixed motion systems [112].

4.3. Design Concept

In the past decade, LEEs were designed as series, parallel, or series-parallel hybrid mechanisms [97]. The former is built with kinematic chains arranged in a single series of links and joints while the latter is built by at least two kinematic chains mostly in closed loops [113]. Serial designs are known for their versatility, ample workspace, simple modeling, and control. Their drawbacks include their limited precision, low stiffness, poor dynamic characteristics, and limited speed and torque. In contrast, the parallel counterpart provides higher stiffness, speed, accuracy, and payload capacity. However, they have reduced workspace and complex geometry, which requires careful control analysis as a downside. Regarding an application point of view, the safety and comfort of the wearers of the exoskeleton come first in robot designs. Mimicking the human anatomic motions and augmenting muscle power comes next. For enhancing safety, the mimicking of the human gait pattern, a combination of both serial and parallel designs, has been employed recently, and is still ongoing, aiming for functionality that is almost closer or equal to that of a human (see Figure 9) [28]. The Recupera-Reha full-body exoskeleton in Figure 9 with two system design configurations; the full-body (left) and wheelchair design mode (right), is a combination of series-parallel (hybrid) designs. The blue highlighted labels represent the full-body system features while the green highlighted labels represent both system designs. The modules for the upper-limb has a link of serial chains at the forearm and elbow joint connected to the wrist. The joints are actuated with serial elastic actuators and are implemented as independent series kinematic chains. The shoulder joint is a parallel mechanism design that provides a large workspace and prevents collision with the human head due to the placement of the actuators behind the shoulder blade (details in [114]). The lower-limb has its hip and ankle joints treated as an ASPM modular design (more details in [101]). Each of the modules of the upper and lower-body are independently coupled, making the full-body a combination of a series-parallel (hybrid) design.

