Review on Lower Extremity Exoskeleton Robot

Na Li, Lei Yan, Hua Qian[*], Hongfang Wu, Jian Wu and Sen Men

School of Technology, Beijing Forestry University, Box 8, Beijing 100083, China

Abstract. The lower extremity exoskeleton robots (LEERs) emerged in 1960s, which can enhance the human walking function, they have been increasingly applied in many fields. This paper will introduce the application of LEERs, the structure of the mechanism, the actuators of the robots, and composition of the control system designed by various universities and research institutes in the last 5 years. Research focuses on the robots are summarized as well to show the main difficulties during the development of the LEERs. This review will provide an essential foundation for the development of the LEERs and offer a meaningful reference for the study of anthropomorphic robots.

Keywords: Exoskeleton, lower extremity, wearable robot, trajectory control, human-robot interaction

1. INTRODUCTION

The lower extremity exoskeleton robot(LEERs) have raised the study upsurge time and again, from Berkeley Lower Extremity Exoskeleton(BLEEX) exoskeleton robot appeared in 2004 to the Brazilian paralyzed teenager wearing an exoskeleton robot kicked off at the 2014 FIFA World Cup. The LEERs are electromechanical devices integrating the behaviors of both human and robot. The robots can be worn on the outside of the body and combine human intelligence and physical robotics together. They can ensure protection, physical support and other functions, hence enhancing the athletic ability. As the bionic robots, the LEERs bring a new world and have been applied in many fields, especially the population aging gets more and more acute in the world. According to statistics, the total number of old people aged over 60 has reached 600million and there are more than 60 countries where the aging population has reached or exceeded 10% of the total population. Aging brings a certain pressure and burden to the family and society because the aging generally suffers such troubles as physical limits, action inconvenience, lack of strength and endurance and so on. To some extent, the LEERs would alleviate the problem of aging, such as the Hybrid Assistive Limb (HAL) developed by the University of Tsukuba, Japan, they can help human to complete the daily life [1-3].

In the medical field, exoskeleton robot together with rehabilitation training can assist patients with spinal cord injury, stroke and lower limb paralysis to perform gait training and so to restore health as soon as possible [4], regaining their confidence in life. These robots include the lower limb rehabilitation exoskeleton Locomat developed by Hocoma AG in Switzerland and the Haptic walker robot developed by Germany neurological rehabilitation center. They have changed the traditional stroke or paraplegic rehabilitation mode, reduced the intensity of the nursing work of medical personnel, and ensured the quality and effectiveness of rehabilitation training [5].

In the military, the combat ability of soldiers is greatly reduced due to carrying heavy weapon equipment, so exoskeleton robots can also help relieve the heavy burden of military equipment. The element of exoskeleton robots is one of the symbols of modern war. The BLEEX Military exoskeleton robot is composed of two bionic metal legs, a power supply unit and a backpack for carrying weight. The wearer actually bears 2.25kg when he is wearing an exoskeleton robot weighing 45kg and carrying a burden weighing 31.5kg [6-10].

In industry, the exoskeleton robots can assist workers to handle cargo to reduce their burden, especially in the situations where traditional wheel tools cannot be used, such as going up and down the stairs and climbing rugged mountain roads. The robots make workers free from heavy labor. The shipyard in South Korea's Daewoo Shipbuilding and Marine Group used a mechanical exoskeleton robot. The equipment weighing 28kg is made of carbon fiber, aluminum and steel. It can follow the movement of the wearer, supporting the weight of the goods and the wearer itself. The battery of this equipment can endure 3 hours. The LEERs are shown in Fig. (**1**).

2. THE MECHANICAL STRUCTURE OF THE LEERS

The mechanical structure design should be accorded with the characteristics of the human body, with the features of light weight, sturdy power and high bionic performance. When the exoskeleton robots are developed for the elders, the structure is supposed to be light and handy to make human feel free and the joints' moving angle of robots should be identical to the motion of human joints as much as possible, the safety of the user should be particularly guaranteed [11].

