J. Shanghai Jiao Tong Univ. (Sci.), 2024, 29(1): 1-15
https://doi.org/10.1007/s12204-022-2489-3

Review of Power-Assisted Lower Limb Exoskeleton Robot

HE Guisong (贺贵松), *HUANG Xuegong** (黄学功), *LI Feng* (李 峰), *WANG Huixing* (汪辉兴)
(School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 219904, China)

Abstract: Power-assisted lower limb exoskeleton robot is a wearable intelligent robot system involving mechanics, materials, electronics, control, robotics, and many other fields. The system can use external energy to provide additional power to humans, enhance the function of the human body, and help the wearer to bear weight that is previously unbearable. At the same time, employing reasonable structure design and passive energy storage can also assist in specific actions. First, this paper introduces the research status of power-assisted lower limb exoskeleton robots at home and abroad, and analyzes several typical prototypes in detail. Then, the key technologies such as structure design, driving mode, sensing technology, control method, energy management, and human-machine coupling are summarized, and some common design methods of the exoskeleton robot are summarized and compared. Finally, the existing problems and possible solutions in the research of power-assisted lower limb exoskeleton robots are summarized, and the prospect of future development trend has been analyzed.
Keywords: power assistance, lower limb exoskeleton robot, research status, key technology
CLC number: TP242 **Document code:** A

0 Introduction

Exoskeleton robot is a shell mechanism that can provide supporting, protecting and helping humans to carry out rehabilitation training[1]. It combines the mechanical energy of the robot with human intelligence and is a collection of bionics, sensing, detection, control, driving, etc. It is also a type of human-mechatronics integration system that can provide the wearer with exercise assistance, assisting mobility and other functions[2]. The exoskeleton robot is equipped with powerful actuators at the joints, and with the help of a built-in multi-sensor system, the exoskeleton robot can obtain the wearer's movement intention and assist with the wearer's movement accordingly[3]. In the past few decades, the development of the exoskeleton robot has made tremendous progress. Universities, research institutions, and industrial companies have been actively pursuing research in this field. Especially in recent years, a variety of exoskeleton robot systems have been developed and tested[4]. According to the body parts supported by the exoskeleton robot, they can be divided into upper limb exoskeleton robot, lower limb exoskeleton robot, whole-body exoskeleton robot, and specific joint supporting exoskeleton robot[5]. This article mainly focuses on the exoskeleton robot of lower limbs and discusses some typical prototypes developed in the world. Lower limb exoskeleton robots can be divided into three categories according to their functions. The first category is power-assisted lower limb exoskeleton robots, which are mainly suitable for healthy people and are used to enhance human functions. For example, it can be used to improve individual combat capabilities in the military. The second type is rehabilitation lower limb exoskeleton robots, which are mainly used in rehabilitation training and rehabilitation treatment for people whose lower limb movement ability impaired. The third type is motion-assisted lower limb exoskeleton robots, which mainly assist the disabled in performing actions that they cannot complete[6-8]. At present, great progress has been made in the research of the motion-assisted and rehabilitation lower limb exoskeleton robots, but there is little research on the power-assisted lower limb exoskeleton robot. The article mainly reviews the power-assisted lower limb exoskeleton robot.

1 Research Status

The research on exoskeleton robots originated in the 1960s. In 1965, with the support of the US Department of Defense, Cornell University and General Corporation proposed the first generation of whole-body exoskeleton robot Hardiman[9]. However, due to the limitations of control, detection, sensing, communication, and energy technology at that time, the prototype was too large,

Received: 2021-09-03 **Accepted:** 2021-11-11
Foundation item: the National Natural Science Foundation of China (No. 52075264)
***E-mail:** huangxg@njust.edu.cn

and only one arm was finally realized. The lower limb exoskeleton robot comes from its branches. Because of the relatively low technical requirements of the upper limb exoskeleton robot, the development cycle is relatively short and the development is rapid, the product is quickly developed and applied[10], but the lower limb exoskeleton robot did not progress until the end of the 20th century[11].

The performance parameters of some typical power-assisted lower limb exoskeleton robots are shown in Table 1.

Table 1 Performance parameters of some typical power-assisted lower limb exoskeleton robots

Name	Mass/ kg	Endurance/ h	Load/ kg	Driving mode
BLEEX	38	20	37	Hydraulic
HULC	24	2—3	100	Hydraulic
HAL-5	5	3	40	Motor
XOS2	95	0.8	90	Hydraulic
Exosuit	10	4	24	Pneumatic muscle
Exo-Hiker	14.1	21	68	Pneumatic spring
DMSE	41	3	30	Hydraulic
Warrior Web	9	24	45	Motor
EKSO	20	6	100	Motor

1.1 Abroad Research Status

In 1978, with the support of the U.S. military, the Massachusetts Institute of Technology began to improve the power-assisted exoskeleton robot[12]. In the 21st century, due to the technological breakthroughs in computers, microelectronics, smart materials, and sensing, the research on continuously power-assisted lower-limb exoskeleton robots has been developed continuously and has been applied in practice. In 2000, the US Department of Defense invested 50 million US dollars to launch the "EHPA" (enhanced human exoskeleton) program, which stimulated the power-assisted exoskeleton robot research in the 21st century[13-15]. The American Berkeley Bionic Company developed the BLEEX lower limb exoskeleton robot under this project and completed prototype test of the first-generation power-assisted lower-limb exoskeleton robot BLEEX in 2004. This is the first energy-sufficient power-assisted lower-limb exoskeleton robot[16]. This lower limb exoskeleton robot is driven by a hydraulic system and has a total of 14 degrees of freedom (DOFs), 7 per leg, of which three are located at the hip joint, three are located at the ankle joint, and one is located at the knee joint. There are more than 40 sensors, which can accurately obtain the position and posture of the exoskeleton robot and the force of the joints in real time. BLEEX can enable the wearer to walk at a speed of 1.3 m/s under no-load conditions[17]. However, due to the system complexity, heavyweight, high power consumption, and poor human-machine coupling, it is uncomfortable to wear and inconvenient to use.

In order to overcome the above shortcomings, the company developed a lower limb booster exoskeleton robot HULC based on BLEEX in 2009 that can greatly increase the wearer's weight-bearing capacity. The exoskeleton robot inherits the advantages of BLEEX and the performance is more excellent and reliable[18]. The wearer can achieve a variety of relatively complex actions after putting it on, the maximum load can reach 100 kg, and the wearer can walk at a speed of 16 km/h under no-load conditions[19], and can work continuously for two to three hours. The exoskeleton robot uses lithium batteries as its power source and is driven by hydraulics like BLEEX. HULC is not only powerful, but also very anthropomorphic. It only takes 30 s for the wearer to complete the two actions of putting on and taking off, which is very convenient.

The HAL exoskeleton robot was developed by the University of Tsukuba, Japan. So far, the fifth generation of the HAL exoskeleton robot system has been developed. HAL is the first commercialized power-assisted exoskeleton robot[20]. With the continuous improvement of the HAL exoskeleton robot, the total mass of HAL-5 is only 5 kg, but it can help the wearer lift 40 kg heavy objects. HAL-5 is the first exoskeleton robot which obtains global safety certification[21]. The exoskeleton robot has a total of 26 DOFs. It is driven by a motor and uses a rechargeable battery which can work continuously for about 3 h. The working process is to obtain the electromyographic (EMG) signal of the wearer's skin by electrodes, and then transmit the signal to the central processing unit (CPU) for processing, so as to determine the wearer's motion intention, and finally make the driver produce the corresponding action, so as to complete the assistance function. HAL-5 can realize various complex actions such as squatting, jumping, and running up and down stairs[22], which fully embodies the man-machine coupling and makes the wearer feel quite comfortable.

The American Raytheon Company launched the XOS2 exoskeleton robot in 2010. The exoskeleton robot is mainly used for individual combat. The driving method is high-pressure hydraulic drive, which can provide strong power. It can enable soldier to penetrate 76 mm thick wooden boards with one hand[23], grab 100 kg heavy objects with almost no effort, and run at a speed of 5 km/h. After wearing the XOS2 exoskeleton robot, the soldier can perform complex and flexible movements, such as mountain climbing and kicking. However, this exoskeleton robot itself is bulky, reaching 95 kg, and it is very inconvenient to wear and take off. It consumes a lot of energy and can only work for 40 min. In contrast, the EKSO exoskeleton robot developed by the American EKSO Bionic Company is more convenient to use. The mechanical structure is made of alloys of aluminum and titanium in order to reduce its mass[24]. The main advantage of this exoskeleton robot is that the control mode can be selected through the joystick, and it can be switched back and forth between active and passive, which can be used for assistance and rehabilitation.