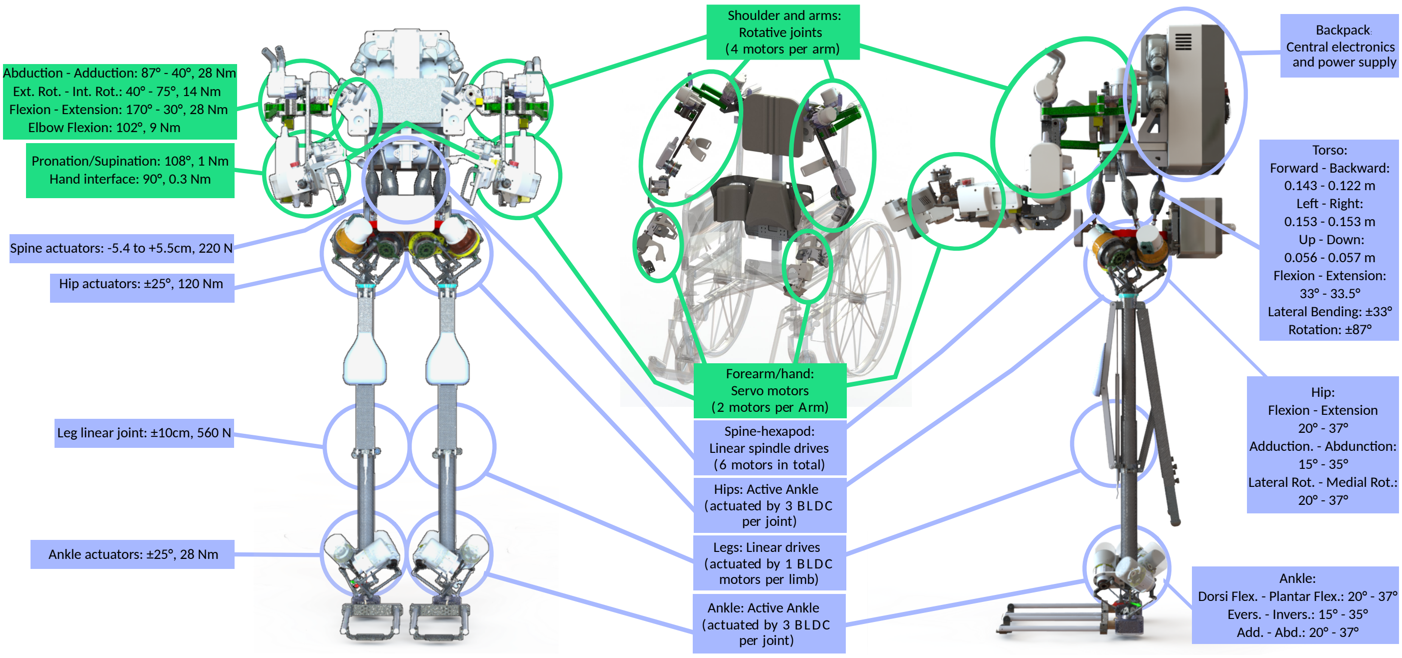


Figure 9. Series-parallel (hybrid) exoskeleton design [28].

The design concept points out the mechatronic structure relative to the hardware usage, which leads to a single leg or a modular form of the hip, knee, and ankle joints for rehabilitation, assistance, and power augmentation towards effective locomotion. Tables 4–6 review the mechanisms used for hip, knee and ankle designs, respectively. The composition of the modular joints as a single leg design for bipedal human walking has also been developed in some considerable research works [28,29,74,104]. From the purview of bipedal walking exoskeletons, the tables give an overview of the significant design features, achievements, and limitations in the current designs. An acronym, not available (N/A), is used for the tables with no available data in the source.

Table 4. Review on hip joint.

Institution/ Name	Actuation	DOF	Absolute ROM	Velocity Limit	Torque Limit	Application Domain	Pros	Cons
HIT China, [115] (2019)	BLDC Motor	3	N/A	N/A	22.3 Nm	Medical	The exoskeleton can stand, sit, and walk with stair ascending modes. A wearable device made from carbon fiber materials with a total mass less than 12 kg, it is designed by first simulating the biomechanics of the human body for joint alignment with the LifeModeler tool. The actuators consist of encoders, planetary gear, and bevel gears to absorb shock.	Difficulty grounding its own weight, with increased consumption power and stability control.
Recupera-Reha, [28] (2019)	"	3	DF-PF = 57°, EV-IN = 57°, AD-AB = 50°	132°/s	120 Nm	Medical	A 41 kg lightweight modular exoskeleton adaptable to different human sizes. Depending on the body part, the device is made from aluminum, steel, polyamide and carbon-fiber reinforced materials. The self-designed modular actuator units are capable of satisfying specific requirements.	The prototype only supports sitting and standing modes and requires optimizing the design to incorporate a walking and running mode.
Necmettin University Turkey, [102] (2017)	"	1	N/A	3190 rpm	N/A	Medical	An 18.5 kg lightweight wearable orthotic device that supports ReWalk. CGA data from human joint motions is used to determine the orientation of the exoskeleton joints. The 24 V DC motors are powered by Li-Po battery pack used for actuation of the hip by 30 W power.	Limited workspace, underactuated, and additionally supported with crutches.
Cuenca University Ecuador, [116] (2017)	DC Servomotor	1	"	N/A	"	Medical	A wearable exoskeleton designed with real time fast data link between six sensors and actuator units with a main process unit.	Limited to few therapy motions due to less DOF.
BLEEX, [85], (2006)	BLDC Motor	3	"	"	"	Military	A 41 kg wearable autonomous exoskeleton designed with extra payload capacity, using a bidirectional hip actuator for stance and swing mode compared to the previous hydraulic actuated variant.	The exoskeleton hip joint axis only aligns with the biological joint from the CGA data.
Yonsei Uni. China, [72] (2013)	"	3	DF-PF = 20°, EV-IN = 50°, AD-AB = 40°	"	79.3 Nm	Medical	A wearable device embedded with sensor and inclinometer at the torso to measure CoP and reaction forces. The CGA estimated a 200 W power required for the hip and knee joint actuators with harmonic drives.	To supplement the stability problem, forearm crutches that are controlled by the upper limbs supports the hip.

Table 5. Review on knee joint.