*Address correspondence to this author at the School of Technology, Beijing Forestry University, Box 8, Beijing 100083, China;
Tel: +8615201309527; E-mail: qianhua@bjfu.edu.cn

Fig. (1). BLEEX robot, HAL robot, Locomat (by Hocoma AG), Haptic walker robot, mechanical exoskeleton(by shipyard in South Korea's Daewoo Shipbuilding and Marine Group).

2.1. The Requirements of Mechanical Structure

A variety of human limb movements are the synthetic result of the four parts' relative motion including the pelvis, thigh, leg and foot [12], linked with the hip, knee and ankle. The adaptability between LEER and wearers with different height and weight should be taken into consideration when it is designed, therefore the length of the thigh, shank and waist should be adjustable [13, 14]. Referring to human physiological data, the length change of thigh and shank is about 6cm for average people with a stature from 160cm to 180cm [15]. The shank length is about 0.246 times the stature, and thigh length is about 0.245 times the stature [16, 17].

In addition, the exoskeleton robot must be also satisfactory to the habitual freedom of motion of each joint [18, 19, 20]. Hip can move around three axes of motion: i.e. flexion/extension, adduction/abduction and internal / external rotation. The knee has only one DOF of flexion/extension, equivalent to a hinge joint. And there are three main DOFs for ankle: pronation/external rotation, dorsiflexion/toe flexion and varus/valgus [4]. Human walking activities are mainly generated by the motion of lower limbs in the sagittal plane, while the other DOFs of the lower limb joints and movements in other body parts help the body maintain balance. Then it is basic to provide two active moments in the sagittal plan. There is a big difference in the moments supply between users with consciousness and users without consciousness. For the latter situation, through the simulation in ADMAS, the moment on the hip to flexion and extension is about 100Nm and the moment on the knee is about 50Nm in the normal walking [21], as shown in Table **1**.

2.2. The Types of Actuators

An important factor confining the commercial development of LEERs is to select a kind of proper actuator that is not only compact and lightweight, but also powerful enough to drive the body's movement. For walking, the flexion/extension movement of hip and knee requires a two-way driving device. The average power of the hip joint is positive

Table 1. The lower limb of exoskeleton's Degree of freedom (DOF) design.

	Joints	DOF	The Scope of Freedoms	Driving Force Needed
The DOFs of joints	hip	Flexion/extension	(-120°)~(65°)	80N/m~100N/m
		Adduction/abduction	(-30°~-35°)~(40°)	Spring or other impedance
		Internal/external rotation	(-15°~-30°)~(60°)	Spring or other impedance
	knee	Flexion/extension	(-120°~-160°)~(0°)	45N/m~70N/m
	ankle	Pronation/external rotation	(-15°)~(30°~50°)	Spring or other impedance
		Dorsiflexion/toe flexion	(-20°)~(40°~50°)	Spring or other impedance
		Varus/valgus	(-30°~-35°)~(15°~20°)	Spring or other impedance

[6, 22, 23], the hip needs to be taken the initiative drive; on the contrary, the average power of knee joint is negative, so many orthoses use dampers to reduce the power of knee joint. When climbing stairs, squatting or jumping, knee joint demands a positive power. Therefore, the knee joint also needs an acting driving. Other degrees of freedom need less driving force, so springs or other impedances are typically used to control.

The driving torque of hip and knee is about 75N/m. Because the total weight of exoskeleton robot itself and burden to support is different, resulting in a fluctuation in the driving force. Among all the joints, ankle joint needs relatively less driving force [24].

In addition, the actuator of exoskeleton robot should have a large output power-to-weight ratio and such characteristics as low inertia, fast response, high precision, as well as safety performance etc. According to the kinds of driving mechanism, the design of actuators can be divided into three categories: hydraulic driving, electric driving and pneumatic driving [25].

2.2.1. Hydraulic Driving Actuators

Hydraulic driving actuators transmit pressure via oil or water with the advantages of simple structure, convenient use, stable operation and high power output, however, the hydraulic oil is easy to leak and cause environmental pollution.