HEXAR is an under-actuated lower limb exoskeleton robot developed by Hanyang University in Korea[25]. HEXAR has a total of 15 DOFs. Through the constant force mechanism, the hip joint module bears the mass of the upper exoskeleton robot system and its load; the ankle joint module bears the total weight of the exoskeleton robot system, and uses its own elastic deformation potential energy to provide propulsion for walking. The wearer can walk at a speed of 1.5 km/h and carry a mass of 40 kg[26]. The exoskeleton robot has six photoelectric encoders on both legs and four pressure sensors on the feet, which can collect the movement information of the human body's lower limbs in real time, and they are used to judge the wearer's movement intention[27]. The LEE power-assisted lower limb exoskeleton robot has been researched and developed by Professor Luo Jinfa from Nanyang Technological University in Singapore[28]. Based on the zero moment point (ZMP) stability criterion[29], the exoskeleton robot is divided into inner and outer sides. The inner side is used for contacting with the wearer, and the outer side is used for assisting. It is also driven by a motor. The biggest shortcoming of LEE is that it cannot withstand large loads.

Soft Exosuit is the first flexible exoskeleton robot designed by Harvard University[30]. Later, under the sponsorship of DARPA in the United States, the second generation of Soft Exosuit was developed. The exoskeleton robot has no rigid components, and the mass is only 12.15 kg, which is convenient to wear. A new type of elastic fabric belt is also designed. It can also provide additional assistance besides the motor[31]. In September 2011, the US DARPA developed the Warrior Web intelligent combat uniform. The mass of the smart combat uniform is only 9 kg, which is lighter and has a power of less than 100 W. The battery mass is only 4.5 kg, but it can work continuously for 24 h. Soldiers wearing Warrior Web can reach a speed of 1.25 km/h with 45 kg load, and reduce energy consumption by 25%[32]. Based on this, the Stanford International Research Institute in the United States has developed a flexible exoskeleton robot Super flex that can mimic the wearer's movement information through sensors and other devices. This exoskeleton robot can provide the wearer with the strength to support the body, and the mass is only 3.63 kg[33]. Australia has developed a new type of passive flexible exoskeleton robot OX, which can transfer most of the soldiers' load to the ground. The exoskeleton robot is equipped with two simple Bowden ropes, the mass is less than 3 kg, the cost is low, and the man-machine coupling is strong[34].

1.2 Domestic Research Status

The study on exoskeleton robots in China started late, and there is still a big gap compared with foreign countries, but good results have been achieved. In 2004, the Chinese Academy of Sciences pioneered the research of power-assisted exoskeleton robots and developed a set of exoskeleton robot prototypes[35]. The exoskeleton robot is driven by a motor and has 6 DOFs per leg. The encoder is used to obtain the wearer's motion state and determine the wearer's motion intention. East China University of Science and Technology developed the ELEBOT exoskeleton robot in 2008. The wearer's movement intention is also obtained through the pressure sensor on the sole of the foot, and it can carry up to 30 kg. The exoskeleton robot uses lithium batteries as power supply[36] and for hydraulic drive, the hydraulic pump is driven by a direct current (DC) brushless motor[37], which can provide very powerful power, but the working pressure is large, the energy consumption is high, and the continuous working time is short.

General Hospital of Eastern Theater Command successfully developed a lower limb exoskeleton robot in 2013. This exoskeleton robot is used for individual combat and can help soldiers bear half of load. It is driven by a motor and the control method is similar to that of HAL. The gait information is obtained in real time by collecting the EMG signal of the wearer's legs, and then the signal is transmitted to the CPU to determine the wearer's movement intention, so as to control the motor to drive the corresponding joint to achieve power assistance[38]. The Naval Aeronautical Engineering Institute has designed a third-generation exoskeleton robot prototype[39]. The exoskeleton robot is driven by elastic elements and motors. The overall mass is 21.2 kg. It can work continuously for 2 h. The walking speed can reach 3.6 km/h under the condition of 30 kg load, and the exoskeleton robot can achieve a series of complex actions such as jumping, squatting, and running up and down stairs.

In 2017, Gao Yongsheng's team at the State Key Laboratory of Robotics and Systems of Harbin Institute of Technology developed a flexible under-actuated power-assisted lower limb exoskeleton robot system. The exoskeleton robot has a mass of 8.6 kg and is driven by Bowden ropes. The joint rotation is driven by a pulley mechanism to achieve the power assistance. The exoskeleton robot can reduce the wearer's heart rate by an average of 10 beats/min when working[40]. In 2018, Shanghai Si Yi Intelligent Technology Company developed a commercial unilaterally power-assisted lower limb exoskeleton robot system Easy Walk X1. The exoskeleton robot adopts a flexible drive method, which can provide help to the wearer's ankle joint, and its mass is less than 3 kg. The exoskeleton robot system is also equipped with voice control and inertial sensors, allowing it to work in different environments and terrains[41]. In addition, Harbin Institute of Technology, Southeast University, Zhejiang University, Nanjing University of Science and Technology have all carried out research on power-assisted lower limb exoskeleton robots and achieved corresponding results.

2 Key Technology

The working principle of the power-assisted lower limb exoskeleton robot is shown in Fig. 1.

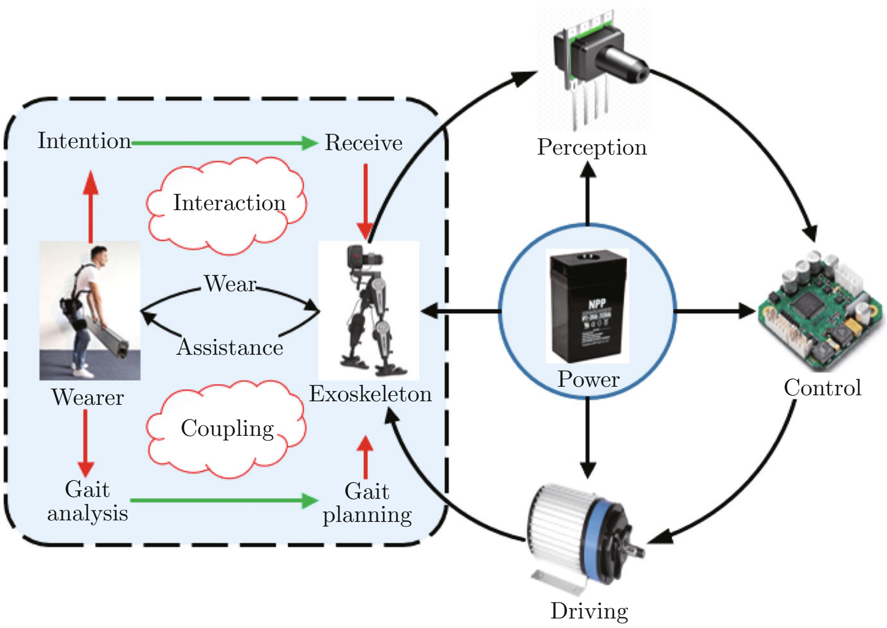

Fig. 1 Working principle of power-assisted lower limb exoskeleton robot

When the wearer generates motion intention, the exoskeleton robot receives the prediction, the sensor collects the signal and sends the signal to the control system for processing, and finally, the drive system will act according to the instructions issued by the control system to drive the exoskeleton robot and achieve assistance. The energy for this process is all provided by the power source. Among them, the idea of human-machine interaction is reflected from the wearer's movement intention to the exoskeleton robot's reception prediction; the completion of the gait planning of the exoskeleton robot through the analysis of the wearer's gait reflects the idea of man-machine coupling.

2.1 Structure Design

The structure design is the most basic part of the research of power-assisted lower limb exoskeleton robots, which determines whether the functions of the exoskeleton robot can be realized normally[42]. The structure design should meet the design principles of anthropomorphism and coordination. On this basis, the DOF of the lower limbs of the human body and the gait of the human body must be analyzed; additionally, the kinematics and dynamics analysis must be completed.

2.1.1 *DOF Analysis of Lower Limbs of Human Body*

The lower limb joints of the human body mainly include hip joint, knee joint, and ankle joint. The three joints coordinate with each other to help the human body walk normally[43]. According to anatomy, the lower limbs of the human body are divided into three reference planes: the horizontal plane, the coronal plane, and the reference plane; three reference axes: the vertical axis, the sagittal axis, and the coronal axis[44]. The motion of the joint is in these three reference planes, rotating around the three reference axes and making translations along the three reference axes. It can be seen that there are 14 DOFs in the lower limbs of the human body, including seven DOFs in each leg, including hip joint flexion and extension, adduction and abduction; knee joint internal rotation and external rotation, flexion and extension, adduction and abduction; ankle joint dorsiflexion and plantar flexion, inversion and eversion.