Institution/ Name	Type	Actuation	DOF	Absolute ROM	Velocity Limit	Force/ Torque Limit	Application Domain	Significant Feature
Recupera-Reha, [28] (2018)	Wearable	Linear BLDC motors.	1	N/A	266 mm/s	560 N	Medical	A wearable device made from a combination of aluminum, steel, and reinforced carbon-fiber. The prismatic joint of the knee is designed with a seat plate and foldable support when required to make angular motions. The actuators and ball screw on the two prismatic joints of the legs can support a total force of 1120 N.
Vrije University Brussel, [104] (2009)	Platform	Pleated pneumatic artificial muscles	Multiple	EV-IN = 60°	N/A	80 Nm	Medical	A 5.8 kg lightweight design made from thermoplastic materials, with artificial muscles that provide air-powered actuation in the design form of four-bar linkage, generating linear motions with a high force output that suits limb rehabilitation. A gravity supportive arm allows the platform device to mimic human posture and balance.
BLEEX, [85] (2006)	Wearable	Electric Motors with harmonic drives	1	EV-IN = 65°	"	34.7 W	Military	The CGA-data determined the knee flexion angles and torques required for alignment with the human knee joint. The generated toe-off and stance torques have enough power to back drive the harmonic drives and actuators in an asymmetric manner.
Meltran V, [9] (2001)	Platform	BLDC Servo motors	1	N/A	"	109 W	Industrial	The linear inverted pendulum mode design approach is used to determine the CoM, which aligns with the human hip joint on the 46 kg robot to maintain posture. It is designed with a synthetic rubber material from Neoprene.
Yonsei University China, [72] (2017)	Wearable	BLDC motors	1	EV-IN = 100°	"	42.2 Nm	Medical	The sensor system design based on the CoP and ZMP determines human intention to move the knee through force reactions measured between the wearer and the device. This enabled the proper mounting of the device onto the human body complex. Duralumin material is used for the joint linkages, and the actuators produce an estimated 200 W.

Table 6. Review on ankle joints.

Institution/ Name	Type	DOF	Absolute ROM	Velocity Limit	Force/Torque Limit	Application Domain	Design Strategy
Beijing University of Tech. [117] (2020)	Wearable	3	DF-PF = 75°, EV-IN = 44°, AD-AB = 72°	N/A	N/A	Medical	Workspace analysis
PARR, [118] (2019)	Platform	3	DF-PF = 68.16°, EV-IN = 32.57°, AD-AB=64.20°	"	"	"	"
ASPM Active Ankle [101] (2019)	Wearable	3	DF-PF = 57.06°, EV-IN = 50°, AD-AB = 66.16°	330°/s	28 Nm	"	Workspace and finding optimal placement of the mechanism in the leg.
Anklebot, [119] (2016)	Platform	2	DF-PF = 70°, EV-IN = 45°	N/A	N/A	"	Workspace analysis
Purdue University Fort Wayne, [120] (2013)	"	3	DF-PF = 100.8°, EV-IN = 56.0°, AD-AB = 99.50°	"	"	"	"
Chongqing University China, [121] (2013)	"	3	DF-PF = 75.60°, EV-IN = 39.0°, AD-AB = 61.90°	"	"	"	"
Yonsei University China, [72] (2013)	Wearable	3	DF-PF = 10°, EV-IN = 25°, AD-AB = 50°	"	"	"	Stability criteria using CoP to determine walking intention.
PKAnkle, [122] (2013)	Wearable	3	DF-PF = 75°, EV-IN = 45°, AD-AB = 30°	90°/s	52 Nm	"	Kinematic optimization (alignment with the human ankle joint complex)

4.4. Modeling Tools

To study the motion of the exoskeleton and its combination with the human musculoskeletal system, we need to understand the geometry, kinematics, and dynamics of the system with the various electronic sensing and measuring devices available. Hence, the interpretation of the above into a form of mathematical equations is termed modeling. The analytical computation of the kinematic and dynamic model of a serial chain robot is largely addressed in [113]. However, the closed chains or parallel structures involve solving complex non-linear equations, which could be too tedious to formulate both analytically and numerically using notable dynamic methods like Newton-Euler, and Lagrangian [97]. Hence, modeling tools are introduced to reduce the stress of solving complex equations generated from closed chain robots.