Using hydraulic driving actuators, the typical lower extremity exoskeleton robot is BLEEX robot, developed by University of California, Berkeley in America in 2004. BLEEX robot was originally a robot of military application to help soldiers carry heavy equipment [26, 27], and later evolved into the elderly rehabilitation robot. BLEEX robot is composed of two metal bionic legs including 14 DOFs. There are 3 DOFs at the hip joint and two of them are equipped with actuators. There is just an active DOF at the knee and 3 DOFs at the ankle, only one installed with actuator. A two-way linear piston-type hydraulic cylinder with a diameter of 19.05mm is used in the BLEEX robot. The

actuator can obtain a relatively high control bandwidth through the compressed fluid. Its weight is light, but it can output larger power. The actuator can continuously provide 6.9MPa for the hydraulic servo valve. In the servo valve, there is some energy loss due to the pressure drop. This hydraulic actuator can provide a power of 1.3kW to perform the flexion/extension movement of hip, knee and ankle.

2.2.2. Pneumatic Driving Actuators

Air is used as the pressure transmitting medium in pneumatic driving actuators. Compared with the hydraulic cylinder, pneumatic cylinder is lighter and cleaner, without pollution [28]. But this kind of cylinder has lower carrying capacity and response speed, so it is seldom used in the application of LEERs.

In the cylinder driving actuators, researchers pay more attention to pneumatic muscle [29], which is a flexible drive similar to human muscle. The maximum stroke of the pneumatic muscle is 25% of the nominal length and its driving force is 10 times larger than a usual pneumatic driving actuator. It can save 60% energy while producing the same force, and can be manufactured according to the specific size. The pneumatic muscle actuators (pMAs) are adopted on the exoskeleton robot developed by the University of Salford [30]. There are 5 DOFs on each leg, including 3 DOFs at the hip joint, another two at the knee and ankle respectively. Pneumatic muscle actuators have the characteristics of low inertia, superior executive ability and a high compression ratio, but they are more complicated to control. It can provide a torque about 60Nm for the exoskeleton robot.

2.2.3. Electric Driving Actuators

Electric driving actuators can be controlled smoothly with high precision and without the problem of leakage as hydraulic and pneumatic actuators have. But due to the small output torque of the motor, a reducer should be used, which introduces backlash and friction loss. This will make an impact on the performance of the control system. In the present studies, the electric actuator is the primary choice of executive mechanism of lower exoskeleton robot.
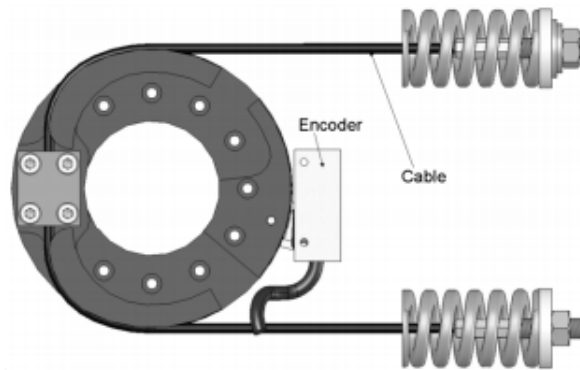
Fig. (2). Rotary series elastic actuator (RSEA).
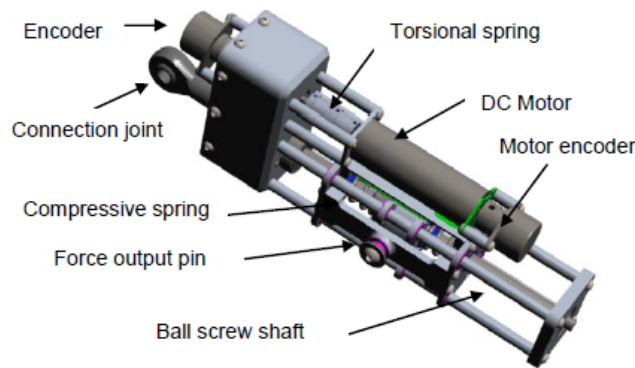
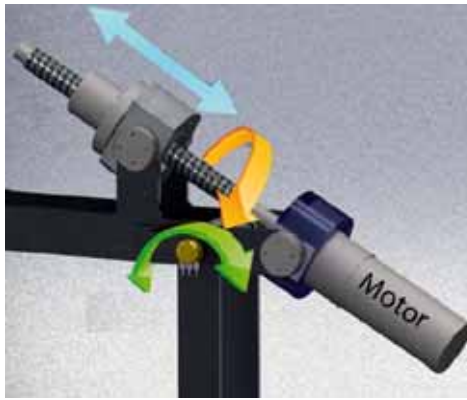**Fig. (3).** The actuator designed by National University of Singapore.