Since the power-assisted lower limb exoskeleton robot is worn in direct contact with the lower limbs of the human body, its DOF must be consistent with the DOF of the lower limbs of the human body. At the same time, in order to ensure comfort and safety when wearing, the motion range of each joint of the lower limb exoskeleton robot should be within the normal motion range of the lower limb joints of the human body.

The range of DOFs of each joint is shown in Table 2.

Table 2 Range of DOFs of each joint

Joint	DOF	Range/(°)
Hip	Flexion/extension	(−120)—(65)
	Adduction/abduction	(−30—−35)—(40)
Knee	Intorsion/extorsion	(−15—−30)—(60)
	Flexion/extension	(−120—−160)—(0)
	Adduction/abduction	(−30—35)—(15—20)
Ankle	Intorsion/extorsion	(−15)—(30—50)
	Dorsiflexion/plantarflexion	(−20)—(40—50)

2.1.2 *Kinematics and Dynamics Analysis*

DOF analysis can only meet the anthropomorphic design requirements of the exoskeleton robot. To realize assisted motion function, the exoskeleton robot and the lower limbs of the human body must move in coordination. It is necessary to establish a mathematical model that describes the position relation of each joint in the space coordinates system to determine the movement posture of the exoskeleton robot, that is, to perform the kinematic analysis. After the kinematics analysis, the relationship between the motion and the torque must be determined, so the dynamic analysis of the exoskeleton robot is required.

The specific steps are: applying the Denavit-Hartenberg (D-H) coordinate analysis method to establish a mathematical model of human-machine coupling, performing the kinematics analysis on the exoskeleton robot, and obtaining the relationship between the exoskeleton robot end and each joint motion parameter. Then the dynamic analysis is conducted to study the relationship between walking force and torque, the driving torque required by the ankle joint is determined according to its position control target, and finally the correctness of the theoretical solution of kinematics and dynamics is verified through simulation.

Kinematics and dynamics analysis can find the torque required by the exoskeleton robot, but the specific gait trajectory of the exoskeleton robot is not clear yet, so the gait planning should be carried out.

2.1.3 *Gait Planning*

On the premise of ensuring anthropomorphism and coordination, reasonable and effective methods are used to complete the gait planning of the exoskeleton robot to ensure the stability of the exoskeleton robot during work. Gait planning is the planning of the end trajectory of the power-assisted lower limb exoskeleton robot, which is an important basis for the bionic design of the wearable exoskeleton robot[45]. The purpose of gait planning is to determine the relationship between the various parts of the exoskeleton robot system, to ensure that the exoskeleton robot body does not interfere with the environment and all the joints of the exoskeleton robot do not interfere each other during work, and to ensure the stability of the overall movement. Because the exoskeleton robot system needs to meet the design principles of anthropomorphism, so the study of its gait must start from the walking movement of the person, usually using time and space parameters to describe the walking movement of the person. In the process of human walking, the time parameter is especially important. The human gait cycle is shown in Fig. 2.

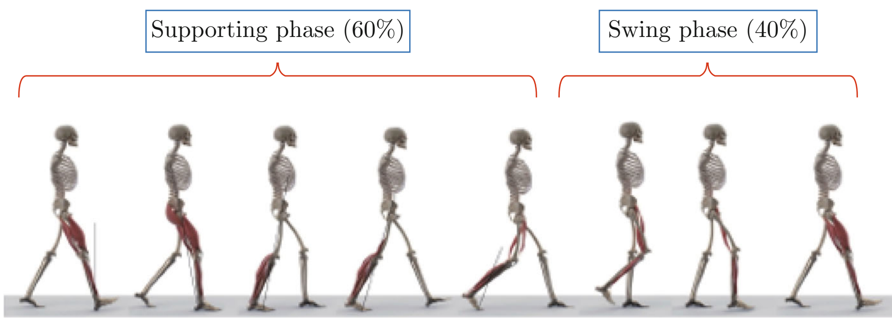

Fig. 2 Human gait cycle

It can be seen that the movement cycle of the lower limbs of the human body is divided into the supporting phase and the swing phase[46]. The supporting phase refers to the single leg or two legs touching the ground, and the swing phase refers to the movement of one leg off the ground while the human body is walking. A gait cycle is from the heel of one foot to the ground until the heel of this foot touches the ground again. As far as a single leg is concerned, the swing phase and the supporting phase account for about 40% and 60% of the entire gait cycle respectively, and both feet are in the supporting phase at the same time, accounting for about 10%, so that the proportion of each phase during exoskeleton robot movement can be obtained. In addition, in the process of human walking, there are some spatial parameters, mainly including step length, stride width, step width, and step frequency[47]. Step length refers to the straight-line distance between the heels of two feet in the direction of travel when a person is walking, generally between 500 mm and 800 mm;

stride width refers to the straight-line distance between the heels of the same foot when it touches the ground twice, and the length of stride width is about twice the step length; step width refers to the lateral distance between two feet, generally about 50—100 mm; step frequency refers to the number of steps taken per unit time during human walking.

Finally, based on the analyzed time and space parameters, the human gait is divided into three/five special posture points by the three/five-point planning method, and the corresponding position and angle coordinates are solved. Then the cubic spline interpolation method is used to perform curve fitting, and the trajectory curve of each joint is simulated. Based on the simulation, the ZMP curve of each joint is solved according to the ZMP dynamic trajectory equation, which is the final gait planning curve. Based on the analysis of the DOF of the human body, kinematics and dynamics analysis, and gait planning, the structure of the power-assisted lower limb exoskeleton robot can be designed. The currently developed exoskeleton robot has achieved the basic function of boosting, but it must take full account of the wearer's comfort, lightness, and flexibility. It is also necessary to further improve the human-machine coordination to make the exoskeleton body more similar to the human body. Since most researchers are relatively fixed in exoskeleton robot size design and freedom of choice, the structure design of the exoskeleton robot is slightly insufficient in terms of innovation, and it is possible to consider increasing the DOF on the toes to improve the structure innovation of the exoskeleton robot. At the same time, the structural lightweight design and man-machine matching design are also the key and difficult points.

2.2 Driving Mode

At present, a large number of studies have been carried out on the driving methods of power-assisted lower limb exoskeleton robots, mainly including motor drive, hydraulic drive, cylinder drive, and pneumatic muscle drive[48].

2.2.1 *Motor Drive*

The motor drive is the most used drive mode in the exoskeleton robot. This driving method can directly use electric energy and can realize high-precision motion control by adjusting the parameters of the motor, and the response is very fast[49]. As shown in Fig. 3, the motor drive mode of the power-assisted lower limb exoskeleton robot is usually divided into two types[50]. One is to install a motor directly on the exoskeleton robot rotating joint and use the rotation of the motor rotor to drive the rotation of the joint. Although this method is simple in structure, it will increase the moment of inertia of the joint. The other is to use an electric push rod to drive, usually Brushless DC motors are used, the motor drives the nut in the ball screw through the transmission element, and the nut pushes the screw to move in a straight line, thereby pushing the hip, knee, ankle and ankle joints of the exoskeleton robot of the lower limbs to rotate, and finally make the exoskeleton robot produce limb movements that imitate the human body to achieve assistance. In contrast, the second driving method is relatively more widely used[51].

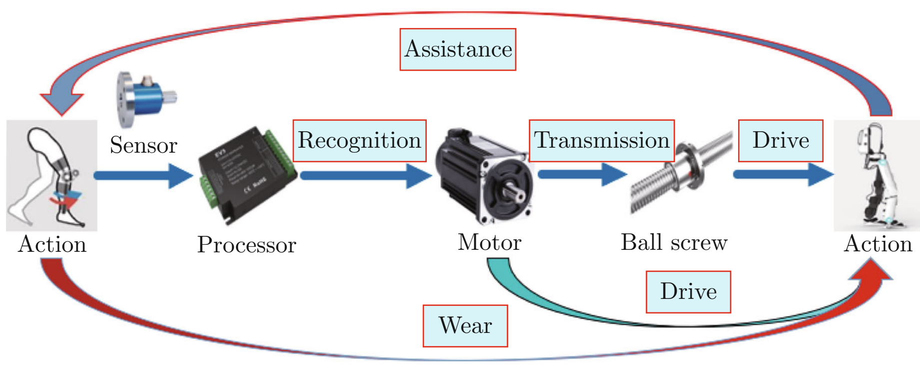

Fig. 3 Working principle of motor drive

2.2.2 *Hydraulic Drive*

The hydraulic drive is a transmission method in which fluid (hydraulic oil) is used as a working medium for energy transmission, including five parts: liquid medium, power source device, execution device, control and adjustment device, and auxiliary device[52]. The hydraulic drive has a high mass-to-energy ratio and can provide strong power for the wearer. Therefore, the power-assisted exoskeleton robot with the hydraulic drive is more suitable for carrying materials and equipment[53]. Hydraulic drives include hydraulic cylinders and hydraulic motors[54], and hydraulic cylinders are commonly used in exoskeleton robots. The working principle of the hydraulic drive is shown in Fig. 4.