Modeling tools are software frameworks used to deal with multi-body dynamic exoskeletons that have complex mechanical systems. Tools like (RBDL [123], HyRoDyn [124], DART [125], and OpenSim [126]) support closed-loop models that contain libraries for efficient computation of kinematics and dynamics (forward and inverse), Jacobian matrix and determinant, and constraints for contact and collision handling. The Hybrid Robot Dynamic (HyRoDyn) solver was recently developed as a modular software workbench. Other open-source library tools like (Drake [127], RBDyn [128], and Pinocchio [129]) support rigid and multi-body dynamic computations. Robot Operating System (ROS) description format files such as Unified Robot Description Format (URDF) and Simulation Description Format (SDF) [130] are loaded as inputs, which give the robot's physical description for the rigid robot system to be modeled using the modeling tools. These tools have been used in the design of humanoid robots [131,132] and also in exoskeletons for human walking [28,124]. Series-parallel hybrid designs for, e.g., Recupera Exoskeleton (see Figure 9) have large degrees of freedom in their spanning tree and computing the complete kinematic and dynamic models can be computationally expensive. This poses a challenge for model-based control approaches. Model simplification approaches like the one described in [28] can be used for reducing the model complexity, which is crucial for the real time dynamic control of exoskeletons with closed loops.

4.5. Control Methods

Two main strategies that employed to control bipedal walking exoskeletons are the model-based and model-free control schemes.

4.5.1. Model-Based Control

The model-based control scheme uses algorithms formulated from either the kinematic or dynamic model of the robot system. Such control schemes include; active impedance control, admittance control, biosignal-integration-based control, optimal control, and machine learning. These approaches have various control criteria ranging from stability control [7], force feedback and torque control, master-slave control, and sensitivity amplification control, among others. The control criteria are mapped out in layers of performance from low, mid, and high-level switching, which can be cascaded and processed by electronic interfaces such as Arduino, field-programmable gate array (FPGA), microcontroller units (MCU), and standard CPUs, to mention but a few. Compliance control is inarguably the most crucial aspect of exoskeleton control. The active impedance control explicitly employs the dynamic model of the exoskeleton mechanism to control the joint position, force, torque, impedance, and compensate for disturbances like steady-state offset. For robots where torque sensing is not available, it is also possible to achieve compliance using the method proposed in [133].

The active impedance control was applied in [134] to improve the dynamic response of the human limbs as an alternative to the biosignal integration technique, which is complex and requires re-calibration of the model parameters. The biosignal integration is a part of neuroscience that creates communication between the exoskeleton and the wearer's brain or muscles by measuring electric potential signals on the surface of the living tissue with the help of sensors like EMG and EEG [58,88,135,136]. The measured signals are collected as training data from different individuals, analyzed by selecting relevant states of the human brain, and classified according to patterns between training data sets, and healthy and unhealthy subjects. The exoskeleton model is used beneath the EMG-based control to capture the whole dynamics of the mechanism in [52]. Other sensors are the inertial measurement unit (IMU), torque encoders, force-sensing resistors (FSR), and many more as additional control elements. For example, a string encoder with IMUs [89], were used in teleoperation to measure the position and orientation of a teaching tool and then to apply the generated signals to a robot manipulator as a haptic device. FSR is applied in [137] to analyze muscle activity patterns during bicycling and in [90] to test the sensing limits in comparison with other sensing devices.

Haptics is a form of tactile feedback technology that takes advantage of the user's sense of touch by applying forces, vibrations, and motions in the form of master-slave operation. It was applied for teleoperation of the CAPIO upper-body exoskeleton in [114] and applied as a force feedback control in rehabilitation after stroke [138] as an additional control approach. Virtual model control is similar to force feedback technology. However, it uses virtual components to create virtual forces applied through real joint torques to create the illusion of connectivity with the robot. It was previously applied in [139] to control the walking of a bipedal robot on level terrain.

Another method is Direct Collocation, which allows solving non-linear optimal control problems based on the direct transcription of the problem. This method approximates the state and control as piece-wise polynomial splines, and the constraints are enforced at the collocation points. Among the most common formulations is the Hermite-Simpson algorithm, which has been used, for example, in [29] as a high-level controller for the ATALANTE lower limb exoskeleton introduced above.

In the meantime, in humanoid robots, there has been a progressive development in the use of optimal control to differentiate between continuous and discrete control problems [87]. To improve robustness and autonomous locomotion, we use the linear quadratic regulator (LQR), Time varying LQR (TVLQR), and other non-linear optimization-based controls combined with state estimation concepts. LQR is an optimal control design technique that provides feedback gains to enable stable and high system performance. It is further applied to find the optimal solution to swing up and balance the underactuated cart table model system that captures the human walking motion [140].