The reducer (demanding large reduction ratio, such as harmonic reducer) is applied to connect the rotary motor with the joint directly. The Hybrid Assistive Limb (HAL) developed by University of Tsukuba, Japan, used this structure. The same as the exoskeleton robot with 7 DOFs on each leg was designed by Yonsei University [31]. Only flexion/extension movement at hip and knee is the active driving. By means of harmonic reducer, 200W Brushless DC motors are selected and as a result of harmonic reducer, the actuators are supposed to provide a 79.3Nm moment for the hip joint and 42.2Nm moment for the knee joint.

A special actuator named Rotary series elastic actuator (RSEA) as shown in Fig. (2), was explored by Human cognition of Florida Institute (IHMC) to drive a power-assist lower extremity exoskeleton robot [32, 33]. There are 5 DOFs on each leg, including 3 active DOFs. The RSEA driving device is mainly composed of a brushless DC motor and a harmonic reducer. On account of the special mechanical structure, the rotary motion of the gear reducer can be transferred into linear motion, compressing the linear rectangular spring to output torque. RSEA can provide accurate force feedback with low impedance. Maximum torque reaches 80Nm and the maximum rotating speed is 6.8rad/s. But when the output torque is too high, the bandwidth is low. Two kinds of encoders are fitted on the actuator, which can

detect the output position and torque respectively in order to achieve the position control, force/torque control and hybrid control.

The second type of actuator converts the rotary motion of the motor into linear motion through some common motion conversion mechanism such as: gear and rack, belt transmission and ball screw. Because the ball screw has the advantages of stable running, high output accuracy and small gap, this switch has been extensively used. For example, the knee-ankle-foot robot designed by the National University of Singapore adopts this idea [34]. Maxon brushless DC motor is selected to be the principal component, and the ball screw outputs the force, as shown in Fig. (3). Due to the use of springs and rotational springs, the average force reaches 300N and the peak value is 700N. This addresses the issue that the peak force is 3 times the average force of the LEER needs.

There are 6 DOFs on the LEER designed by the Federal University of Rio Grande do Sul, Brazil [35], and only the hip and knee are active driving. A 24V/150W DC motor is put into use and through the planetary gear reducer, and the force is output by the screw nut, as shown in Fig. (4). The outer of the rotating joint is connected with the planetary gear reducer and the inner of the rotary joint is connected with the screw nut.

Fig. (4). The actuator designed by the Federal University of Rio Grande do Sul, Brazil.
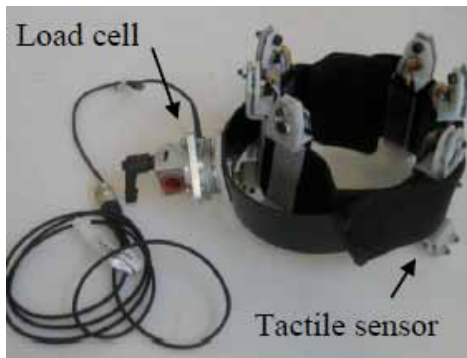
Fig. (5). A new type of pressure sensor.