The sensor sends the collected digital signal to the control system for identification and processing and then issues instructions to drive the hydraulic cylinder to move, and the thigh and calf of the lower limb exoskeleton robot directly connected to it are driven by the expansion and contraction of the hydraulic cylinder.

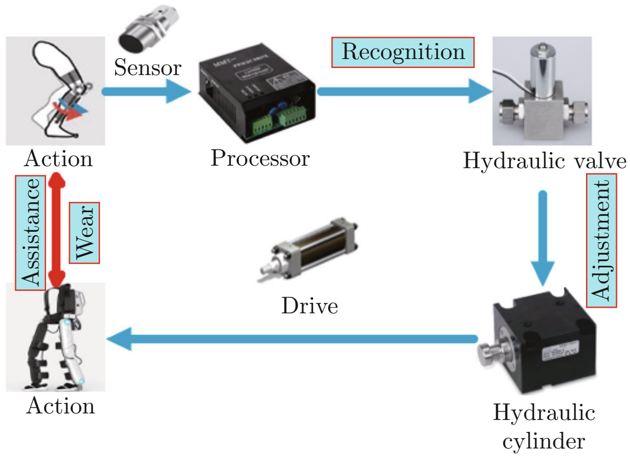

Fig. 4 Working principle of hydraulic drive

Corresponding movements with the feet to synchronize and coordinate with the wearer's movements are made to achieve assistance. When using this drive method, it is important to consider the issue of lightweight[55].

2.2.3 *Cylinder Drive*

The cylinder drive is a transmission method that uses the gas generated by the air source device as a working medium for energy transmission[56]. Compared with motor drive and hydraulic drive, cylinder drive is currently less used in power-assisted lower limb exoskeleton robots[57]. Its working principle is similar to that of hydraulic drive, the cylinder piston is directly connected to the thigh, calf, and foot of the exoskeleton robot of the lower limb, as shown in Fig. 5. The signal reaches the control valve through the controller, and the control valve makes corresponding actions to make the piston move linearly under the action of compressed gas. Finally, the rectilinear motion of the lower limb exoskeleton robot piston is transformed into the joint rotation of the lower limb exoskeleton robot, which synchronizes and coordinates with the wearer's motion to achieve power assistance.

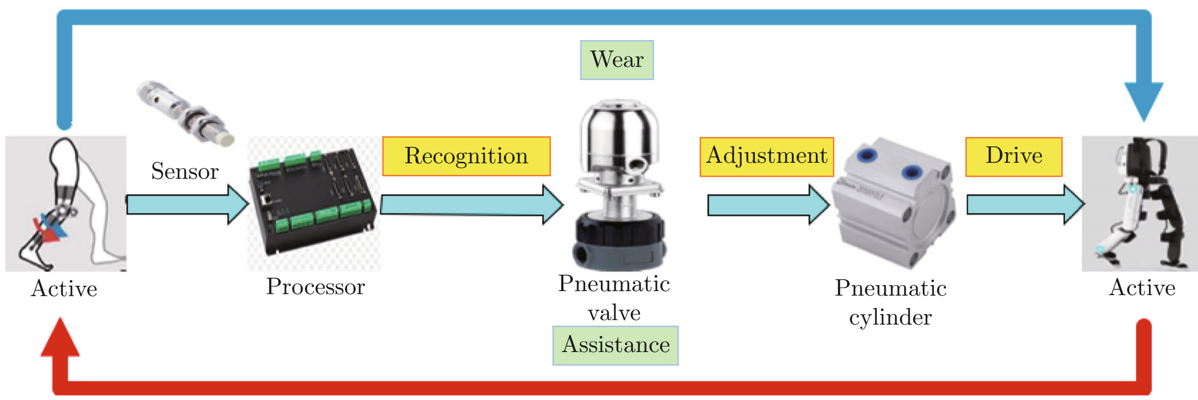

Fig. 5 Working principle of cylinder drive

2.2.4 *Pneumatic Muscle Drive*

Pneumatic muscle drive is a new type of drive method, which uses an anthropomorphic design idea[58]. Due to the inherent compliance and limited maximum contraction of pneumatic muscles, this driving method is commonly used in flexible exoskeleton robots[59]. Each rotary joint of the lower limb exoskeleton robot is driven by two pneumatic muscles. The working principle of pneumatic muscle drive is shown in Fig. 6. The length of the artificial muscle is changed by the compression of gas, and then the movement of the exoskeleton robot of the lower limb is driven by the expansion and contraction of the artificial muscle, so as to achieve power assistance. The driving efficiency of pneumatic artificial muscles is relatively high. Pneumatic muscles have small mass but high energy output, and pneumatic muscles also have the characteristics of automatic braking. At the same time, it is so safe in human-machine interaction when pneumatic muscles are used to drive, so it is very suitable as a wearable flexible air pressure driver. At present, the pneumatic muscle drive is not mature and the economy is poor. There are few power-assisted lower limb exoskeleton robots using this drive method[60].

The comparisons of the four driving modes are shown in Table 3.

In summary, motor drive, hydraulic drive, and cylinder drive have adverse effects on noise, volume, and quality, while pneumatic muscles are difficult to control. Therefore, improving the existing driving method and adopting a combination of rigid and flexible driving measures to reduce the mass and volume of the driving system are important. Those are also the bottlenecks restricting the development of exoskeleton robots.

2.3 Perception Technology

As shown in Fig. 7, the perception system is equivalent to the human nerves. Through this technology, the exoskeleton robot of the lower limbs can be better aligned with the wearer's movement, and the accuracy of the control system can be improved[61].

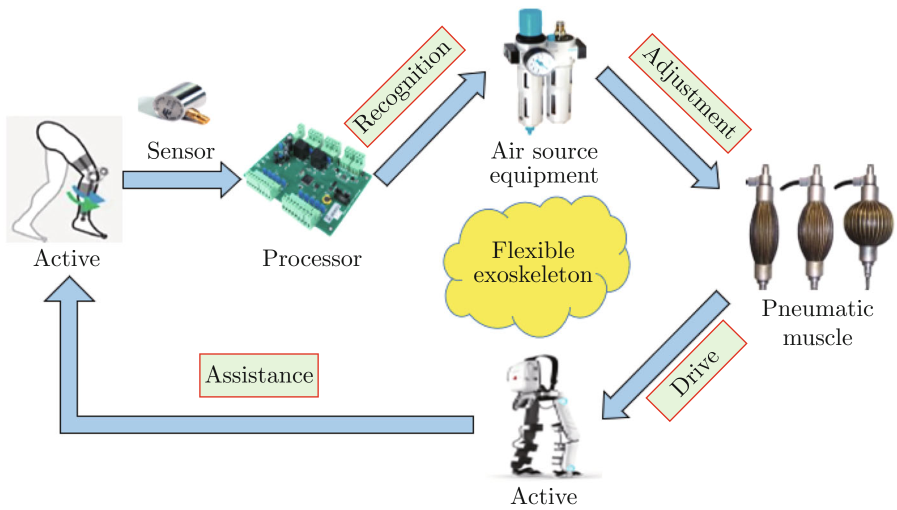

Fig. 6 Working principle of pneumatic muscle drive

Table 3 Comparisons of four driving modes

Driving mode	Advantage	Disadvantage	Typical product
Motor	Lower noise	Large inertia	HAL
	High precision	Poor balance	LEE
	Simple structure	Speed reducer	ReWalk
Hydraulic	High energy ratio	Inefficiency	BLEEX
	Overload protection	Pollution	HULC
	Variable speed	Low precision	XOS2
Cylinder	Low cost	Hard to control	PAGO
	safe	high noise	POGO
	Direct drive	Low precision	PAS
Pneumatic muscle	Comfortable wear	Nonlinearity	KNEXO
	Efficiency	Poor tensile strength	HLLE
	Light quality	Small trip	RUPERT