4.5.2. Model-Free Control

The model-free control scheme uses the trial-and-error learning method without having an analytical model of the system to evaluate its control performance. Such schemes are classical control techniques like the proportional, integral, and derivative (PID), fuzzy control, neural networks, haptics, and virtual model control, to mention but a few. Fuzzy control is also a method that can be considered for the exoskeleton, especially when the dynamical model cannot be accurately formulated. This method is composed of modules that create the input membership functions, and defines the set of rules for processing by the inference engine [141]. Based on the EMG signal, this method has been used as a Neuro-Fuzzy controller in [142] to control a lower limb exoskeleton for motion assistance of physically weak people.

In addition to the two control schemes, other methods have been proposed, such as adaptive oscillator-based control, which has also been widely used in exoskeleton control. This method was originally proposed by [143] to synchronize the instantaneous frequency to any cyclic signal. Later it was used in robotics for pattern generation [144], then extended to the control of exoskeleton robots. In [145], this methodology was used to control a whole-body exoskeleton for gait assistance, which can adapt to motion pattern variations.

Table 7 shows a review of the current state of the art for the control strategies and methods used in the domain of biped exoskeleton. It further highlights some mechatronic details and the choice of programming environment.

Table 7. Review on control methods and approaches for LEE.

Institution/ Name	Programming Language	Control Methods	Mechatronics Feature
Recupera-Reha, [28,52] (2018)	Matlab, Python, Ruby, C++	Kinematic and Dynamic Model. Position, velocity, force and torque control. Low and mid level control hierarchy.	EMG and EEG sensors, FPGA electronics, Eyetracker, especially in Virtual Reality-based serious gaming.
University of Cuenca Ecuador, [116], (2017)	Matlab	"	EMG and EEG sensors.
DRACO, [146], (2019)	"	PID feedback controllers, observers, and estimators.	Viscoelastic liquid cooled actuator (VLCA).
Vanderbilt University Nashville [147], (2021)	"	PD position control with a feedback sensing	Hydraulic actuators. IMU sensors and digital signal processor.
KIT-CO-1 [62], (2015)	Matlab, C++	PID controllers	Linear series elastic actuators. Force signals processed by Arduino.
ATALANTE, [29], (2018)	"	Hybrid control combining dynamic model and state machine, gain tuning using virtual constraints via feedback control.	BLDC Motors, digital encoders with IMUs to measure joint velocity and displacements. Force sensors for detecting ground contacts.
MINDWALKER, [74] (2014)	Matlab simulink	CoM transition with finite-state machine based controller.	Series elastic actuator. Motion steps are triggered using arm muscle attached to IMU, EMG, and EEG sensors
HEE, [148], (2016)	"	Fuzzy self-adaptive PI controller	No Information

5. Discussion and Future Research Directions

This section discusses the overall existing methods in the design and control of biped walking exoskeleton robots and proposes a paradigm shift as future research directions.

5.1. Discussion

The significance of improving the design and control of the bipedal walking exoskeleton is critical due to its applicability to the daily life of humans to either assist or augment power. For medical application rehabilitation purposes, careful design and control analysis must be met to imitate the natural human gait patterns. Therefore, misalignment of the exoskeleton joint articulation with the human biological limb will cause pain to the patient and increase the injury sustained. In industrial and military applications, precision is required to achieve specific tasks. Without effective control, there will be no dexterity in manipulation. These exoskeletons are still not readily available for individual use due to the size, cost, and safety measures. They are developed in healthcare and research facilities or upon special request.

A question to ask is; how do we make the exoskeletons affordable to all without compromising the quality and performance of the sensors, drives, or actuators? Generally, exoskeletons are underactuated in their designs but then, how do we compensate for all human biological ranges of motion? In addition, there is a need to exploit other materials such as carbon fiber, silicon, and aluminum alloys to minimize costs in designing lightweight robots. In the design of actuators, selecting components that best suit an exoskeleton requires torque, power, backdrivability, high bandwidth, efficiency, and most importantly safety. The advantages of electric actuators are their compact size, low cost, less noise, less weight, and easy sourcing of power. Unlike hydraulic and pneumatic actuators, which have the disadvantage of being heavy, space-consuming, expensive, and, most importantly, do not respect modularity. Geared electric motors have high friction, which makes force control difficult. SEA is a compromise, but still has bandwidth limitations for control loops. In contrast, direct drives and quasi-direct drives are perfect actuators for building next generation exoskeleton devices. The actuators are lightweight, less expensive, and meet the requirements for efficient and quality exoskeleton designs. Therefore, a paradigm shift into quasi-direct drives could be a better actuation option for developing biped walking exoskeletons.