In a word, the common form is the electric driving actuators while the hydraulic and pneumatic driving actuators are rare. The selection of the actuation is the main difficulty in the mechanical design. In the experimental stage, the majority of actuators may be failed to offer the enough moments in the normal actions.

3. THE CONTROL SYSTEM OF THE LEERS

In the lower extremity exoskeleton system, the design of the control system is crucial, which determines the control efficiency and whether the function of exoskeleton robot can be realized. Intelligent control system generally includes three levels: perception layer, decision layer and execution layer.

The perception layer refers to the detection of the external environment, the robot itself and the information of the user, such as the obstacle in the environment, the characteristics of human body, as well as the robot motion state and so on. This layer mainly relies on the multi-sensor information fusion technology. The decision layer is equivalent to the human brain. Based on information obtained from the sensing layer, the exoskeleton robot can judge what kind of control strategy should be used. The function of the execution layer is to drive the motor according to the judgment of the decision layer to make the lower extremity exoskeleton carry out its action.

3.1. Sensor Selection

In the process of selecting sensors, sensitivity, accuracy, stability and installation location should be confirmed carefully [36, 37].

3.1.1. Angle Sensor

In the LEERs, angle sensors mainly include encoders, angular acceleration sensors, IMU (inertial measurement units) sensors, gyroscope and inclinometer.

The encoder is normally installed at hip, knee and ankle to gauge joint moving angle in order to realize the feedback control of joint. Angular acceleration sensors are usually assembled on the thigh, shank and arm to obtain the angle, angular velocity and angular acceleration of the thigh, shank and arm. This can be used to distinguish the motion state of human body, and judge the people walking consciousness or perform Zero Moment Point (ZMP) position calculation. The IMU sensor consists of 3 sensors: three-axis gyro, three-axis accelerometer and three-axis magnetometer. The IMU sensor is mounted on the leg to sense the motion state of human body [38]. Gyroscope (or the inclinometer) is usually fixed on the back to measure the angle between the upper torso and vertical direction. Gyro and acceleration sensors are utilized to predict human walking gait in the experiment carried out by Japan Hokkaido University [39].

3.1.2. Pressure Sensor

The pressure sensors can detect human body's mass transfer process, and generally fixed on the sole, or on the bottom of crutches or legs of walkers. Sometimes, the pressure sensor can be replaced with a foot contact switch. The sensed pressure information can be used to determine the phase running state, and is also the important information for ZMP position calculation. The pressure sensor can also be settled on the drive, to conduct the feedback control over the exoskeleton robot force/torque.

The pressure sensors can also be placed on the straps, which are used to detect the interaction force between the user and the exoskeleton. A new type of sensor has been devised by University Twente [40], as shown in Fig. (**5**). The pressure hinders the photosensitive diode to receive the light from the LED, thus affecting the current output. Each sensor has 8 channels. Three sensors are mounted on the front and rear sides of the straps respectively.

3.1.3. Biological Signal Sensor

Biological signal contains a wealth of human motion information. In exoskeleton system, useful information is usually extracted from the biological signal to identify the effect of external stimulation on the human body. Human biological signals include EMG signal, EEG signal, ECG signal and EOG signal. The EMG signal is most employed in control system [41]. Although the EMG signal is very weak and with many noises, it can directly respond to the activity status in human muscle [42].

However, there are several difficulties to control the exoskeleton with the EMG signal: (1) it is difficult to produce the same EMG signal for one person doing the same action. (2) for a special action, the extent and pattern of muscle activity are different for different people. (3) a joint motion involves a lot of muscle and it is difficult to perform real-time motion prediction. (4) opposing muscle has a negative effect on the formation of joint driving force. (5) different joint positions will change the effects of every muscle on the same action.