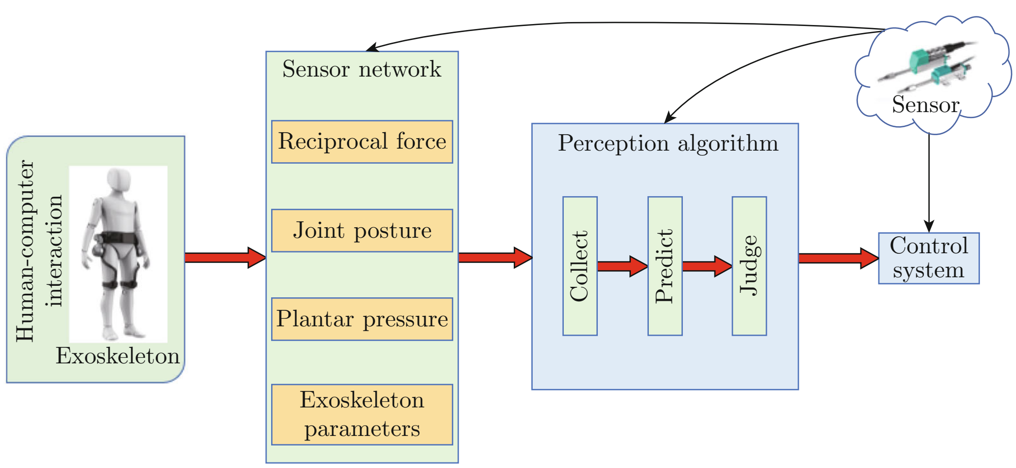

Fig. 7 Structure diagram of perception system

In order to control the lower limbs exoskeleton robot to provide intelligent and effective assistance to the human body, it is important to obtain different types of movement data of the wearer during exercise. The measured data can analyze the wearer's movement state and identify the wearer's movement intention[62]. At present, the human motion intention recognition of the power-assisted lower limb exoskeleton robot mainly relies on sensors.

Single sensor usually does not meet the system requirements. In order to obtain higher performance parameters, the exoskeleton robot system is usually equipped with different types of sensors to measure the data such as body posture, joint angle, human-machine interaction force, EMG signal, and electroencephalography (EEG) signal, and the multi-sensor data fusion algorithm is used to comprehensively process the collected data. According to the type of data measured, sensors can be divided into biosensors and physical sensors. The biosensor is mainly used to obtain the EMG and EEG signals of the human body, so as to identify the movement intention and realize human-machine interaction. The physical sensor is the premise of human-machine interaction. It can be used to obtain the kinematic and mechanical information of exoskeleton robots, so as to control the exoskeleton robots accurately. The simultaneous operation of the two sensors can not only greatly improve the comfort of the wearer, but also ensure the safety of the wearer. The layout description of some commonly used sensors in lower limb exoskeleton robots is shown in Table 4.

Table 4 Layout description of some commonly used sensors in lower limb exoskeleton robots

Sensor	Installation position	Measured signal	Effect
Encoder	Hip	Rotation angle	Control joint position
	Knee	Rotation angle	
	Thigh	Angular velocity	Recognize gait
Inertial sensor	Leg	Angular acceleration	
Pressure sensor	Shoe sole	Counteracting force	Collect interaction force
	Shoulder	Shoulder interaction force	
	Middle thigh	Leg interaction force	
	Backplane	Back interaction force	
EMG sensor	Skin	EMG signal	Identify intent

However, for the flexible exoskeleton robot, some new soft sensors are needed to correctly control and evaluate the soft coat, such as strain sensor made of silica gel, which can not only reduce the measurement error, but also further reduce the mass of the exoskeleton robot and realize lightweight. Recognizing the movement intention quickly and accurately is the prerequisite for realizing the coordinated control of the exoskeleton robot. At present, there are still many technical challenges in motion intention recognition, such as sensor technology and multi-sensor data fusion algorithm

2.4 Control Method

Control is the most core technology in the research of lower limb exoskeleton robots. Figure 8 is the structural block diagram of the exoskeleton robot control system. In the exoskeleton robot, the control system is equivalent to the human brain, and its primary purpose is to ensure the human-machine coordination. At present, the control methods for power-assisted lower limb exoskeleton robots mainly include ZMP control, sensitivity amplification control, human-machine interaction force feedback control[63], master-slave control, and EMG control.

2.4.1 *ZMP Control*

ZMP represents the point of zero moments, at which the horizontal component of the external force moment of the lower exoskeleton robot is zero[64]. When the projection of the ZMP on the ground is within the effective support range, the exoskeleton robot keeps walking stably. This method is used to ensure the stability of the exoskeleton robot at work. The working principle is to feedback the body's posture through sensors installed at the exoskeleton robot feet and joints, and then estimate the ZMP position of the power-assisted lower limb exoskeleton robot. If the projection of the ZMP of the power-assisted lower limb exoskeleton robot on the ground is not within the effective support range, the cast shadow of the exoskeleton robot needs to be controlled so that the ZMP projection falls within the effective support range again, and the coordinated movement between the robot and the human lower extremities can be achieved. This method is mainly used in the early study of lower limb exoskeleton robots[65].

2.4.2 *Sensitivity Amplification Control*

Sensitivity amplification control defines the transfer function between the force exerted by the wearer on the exoskeleton robot and the output of the exoskeleton robot as a sensitivity function, which is maximized by the controller so that the movement of the exoskeleton robot can be controlled with a small force. In this method, the wearer's motion intention is judged by the inverse kinematics calculation results of the power-assisted lower limb exoskeleton robot, and the control accuracy is determined by the accuracy of the

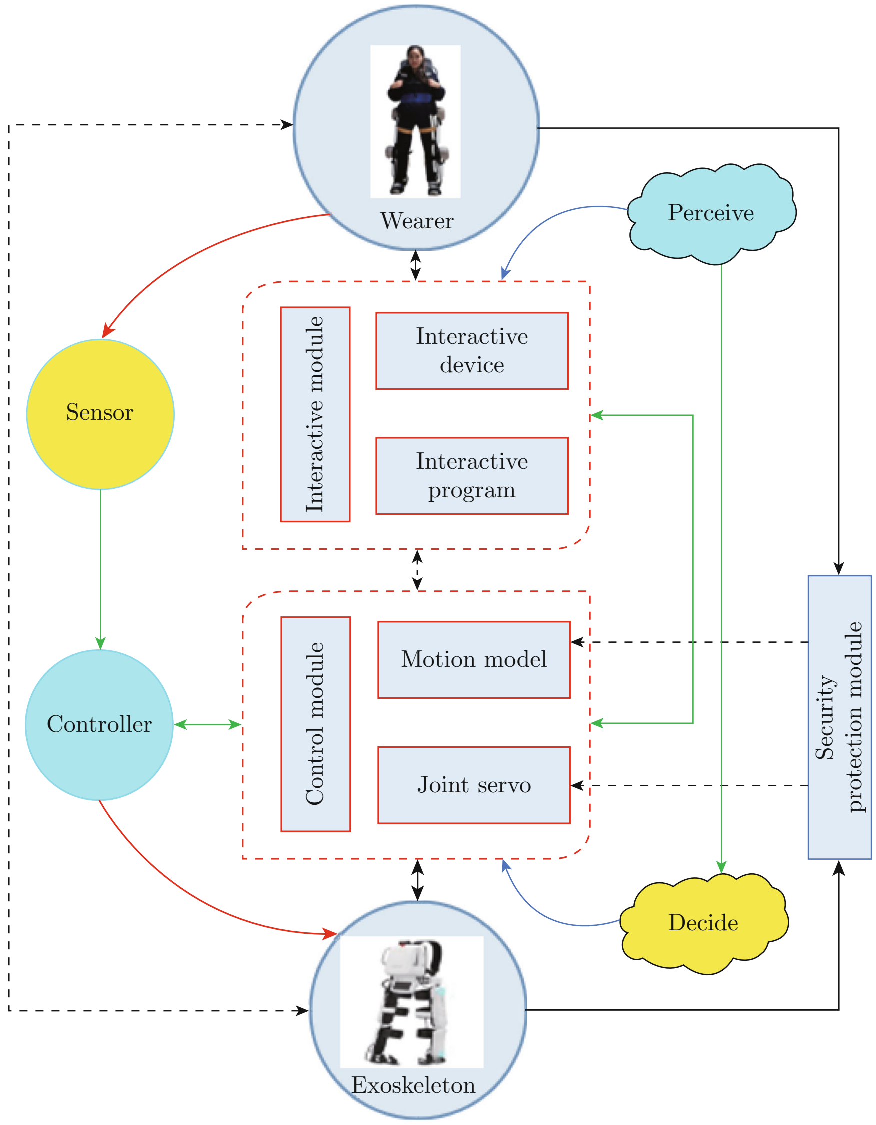

Fig. 8 Structural block diagram of exoskeleton robot control system

inverse kinematics model. The sensitivity amplification control is different from other control methods in that it does not require any sensors. At the same time, it can control the coordinated movement of the lower limb exoskeleton robot and the wearer. Sensitivity amplification control is mostly used for power-assisted lower limb exoskeleton robots with increased load[66].