The Model Predictive Control (MPC) is a model-based control method that has found increasing utility in emerging complex engineering applications, including uncrewed vehicles, humanoid robots, and biomedical systems [149]. The MPC algorithm enables robots to be sufficiently responsive to perform dynamic tasks in real-time. It is achieved by updating the motion planning based on the current measured state of the robot at a sufficiently high-frequency [150].

MPC and LQR algorithms are based on optimal control methods. They are often used for trajectory tracking in robotics and for articulated vehicles [151,152]. However, experiments have shown that MPC performs better than LQR [153], considering the modification of the robot's state according to its environment when updating the command. Moreover, it allows reacting quickly enough to this modification by recomputing a new motion planning that allows, in the case of exoskeletons, to have a reactive and robust control to adjust a disturbing trajectory by a potential obstacle or instability of the patient. Thus, the combination of MPC and machine learning was recently applied by the authors in [154] to develop autonomous vehicles for enhancing safety and comfort. MPC control approach can provide robust, safety and oriented control, but in situations where the system is complex and challenging to model, the MPC may have to utilize other model learning techniques to control the system efficiently. To this end, we can integrate MPC-model-based control with Artificial Intelligence (AI) in the form of adaptive learning as a trade-off to the complex modeling of systems and uncertainties inherent in machine learning techniques.

The AI control techniques such as fuzzy logic (FL), neural network (NN), and genetic algorithms have been applied to powered robots. In the past, FL was used as a form of decision-making technique on uncertain input data by setting some rule-bases to obtain a set of control actions as output to the controller. In [155], an FL controller was applied to control the joint motions of an exoskeleton robot model. The simulation results showed good trajectory tracking responses from the lower limb joints, but their response due to disturbances is not satisfactory since humans will wear the exoskeleton device. A shift to machine learning, also as part of AI, came into existence in supervised learning. This form of machine learning requires a lot of data, time, and training sessions to recognize speech and images and to determine position and orientation.

With the introduction of NN, now referred to as deep learning (DL), a series of neurons are connected in layers, which try to mimic the form of how the human brain analyzes and processes data. They are capable of learning from unlabeled data without human supervision (unsupervised learning) and creating patterns for decision-making to perform some tasks. However, the majority of NNs are trained in a supervised way by humans (supervised learning) [156,157]. With the exponential growth in AI, DL is valid in reinforcement learning (RL) as a function approximator. RL uses some forms of trial and error training that teaches machines and robots the model of a system by reinforcing its ideas and establishing a result. They have recently been employed in the control of exoskeletons in [158,159] which demonstrated efficient squatting assistance with human interaction. However, future work is needed to further extend the framework to a variety of human walking patterns. This work is still an open issue.

Various control design methods are already successful in other domains (e.g., humanoid robots). The Atlas from Boston Dynamics showcased its humanoid robot, which can walk like a human while traversing uncertain terrain [87]. Complex humanoid robots such as Atlas successfully achieved balance and control in motion planning and locomotion by combining the full kinematic model with a reduced dynamic model (e.g., CoM, CoP) of the robot instead of the full dynamics, which could be computationally prohibitive in solving trajectory optimization. The analysis and control of the RH5 humanoid robot in [132] is based on differential dynamic programming (DDP). The full-body trajectory optimization of RH5 showcased contact stability with DDP while generating walking trajectories using the classical control technique (Proportional-Derivative) position control. The MIT Cheetah 3 Robot [160] showed good gait performances using the MPC model with a reduced dynamics (using CoM) of the robot to determine ground reaction forces. Without the kinematics of the leg, the approach helped reduce the optimization problem to a quadratic program formulation that captures the dynamics of the robot's locomotion.