In the LEERs, a single sensor is far from enough. It is generally a comprehensive application of several sensors to obtain human and robot information. So it is vital to select appropriate sensors to obtain information. In the BLEEX system, there is one encoder, two linear accelerometers, and one six-axis force sensor on each actuator. In addition, there are two foot switches, two pressure distribution sensors and one inclinometer in the system. The sensors are so much that the robot is sensitive to the external force and fail to distinguish whether the disturbance comes from the user. In the design of the knee-ankle-foot robot developed by the National University of Singapore, the IMU sensor, the joint angle sensor mounted on the human thigh and shank are united together to estimate the motion state of human and robot. The plantar pressure sensor is attached to sense the walking phase and the EMG signal is involved to monitor the muscle recovery process [34]. In the eLEGs system, the

information received from the angle sensor settled on the arm and the pressure sensor on the cane top is used to calculate the intention of walking [43-45].

3.2. Structure of Control System

In the LEERs, control system generally includes sensor data acquisition module, control module and motor drive module. In many exoskeleton systems, PC is utilized to receive and process sensor information and then send commands to the control motor.

CAN bus, abbreviation of the Control Area Network, is most commonly used in the control system of LEERs [46]. The control system of the robot developed by Yonsei University (Korea) is comprised of 5 blocks of DSP. There are 7 angle sensors, 4 force sensors and one ground contact sensor on each leg of the exoskeleton robot. Thus two pieces of DSPs are to collect sensor information on the left and right legs separately, and another two pieces of DSPs are to drive the motors on the left and right legs respectively. The last DSP as the main control board receives the information of the inclination or the sensor DSPs and sends commands to motor's DSPs at the same time through the CAN bus.

In the exoskeleton robot system developed by Zhejiang University, China, ARM9 is as the host computer and DSP is as the lower position machine [47]. SPI serial peripheral interface connection is adopted between the master and slaver controller and keeps the real time communication. CAN bus mode is applied between the slave and motor controllers. The slave is mainly responsible for gathering the location information and sensor information of every joint, as well as making these parameters feedback to the master controller. The main task of the master is managing the organization and task planning after receiving the information from the slave, then sending specific data format control instruction and control parameters to the slave. The SPI serial peripheral interface is a high-speed synchronous serial input/output port, used for the communication between the processor and controller or between controller and an external chip.

4. RECENT RESEARCH FOCUSES

In addition to an anthropomorphic mechanical structure and an effective control system, the design of LEER needs higher requirements, such as walking safety performance, natural movements, the adaptability of the human body and the capability to provide power in accordance with the requirements.

4.1. Stability Method

The most important is the safety performance when wearing the exoskeleton robot for the people whose limb strength is insufficient [48], especially when it is difficult to master the balance of the elderly and patients with paralysis.

In the biped walking robot, zero moment point (ZMP) theory which was put forward by Yugosivia scholars, is usually adopted to measure whether a system is stable or not. If

the robot' ZMP is always located in the support polygon range of the robot foot, the system can remain stability. Anti-falling control was tested to calculate the ZMP position according to the foot switch and joint encoder in the Saga University. If the ZMP position is not within a predetermined range, the hip joint moment of the supporting leg will be required to adjust to change the position relationship of the joint, in order to make the system stable.

Center of Pressure (CoP) theory is also used to conduct the anti-falling control, which is widely used in the medical field. The location of the CoP also represents the transfer of mass block, and coincides with the position of ZMP. The full body exoskeleton robot developed by Nara Institute of Science and Technology, Japan, has performed the simulation to verify that the CoP is not only helpful to walk booster but also able to prevent falling [49]. Both in the development of medical robots by Yonsei University and ATLAS robot in Madrid Robot Automation Center [50], CoP stability control are adopted.

4.2. Trajectory Generation

University of Sao Paulo has conducted the trajectory control on the RGO exoskeleton robot [51]. Walking trajectory is influenced by trace amplitude, step distance and the track time. Then the trajectory is obtained from three algorithms combining the parameter optimization method, such as inverse dynamics, direct dynamics and impedance control. In addition, integrated ZMP stability control with inverse dynamics, two neural networks are adopted to plan the trajectory of robot joints [52]. Artificial Neural Networks (ANNs) and developed forward neural networks (FFNs) have been successfully to predict and forecast ahead [53, 54].