2.4.3 *Human-Machine Interaction Force Feedback Control*

Human-machine interaction force feedback control requires a force sensor to be installed between the human and the exoskeleton robot to measure the force signal between the exoskeleton robot and the contact point of the wearer, and then the force information is sent to the CPU for processing, so as to judge the movement intention of the wearer and control the power output of the exoskeleton robot. The key to human-machine interaction force feedback control is to minimize the interaction force between the human and the exoskeleton so that the wearer can hardly feel the existence of the exoskeleton robot[67]. The human-machine interaction force is analogous to the force between the exoskeleton robot and the environment, which increases the comfort of the wearer and realizes the human-machine coupling. Using this control method, the human-machine interaction interface is designed based on the interaction force between the wearer and the exoskeleton robot. Human-machine interaction force feedback control is one of the most widely used control methods in the design of power-assisted lower limb exoskeleton robots.

2.4.4 *Master-Slave Control*

Master-slave control is generally used in remote robotic operating system, and the purpose is to make remote machine imitate the operator's actions. In order to continuously capture the movement of the human body, the operator must wear a main exoskeleton robot device. The goal of this method is to control the joint angle of the machine to track the corresponding joint angle of the human body through feedback. This control method not only controls the position and direction of the terminal, but also controls the posture of the entire device[68]. This requires that enough space should be reserved between the wearer and the exoskeleton during exoskeleton design, which makes the design of the exoskeleton very complicated and inconsistent with the design principles of lightweight and coordinated control of the power-assisted lower limb exoskeleton robot.

2.4.5 *EMG Control*

The principle of EMG control is to obtain the wearer's EMG signal through the EMG sensor installed on the wearer's surface skin. After processing, different algorithms are used to judge the human's movement intention, and then control the movement of the exoskeleton robot, so as to make the lower limb exoskeleton robot and the wearer's behavior in harmony. Since the EMG signal changes before muscle contraction, flexion and extension, this method has no hysteresis, and it can control the exoskeleton robot of the lower limbs in real time to provide the assistance to the wearer. However, because this control method requires installing sensors on the wearer's surface skin, the control method is less comfortable and has poor practicability[69], so it is rarely used at present.

The comparisons of five control methods are shown in Table 5.

Table 5 Comparisons of control methods

Control method	Advantage	Disadvantage	Typical product
ZMP	Convenient Reliable	Poor coordination	XOR
		Low precision	LEE
		Static walking	AABLE
Sensitivity amplification control	No sensor needed	Strong interference	BLEEX
	Small driving force	Low precision	XOS
			EKXO
Human-machine interaction force feedback control	Coordinate	Hysteresis	EXOP
	High precision	Inconvenient	LOPES
	Flexible	Discomfort	KUKA
EMG control	No hysteresis	Sensitive	ROGO
	Follow-up	Complex	HAL
	Convenient	Discomfort	REX
Master-slave control	High precision	Large mass	Hardiman

The above control methods for the exoskeleton robot can accurately and timely control the exoskeleton robot movement, but most of these control methods are to control the wearer to do some simple and slow movements. Once the wearer makes high-speed and complex movements, the accuracy of these control methods will be reduced, and even the exoskeleton robot cannot achieve the prospective action. Therefore, it is an urgent problem to put forward a better control method.

2.5 Energy Management

Insufficient continuous working time is a common problem in power-assisted lower limb exoskeleton robots, so energy management has become a key difficulty in the development of exoskeleton robots. At present, most of the lower limb exoskeleton robots are powered by battery and engine. The battery is safe and reliable as a power source, easy to replace, and has low noise. However, the power density and energy density of the battery are relatively low, and it cannot continue to supply power to the exoskeleton robot. There are also problems such as long charging time and inconvenience[70]. As a power source, the engine has large output power, and the power supply lasts for a long time, but it is noisy and polluting during operation. Compared with the battery, the engine is more difficult to control and the quality is larger. In summary, both power sources have major shortcomings, which greatly limit the development of power-assisted lower limb exoskeleton robots.

Since the power source of the exoskeleton robot must be movable, this requires that the selected energy source must have sufficient power and be safe, but most of the existing power sources are relatively heavy and have a very limited continuous energy supply time. At present, researchers have begun to explore a series of new energy technologies such as solar energy, bioenergy, and fuel cells, hoping to effectively solve this key difficulty in the future.

2.6 Human-Machine Coupling

The human-machine coupling comes from the communication behavior between people. While the exoskeleton robot satisfies the human, the human must also adapt to the action of the exoskeleton robot[71]. Human-machine coupling is the most significant feature of exoskeleton robots that is different from traditional robots. The human-machine coupling mechanism realizes the connection between the wearer and the exoskeleton robots so that the two unite to form a human-machine coupling system. In the design of the power-assisted lower limb exoskeleton robot, in order to achieve human-machine coupling, it is necessary to consider the design principles of safety, comfort, flexibility, lightweight, anthropomorphism, etc.

Since the lower limbs of the human body are in direct contact with the exoskeleton robot, it is important to ensure the safety of the wearer. Generally, limited devices are designed at the joints of the power-assisted lower limb exoskeleton robot or programmed to limit the rotation angle to prevent injury to the joints. On the other hand, it is also necessary to consider that the exoskeleton robot may collide and fall during working. Therefore, a set of scientific evaluation methods must be established, which also improves the comfort and flexibility of the wearer. For lightweight, because the design of the exoskeleton robot mostly uses metal materials, aluminum alloy has become the first choice. This material not only has low density, but also has the advantages of good plasticity and corrosion resistance. Moreover, it is easy to process, environmentally friendly and it does not harm the wearer's skin. In the future, new polymer materials will become the first choice for exoskeleton robot design[72]; the ultimate goal of anthropomorphic design is to make the designed structure adapt to the structure and contour size of human body. It is closely related to the calculation accuracy of its inverse kinematics.

In addition, because there are differences between individuals, this requires that the power-assisted lower limb exoskeleton robot must have a strong learning ability to meet the requirements of different wearers. Therefore, the application of machine learning to exoskeleton robots is also a key issue.

3 Conclusion

It can be seen that the United States, Japan, and other countries started earlier on the exoskeleton robot researching, and they have developed some representative prototypes. In contrast, it started relatively late in China, and most of the research on power-assisted lower limb exoskeleton robots is still in the experimental stage.

Structure design and human-machine coupling are inseparable from inverse kinematics. Various inverse kinematics algorithms should be optimized to improve the calculation accuracy and ensure that the lower limb exoskeleton robot provides power without hindering the wearer's activities. In the future, titanium alloy materials, high-strength fiber materials, and new polymer materials should also be used to design the power-assisted lower limb exoskeleton robots to solve the problem of lightweight design. At the same time, the emerging flexible lower limb exoskeleton robot will further improve the degree of human-machine coupling.

The choice of driving mode is very important for the research of exoskeleton robots. Each of the four driving modes has its own advantages and disadvantages. For the power-assisted lower limb exoskeleton robot, motor driving is the most used, which not only has low noise and no pollution, but also meets the requirements of lightweight design. The high-torque-density micro direct-drive motor with lightweight, large torque, and no need to cooperate with reducer is the development direction of the driving method in the future.

In terms of perception technology, physical sensors mostly use angle sensors and force sensors, and biosensors mostly use EMG sensors. Highly integrated microsensors will become the development direction of exoskeleton robot sensing technology, which can not only reduce the number of sensors and simplify the exoskeleton robot system, but also improve accuracy and environmental adaptability.

In the choice of control method, the early master-slave control and ZMP control have gradually transitioned to sensitivity amplification control, but this method will amplify interference. There are also a few exoskeleton robots that choose human-machine interaction force feedback control and electromyography control, but there is a certain hysteresis and poor universality. Therefore, hybrid control should be the focus of future research on power-assisted lower limb exoskeleton robots, which combines the advantages of multiple control methods, while avoiding the shortcomings of various control methods.