Technological advances have paved the way for combining AI and neuroscience to achieve efficient and reliable control of human-machine interaction. For example, the demonstration of an essential EEG signal based on human brain feedback in [161] is used to reinforce robot learning in human-robot interaction. Furthermore, the application of Event-related potential (ERP) has created a communication gap between the human brain and the computer or machine interface. In [162], a single trial data analysis is used to classify the activities of the brain by the influence of an ERP, which could be used as a vital tool for the interpretation of brain processes. Bionics and cybernetics are both theories of biological systems regarding the design and control of human-to-machine or human-to-robot interaction. It has shown how technology is progressing. Human motion intent is best reflected on the leg muscles. Using EMG sensors to measure the electrical activity of the lower limb muscles will give additional and effective control of a bipedal walking pattern. The measured signals, fed as inputs to the controller, will give a good estimation when combined in parallel with the model of the exoskeleton mechanism, thereby producing an effective control strategy.

5.2. Future Research Directions

To design and effectively control a robust, stable, and low-cost bipedal exoskeleton robot with wide motion ranges similar to the natural human gait pattern, the focal point for future research directions should be centered on the following features:

5.2.1. Human-Robot Interaction

The exoskeleton device that supports the human body externally enables humans with lower limb disabilities to walk again by enhancing locomotion. Patients with joint diseases caused by OA and paralysis have weaker muscles that are insufficient to allow for convenient self locomotion. There are already efficient exoskeleton designs present in research and clinical institutions but that are not available or sustainable to society. The sustainability reasons may vary from individual prototypes, but generally, trust, confidence, and the feeling of being in control of an exoskeleton when strapped to the human body is not felt, and that alone creates fear to the wearer. Therefore, there is a need to know the motion intent of the limbs to give input to the controller as a feedback control element. The application of biosignal integration should be incorporated with the model-based control for effective human-robot interaction. Designing robot devices without efficient communication with humans is not sufficient enough to be relied on entirely. For a reliable and effective human-robot interaction, the robot should interpret and send feedback of its current condition to the human interface. Therefore, control instructions must be integrated into the robot design as discussed in [58] which also forms a part of the safety standards.

It is a well-known fact that AI solutions produce predictions and results for multiple use-cases much faster than humans, but then, humans have emotions and can adjust when they make wrong decisions, whereas it is difficult for robots to comprehend the sense of emotion and make adjustments when wrong decisions are made. To this end, we are not confident of the predictions, decisions, and results obtained through tasks conducted by AI. Additionally, we do not entirely know why the decisions made to obtain specific tasks will correct the wrong decisions made. Therefore, a shift to the next generation of AI is called Explainable Artificial Intelligence (XAI), which is a new technological approach that enables human-robot interaction to adapt, learn, optimize functions, and return intuitive feedback that is reliable, accurate, informative, and with decisive results. Furthermore, XAI is capable of continuous model evaluation [163,164] to improve model performances by combining human instincts, ML algorithms used as black-boxes in describing AI model, and the features that influence the output based upon the input decisions as a glass-box model [165]. Using XAI combined with the noninvasive EEG and EMG signals, and model-based MPC, an efficient human-robot interaction for bipedal walking exoskeleton robot is feasible.

5.2.2. Control and Safety

Safety in robotics is a challenging problem, especially when it involves human-robot interaction (HRI). The most effective way of ensuring safety in HRI is to implement safety criteria during the design phase rather than the application phase. This criterion makes the robot permanently safe. In order to enhance reliability, safety can be achieved during the design phase by three-level approaches [58].

The first level occurs at the preliminary stage of the mechatronic design, referred to as the "safety by design." This safety by design level requires innovative technology such as 3D printing to intensify the usage of lightweight materials for the hardware. Methods using internal cabling, embedded power units, and electronic components already exist, aiming to create a compact hardware structure. It is also accompanied by the introduction of shock absorbers like dampers or springs to subdue the effect of forces exerted on the human body by the actuators or external obstacles that come in contact with the human body. Finally, as an integrated form of safety to regulate forces exerted by contact, the introduction of sensors in [166,167] that can stimulate the sense of touch and motion could be combined with the visual sensors. Additionally, the transmission of forces through soft tissues using elastic fibers, and viscoelastic elements can compensate for unnecessary force.