For stroke patients, there is typically one leg injured. The trajectory control of swing phase for the injury leg is a difficulty. University of Tsukuba in Japan launched the study of trajectory control with a half-side HAL robot [55]. The wearer's right hand holds a crutch, with three force sensors mounted on its top. The right leg is healthy and the injured left leg is wearing a half-side HAL. The trajectory of the left leg is controlled by principal component analysis according to the vigorous leg motion information and crutch information. South Korea University also conducted a similar study, recording the information of healthy leg's swing phase to control the injured leg's trajectory with the nerve network method [56]. Through human movements seem symmetrical, the "imitator" control may make the human feel inflexible.

Researchers in University Twente adopted a terminal model predictive control (MPC) method, creating joints trajectories online according to the basic moving parameters of the gait such as step, swing span and walking speed. The experiments proved that people with different walking characteristics could achieve lower limb walking booster [57], when wearing an exoskeleton robot.

Japan Nagoya University assumed that swing phase step distance is equal to the walker moving distance. Robot named Wearable Power-Assist Locomotor was carried out the test to achieve the step distance control of the swing phase in the process by walking [58]. There are 6 active driving joints on WPAL robot, and each of them is equipped with one encoder. The encoder information is sent to the PID motor controller in the backpack and then the motor controller communicates information with a computer through the CAN bus. The pressure sensor is mounted on the robot foot, and sends the information to the computer through A/D conversion module. Besides the help of a walker to maintain balance, two three-axis angular acceleration sensors are installed on the walker and the information will be communicated to the computer via Bluetooth. So it can gauge the stride expectation in the process of walking through the analysis on the signal of the acceleration sensor and the polynomial approximation method, so as to realize the swing phase trajectory control. However, the assumption is too idealistic about the equation between walker and swing step distance that may bring the uncomfortableness to the user.

Trajectory of exoskeleton robot is also under the influence of environment. A laser range sensor was fitted on the robot knee joints to enhance the exoskeleton robot's perception ability to environment in Japan Saga University [59]. Laser ranging sensor could sense the distance and size of obstacles. When the obstacle is small, the exoskeleton robot can step over the obstacle, or one foot of the robot will fall on the obstacle and move on.

4.3. Movement Intention Recognition

Ground reaction force reflects the position of the gravity center of the human body and robot. Gravity is a kind of reliable identification information for walking consciousness. Because the body torso's inclination angle has a close relationship with the position of the gravity center, this angle can be used as the second kind of effective recognition information of consciousness. In view of the above two types of information, University of Tsukuba, Japan, has put forward two approaches to realize the awareness recognition of human walking with HAL-3 [60]. The first method is to measure the gravity distribution on the right and left foot by foot pressure sensors. If the pressure on the left foot is larger, this foot is the supporter, otherwise, the right foot is the supporter. But this method is not particularly reliable for feeble patients and the elderly. The second way is to check the angle of human torso deviation from the vertical line by the sensors placed on the human body. In the process of walking, the trunk deviation angle can reach 0.07rad and it is set a threshold of 0.05rad. The threshold can be searched using Gaussian mixture model [61]. When the left deviation angle is larger than 0.05rad, the left foot is the supporter, or the right foot is the supporter.

There are primarily two kinds of methods to achieve the recognition control of conscious movements based on EMG signal [62]. The first method is neural-fuzzy control which is the combination of fuzzy control and neural control. It is highly effective and can eliminate the control difficulties of the EMG signal. But as the increase of the exoskeleton's DOFs, control rules will become more complicated. The second kind of method is the muscle-model-oriented control. The torque of exoskeleton robot is obtained from the joint

torque matrix generated by actual muscle activity. This method is simple and reliable without limitation of the number of DOFs. However, the EMG signals will be affected by the wearer's lower limb posture, and the matrix needs to be adjusted. At present, there is much research combining the two methods. And Saga University adjusted the matrix using a neuro-fuzzy approach.