Energy management has always been a difficulty in the key technology of exoskeleton robots. The battery has low energy power density and takes a long charging time, and the engine is noisy and polluting. At present, the new fuel cell being developed is expected to solve this series of problems.

References

[1] TAKAHASHI K Z, LEWEK M D, SAWICKI G S. A neuromechanics-based powered ankle exoskeleton to assist walking post-stroke: A feasibility study [J]. *Journal of Neuroengineering and Rehabilitation*, 2015, **12**: 23.

[2] LI Y, HASHIMOTO M. PVC gel soft actuator-based wearable assist wear for hip joint support during

walking [J]. *Smart Materials and Structures*, 2017, **26**(12): 125003.

[3] JACKSON R W, COLLINS S H. Heuristic-based ankle exoskeleton control for co-adaptive assistance of human locomotion [J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2019, **27**(10): 2059-2069.

[4] LEE Y, KIM Y J, LEE J, et al. Biomechanical design of a novel flexible exoskeleton for lower extremities [J]. *IEEE/ASME Transactions on Mechatronics*, 2017, **22**(5): 2058-2069.

[5] BURTON A. Expecting exoskeletons for more than spinal cord injury [J]. *The Lancet Neurology*, 2018, **17**(4): 302-303.

[6] PUENTES S, KADONE H, KUBOTA S, et al. Reshaping of gait coordination by robotic intervention in myelopathy patients after surgery [J]. *Frontiers in Neuroscience*, 2018, **12**: 99.

[7] RAO L J, XIE L, ZHU X B. Research and design on lower exoskeleton rehabilitation robot [J]. *Machine Design & Research*, 2012, **28**(3): 24-26 (in Chinese).

[8] QUINTERO H A, FARRIS R J, GOLDFARB M. A method for the autonomous control of lower limb exoskeletons for persons with paraplegia [J]. *Journal of Medical Devices*, 2012, **6**(4): 0410031-0410036.

[9] PRASSLER E, BARONCELLI A. Team ReWalk ranked first in the cybathlon 2016 exoskeleton final [industrial activities] [J]. *IEEE Robotics & Automation Magazine*, 2017, **24**(4): 8-10.

[10] HARTIGAN C, KANDILAKIS C, DALLEY S, et al. Mobility outcomes following five training Sessions with a powered exoskeleton [J]. *Topics in Spinal Cord Injury Rehabilitation*, 2015, **21**(2): 93-99.

[11] HA K H, MURRAY S A, GOLDFARB M. An approach for the cooperative control of FES with a powered exoskeleton during level walking for persons with paraplegia [J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2016, **24**(4): 455-466.

[12] MILIA P, DE SALVO F, CASERIO M, et al. Neurorehabilitation in paraplegic patients with an active powered exoskeleton (Ekso) [J]. *Digital Medicine*, 2016, **2**(4): 163.

[13] FARRIS D J, ROBERTSON B D, SAWICKI G S. Elastic ankle exoskeletons reduce soleus muscle force but not work in human hopping [J]. *Journal of Applied Physiology*, 2013, **115**(5): 579-585.

[14] HYUN D J, LIM H, PARK S, et al. Development of ankle-less active lower-limb exoskeleton controlled using finite leg function state machine [J]. *International Journal of Precision Engineering and Manufacturing*, 2017, **18**(6): 803-811.

[15] LI Z J, YUAN Y X, LUO L, et al. Hybrid brain/muscle signals powered wearable walking exoskeleton enhancing motor ability in climbing stairs activity [J]. *IEEE Transactions on Medical Robotics and Bionics*, 2019, **1**(4): 218-227.

[16] XIAO Y F, JI X J, WU H, et al. Bionic knee joint structure and motion analysis of a lower extremity exoskeleton [C]//*2020 4th International Conference on Robotics and Automation Sciences*. Wuhan, China: IEEE, 2020: 91-95.

[17] MARTINEZ A, LAWSON B, GOLDFARB M. A velocity-based flow field control approach for reshaping movement of stroke-impaired individuals with a lower-limb exoskeleton [C]//*2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. Honolulu, HI, USA: IEEE, 2018: 2797-2800.

[18] BOGUE R. Exoskeletons and robotic prosthetics: A review of recent developments [J]. *Industrial Robot*, 2009, **36**(5): 421-427.

[19] MARCHESCHI S, SALSEDO F, FONTANA M, et al. Body Extender: Whole body exoskeleton for human power augmentation [C]//*2011 IEEE International Conference on Robotics and Automation*. Shanghai, China: IEEE, 2011: 611-616.

[20] GU C H, GAO M H, QIAN W X, et al. Gait recognition and robust autonomous location method of exoskeleton robot based on machine learning [C]//*2019 4th International Conference on Control and Robotics Engineering*. Nanjing, China: IEEE, 2019: 110-114.

[21] ZHANG T, HUANG H. Design and control of a series elastic actuator with clutch for hip exoskeleton for precise assistive magnitude and timing control and improved mechanical safety [J]. *IEEE/ASME Transactions on Mechatronics*, 2019, **24**(5): 2215-2226.

[22] SUZUKI K, MITO G, KAWAMOTO H, et al. Intention-based walking support for paraplegia patients with Robot Suit HAL [J]. *Advanced Robotics*, 2007, **21**(12): 1441-1469.

[23] HE Y, LI N, WANG C, et al. Development of a novel autonomous lower extremity exoskeleton robot for walking assistance [J]. *Frontiers of Information Technology & Electronic Engineering*, 2019, **20**(3): 318-329.

[24] LOUIE D R, ENG J J. Powered robotic exoskeletons in post-stroke rehabilitation of gait: A scoping review [J]. *Journal of Neuroengineering and Rehabilitation*, 2016, **13**(1): 53.

[25] TAMEZ-DUQUE J, COBIAN-UGALDE R, KILICARSLAN A, et al. Real-time strap pressure sensor system for powered exoskeletons [J]. *Sensors*, 2015, **15**(2): 4550-4563.

[26] ASBECK A T, SCHMIDT K, GALIANA I, et al. Multi-joint soft exosuit for gait assistance [C]//*2015 IEEE International Conference on Robotics and Automation*. Seattle, WA, USA: IEEE, 2015: 6197-6204.

[27] YU S N, LEE H D, LEE S H, et al. Design of an underactuated exoskeleton system for walking assist while load carrying [J]. *Advanced Robotics*, 2012, **26**(5/6): 561-580.

[28] KIM W, LEE H, KIM D, et al. Mechanical design of the Hanyang exoskeleton assistive robot (HEXAR) [C]//*2014 14th International Conference on Control, Automation and Systems*. Gyeonggi-do, Korea: IEEE, 2014: 479-484.

[29] ZHOU S Z, CHEN Z, SONG W, et al. Design and gait realization of power-assisted lower limbs exoskeleton

[C]//*2019 IEEE International Conference on Cybernetics and Intelligent Systems and IEEE Conference on Robotics, Automation and Mechatronics*. Bangkok, Thailand: IEEE, 2019: 101-106.

[30] WANG L T, WANG S Q, VAN ASSELDONK E H F, et al. Actively controlled lateral gait assistance in a lower limb exoskeleton [C]//*2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. Tokyo, Japan: IEEE, 2013: 965-970.

[31] ZHOU M G, WANG H D, ZENG X Y, et al. A systematic analysis for the Global Burden of Disease Study 2017 [J]. *Lancet*, 2019, **394**(10204): 1145-1158.

[32] CAO H, LING Z Y, ZHU J, et al. Design frame of a leg exoskeleton for load-carrying augmentation [C]//*2009 IEEE International Conference on Robotics and Biomimetics*. Guilin, China: IEEE, 2009: 426-431.

[33] SCHIELE A. Ergonomics of exoskeletons: Objective performance metrics [C]//*World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. Salt Lake City, UT, USA: IEEE, 2009: 103-108.

[34] DING Y, GALIANA I, ASBECK A T, et al. Biomechanical and physiological evaluation of multi-joint assistance with soft exosuits [J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2017, **25**(2): 119-130.

[35] YANG Z Y, GUI L H, ZHANG J, et al. Research status and development trend of energy-assisted exoskeleton suit [J]. *Journal of Shandong University of Science and Technology* (*Natural Science*), 2012, **31**(5): 41-49 (in Chinese).

[36] KOOPMAN B, VAN ASSELDONK E H F, VAN DER KOOIJ H. Speed-dependent reference joint trajectory generation for robotic gait support [J]. *Journal of Biomechanics*, 2014, **47**(6): 1447-1458.