The second level of safety involves controlling the hardware components, referred to as the "low-level control." The low-level control involves controlling the joint actuators using force and torque rather than position level control [168]. In the presence of an obstacle, the positional control cannot change its initial trajectory except for when it hits the obstacle.

However, with force control, the robot trajectory can change by adjusting the torque on its joints.

The third level of safety is termed "mid-level control", which also has to do with control of the overall system. This approach offers robust safety to humans since it involves using sensors both internally and externally to the robot. The sensors describe the robot's current state's intended trajectory and give feedback control before navigating the path. To guarantee safety at this level, it is important to consider the limitations of positions, velocities, and torque of every human joint as well as the exoskeleton system at the level of trajectory design and feedback control. Advanced trajectory optimization methods usually offer such possibilities either as soft or hard constraints [132,169].

In every mechatronic design, safety comes first. Therefore, the mechanical structure of the exoskeleton must be designed such that it at least aligns with the anatomical structure of the human limb. As a result, it will prevent pains and more injuries while wearing the exoskeletons by patients, but it will also be safe and give the user a natural biological feeling. As a form of optimization, incorporating non-linear optimal control techniques and model-based control methods with AI integrated with biosignal technology, the future is bright for the disabled to have an artificial device that could seem natural enough to depend on entirely.

5.2.3. Cost

The cost of procuring exoskeleton devices for military applications may not be necessary since design requests are specifically from the government to improve national security. In industrial application, start-up industries and already established companies may wish to enhance the muscular strength of their workers, reduce fatigue, and provide fast workability with extra precision. In the case of medical applications, exoskeleton devices for personal usage are not affordable for low-income earners. The goal of developing medical exoskeleton devices is to assist the disabled and augment power for industrial purposes. Affordability should also be a vital key to consider while designing robots for these applications. The aim of the design could be defeated if the purchasing price is relatively high. Therefore, to make the device affordable and equally not compromising the quality and efficiency, the material technology used in building the hardware for the exoskeleton device should be lightweight and compact. The mechanical and electronic components such as actuators, sensors, power units, and configurable integrated circuits should be efficient, affordable, available, and conform to performance. There is a need to apply new technologies such as carbon nanotubes to produce artificial muscles to replace motor actuators, since carbon is abundant in nature.

Silicon is readily available in nature with abundant quantity. It is cheap, synthetically purified into wafers, and serves as insulators and semiconductors for power transmission. Chips formed from the fabrication of the wafers can adapt to new information in transmitting signals for human-robot interaction. The silicon chips can be designed as integrated circuits embedded in the actuators, sensors, and other electronic devices for controlling the exoskeleton hardware framework. Robotics is primarily about actuators. If we can focus on actuator designs with readily available elements found in nature, we can achieve efficient exoskeleton control at a low cost.

6. Conclusions

The prospects of bipedal walking with exoskeleton devices for both medical and industrial applications are bright and already in high demand for patients suffering from SCI, OA, aged persons, and the general population. Advancement in technology has come to encompass the conventional mobility aids such as crutches, walkers, and wheelchairs, which the lives of disabled people depend on, but that may have reduced the quality of their lives. This survey paper has reviewed the current state of the art on wearable exoskeleton robots for biped human walking based on design and control methods to enhance the rehabilitation of weak lower limbs and load augmentation during locomotion.

The challenges of these bipedal exoskeleton robots, from the perspective of their mechatronic design, have been summarized. The main focus was on the challenge of designing robots that are compliant to the human anatomical walking movement while meeting the criteria of safety, stability, effective rehabilitation, assistance, and effective control. To produce highly compact, effective, and low-cost prototypes for commercial use, some optimized control strategies have been proposed to help curb some of the challenges faced by biped exoskeleton robots for human walking. In our opinion, electric actuators are more reliable to use than their hydraulic and pneumatic counterparts due to the advantages they offer. A perfect solution for building the next generation of exoskeleton devices will be to use quasi-direct drives, which is a better actuation approach. The current trend in developing modular exoskeleton devices as an external supportive device for every joint of the lower limb is promising. It has also motivated neuroscientists to apply bionics in exoskeleton design to improve the quality of life of humans. Orthosis is the future of biped walking exoskeletons. If we can apply the underlying design and control methods from locomotion approaches in the form of holistic medicine, then we will have stable, safe, and mobility-efficient wearable exoskeleton robots.

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