[37] KIM M, LIU C, KIM J, et al. Bayesian optimization of soft exosuits using a metabolic estimator stopping process [C]//*2019 International Conference on Robotics and Automatio*. Montreal, QC, Canada: IEEE, 2019: 9173-9179.

[38] COLLINS S H, WIGGIN M B, SAWICKI G S. Reducing the energy cost of human walking using an unpowered exoskeleton [J]. *Nature*, 2015, **522**(7555): 212-215.

[39] WITTE K A, FATSCHEL A M, COLLINS S H. Design of a lightweight, tethered, torque-controlled knee exoskeleton [J]. *IEEE International Conference on Rehabilitation Robotics*. London, UK: IEEE, 2017: 1646-1653.

[40] WANG S Q, WANG L T, MEIJNEKE C, et al. Design and control of the MINDWALKER exoskeleton [J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2015, **23**(2): 277-286.

[41] JAFARI A, TSAGARAKIS N G, VANDERBORGHT B, et al. A novel actuator with adjustable stiffness (AwAS) [C]//*2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. Taipei, China: IEEE, 2010: 4201-4206.

[42] MASUD N, SMITH C, ISAKSSON M. Disturbance observer based dynamic load torque compensator for assistive exoskeletons [J]. *Mechatronics*, 2018, **54**: 78-93.

[43] MORENO J C, BRUNETTI F, NAVARRO E, et al. Analysis of the human interaction with a wearable lower-limb exoskeleton [J]. *Applied Bionics and Biomechanics*, 2009, **6**(2): 245-256.

[44] FARRIS R J, QUINTERO H A, GOLDFARB M. Preliminary evaluation of a powered lower limb orthosis to aid walking in paraplegic individuals [J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2011, **19**(6): 652-659.

[45] JIN X, PRADO A, AGRAWAL S K. Retraining of human gait: Are lightweight cable-driven leg exoskeleton designs effective? [J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2018, **26**(4): 847-855.

[46] ZHAO Y J, XU C, ZHANG J Z. Key technological analysis and study on exoskeleton of human-body lower limbs [J]. *Journal of Machine Design*, 2008, **25**(10): 1-5 (in Chinese).

[47] HAN J W. Development and application of electro-hydraulic servo-system [J]. *Machine Tool & Hydraulics*, 2012, **40**(2): 7-10.

[48] LI N, N L, AN H, al. Review on lower extremity exoskeleton robot [J]. *The Open Automation and Control Systems Journal*, 2015, **7**(2): 441-453.

[49] HONG Y P, KOO D, PARK J I, et al. The SoftGait: A simple and powerful weight-support device for walking and squatting [C]//*2015 IEEE/RSJ International Conference on Intelligent Robots and Systems*. Hamburg, Germany: IEEE, 2015: 6336-6341.

[50] GASPARRI G M, BAIR M O, LIBBY R P, et al. Verification of a robotic ankle exoskeleton control scheme for gait assistance in individuals with cerebral palsy [C]//*2018 IEEE/RSJ International Conference on Intelligent Robots and Systems*. Madrid, Spain: IEEE, 2018: 4673-4678.

[51] MIYAZAKI T, TAGAMI T, MORISAKI D, et al. A motion control of soft gait assistive suit by gait phase detection using pressure information [J]. *Applied Sciences*, 2019, **9**(14): 2869.

[52] THAKUR C, OGAWA K, TSUJI T, et al. Soft wearable augmented walking suit with pneumatic gel muscles and stance phase detection system to assist gait [J]. *IEEE Robotics and Automation Letters*, 2018, **3**(4): 4257-4264.

[53] THATTE N, SHAH T, GEYER H. Robust and adaptive lower limb prosthesis stance control via extended Kalman filter-based gait phase estimation [J]. *IEEE Robotics and Automation Letters*, 2019, **4**(4): 3129-3136.

[54] OUYANG X P, FAN B Q, DING S. Status and prospects of the lower extremity exoskeleton robots for human power augmentation [J]. *Science & Technology Review*, 2015, **33**(23): 92-99.

[55] GASPARRI G M, LUQUE J, LERNER Z F. Proportional joint-moment control for instantaneously

adaptive ankle exoskeleton assistance [J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2019, **27**(4): 751-759.

[56] SCHMIDT K, RIENER R. MAXX: Mobility assisting textile exoskeleton that exploits neural control synergies [M]//Converging clinical and engineering research on neurorehabilitation II. Cham: Springer, 2016: 539-543.

[57] MATSUURA D, FUNATO R, OGATA M, et al. Efficiency improvement of walking assist machine using crutches based on gait-feasible region analysis [J]. *Mechanism and Machine Theory*, 2015, **84**: 126-133.

[58] GALLE S, DERAVE W, BOSSUYT F, et al. Exoskeleton plantarflexion assistance for elderly [J]. *Gait & Posture*, 2017, **52**: 183-188.

[59] AZEVEDO COSTE C, SIJOBERT B, FROGER J. FES-drop-foot correction: From pre-programmed patterns to online modulation [M]//Converging clinical and engineering research on neurorehabilitation II. Cham: Springer, 2016: 971-974.

[60] LEE H, LEE B, KIM W, et al. Human-robot cooperative control based on pHRI (Physical Human-Robot Interaction) of exoskeleton robot for a human upper extremity [J]. *International Journal of Precision Engineering and Manufacturing*, 2012, **13**(6): 985-992.

[61] SCZESNY-KAISER M, HÖFFKEN O, AACH M, et al. HAL® exoskeleton training improves walking parameters and normalizes cortical excitability in primary somatosensory cortex in spinal cord injury patients [J]. *Journal of Neuroengineering and Rehabilitation*, 2015, **12**: 68.

[62] LI M, MENG W, HU J W, et al. Adaptive sliding mode control of functional electrical stimulation (FES) for tracking knee joint movement [C]//*2017 10th International Symposium on Computational Intelligence and Design*. Hangzhou, China: IEEE, 2017: 346-349.

[63] JIA S, HAN Y L, LU X L, et al. Design of lower extremity exoskeleton based on analysis on special human gaits [J]. *Robot*, 2014, **36**(4): 392-401 (in Chinese).

[64] CHEN G, CHAN C K, GUO Z, et al. A review of lower extremity assistive robotic exoskeletons in rehabilitation therapy [J]. *Critical Reviews in Biomedical Engineering*, 2013, **41**(4/5): 343-363.

[65] LI J, ZHU L Y, GOU X F. Research on lower limbs exoskeleton rehabilitation robot and its key technologies [J]. *Chinese Medical Equipment Journal*, 2018, **9**(8): 95-100.

[66] SPAICH E G, BØG M F, ERKOCEVIC E, et al. Gait orthosis lokomat combined with functional electrical stimulation for foot drop correction: A feasibility study [C]//*Replace, Repair, Restore, Relieve: Bridging Clinical and Engineering Solutions in Neurorehabilitation*. Cham: Springer, 2014: 751-757.

[67] KWON S H, LEE B S, LEE H J, et al. Energy efficiency and patient satisfaction of gait with knee-ankle-foot orthosis and robot (ReWalk)-assisted gait in patients with spinal cord injury [J]. *Annals of Rehabilitation Medicine*, 2020, **44**(2): 131-141.

[68] SCZESNY-KAISER M, TROST R, AACH M, et al. A randomized and controlled crossover study investigating the improvement of walking and posture functions in chronic stroke patients using HAL exoskeleton: The HALESTRO study (HAL-exoskeleton STROke study) [J]. *Frontiers in Neuroscience*, 2019, **13**: 259.

[69] SCZESNY-KAISER M, KOWALEWSKI R, SCHILDHAUER T A, et al. Treadmill training with HAL exoskeleton — A novel approach for symptomatic therapy in patients with limb-girdle muscular dystrophy — Preliminary study [J]. *Frontiers in Neuroscience*, 2017, **11**: 449.

[70] DUAN Q C, HE D F, LIU B, et al. Establishment and analysis of lower extremity exoskeleton robot ergonomics restrictions model [J]. *Machine Design and Manufacturing Engineering*, 2015, **44**(1): 50-53 (in Chinese).

[71] SIVIY C, BAE J, BAKER L, et al. Offline assistance optimization of a soft exosuit for augmenting ankle power of stroke survivors during walking [J]. *IEEE Robotics and Automation Letters*, 2020, **5**(2): 828-835.

[72] CHEN C J, ZHANG Y, LI Y J, et al. Iterative learning control for a soft exoskeleton with hip and knee joint assistance [J]. *Sensors*, 2020, **20**(15): 4333.