The man-robot interaction forces include the ground contact pressure (GCP) and body contact force (BCF). Ground contact pressure can ensure the motion consistency of the human body and robot, but its control algorithms are very complex. And GCP control algorithm is appropriate for the control of supporting legs. Body contact force is produced by the body's energy consumption, and suitable for the control of the swing phase. Therefore, a type of hybrid control method has been presented by the Chinese Academy of Sciences based on man-robot interaction force. This can realize the recognition control of human consciousness movements separately for the swing and stance phase, and the exoskeleton trajectory planning [63]. Hybrid control method mainly includes three parts: gait recognition, human motion perception (including GCP controller and BCF controller), and the trajectory tracking controller. Gait recognition uses pressure sensors at the heel and toe to judge the leg whether it is in the support phase or not. If the leg is in the support phase, the GCP controller is utilized to sense the human action. On the contrary, BCF controller is used to perceive the moving information of the swing leg. Trajectory tracking controller is a PID controller to achieve the trajectory control of the exoskeleton.

4.4. The Identification of Movement Phase

The gait cycle of the human body starts from the heel touchdown of the reference limb, and ends with the same heel touchdown again [64]. According to the motion of each leg in the whole gait cycle, it can be split into the swing phase and stance phase. Support phase refers to the course from the heel touchdown to toe off. That is the foot supporting contact time, making up about 60% of the gait cycle. Swing phase refers to the proceeding from the toe off the ground to the heel touchdown. That is the moment of foot off the ground, accounting for about 40% of the gait cycle. In the light of the two legs' posture, the entire gait cycle can be divided into single support phase (SSP), double support phase (DSP), double impact phase and switch phase [65]. Double impact phase and switch phase in the whole gait cycle are very small. Therefore, the gait cycle of the normal human body is generally composed of a single support phase and a double support phase.

A kind of GF set theory has been put forward by Shanghai Jiao Tong University, China, to mark the four types of action state for a single leg [66]. So the total states for two legs are 16. Four processes of movement are analyzed, such as walking, running, jumping and squatting, in order to find the particular action state of each movement. The specific movement state for walking is that the left (right) foot is on tiptoe while the other one is heel touchdown. Peculiar moment for running is that both feet are not in contact with the ground, and with a state of freedom. Exceptional action for jumping is that both the heels are in line contact with the ground. Special point for squatting is that both toe tips are in line contact with the ground. Referring to these unique action features, the control mode can be converted to another to achieve the phase recognition of action.

A new form of machine learning algorithm has been raised by University of Electronic Science and Technology, China [67]. The performance of an ensemble is better than a single classifier[68].On the basis of gait phase number, the walking cycle is divided into three categories: 2 phases (stance and swing), three phases (D-stance, S-stance and swing) and 7 phases (Heel strike, full foot, Mid-stance, Heel-off, Posterior swing, Mid-swing and Anterior swing). Action phase of the human body's lower extremity can be distinguished by the data obtained from the pressure sensors on the toe and heel, from the three-axis gyroscope and joint encoders, with the method of data mining and C4.5 algorithm analysis.

The recognition of the beginning and end of walking has been realized by University of Ljubljana with IMU sensor and plantar pressure sensor [69]. Walking beginning means the pressure center starts to move. The end of walking indicates that the braking force of the leading foot increases and the driving force of the other foot reduces. In the experiment, combined with the location of body joints, the beginning and end of walking have been found.

4.5. Human and Robot Interaction

In the present study, the exoskeleton robot is more to be a predefined action model to assist the movement of the human body, while ignoring the adaptability of the human body. The ALEX exoskeleton designed by the University of Delaware has been established to study the human-robot compatibility. The interaction between the human body and robot should be "assist as needed" as much as possible, and produce the desired trajectory through the force field controller (FFC) [70]. In order to improve the comfort of the human body while walking, the degree of freedom in the pelvis should be increased [71], and also the influence of the load should be considered [72].

Human/robot interaction is another difficulty in the lower extremity exoskeleton system. The contact areas of the human body and the exoskeleton are bands and the soles of feet [73]. Bands can make wearer and exoskeleton contact tightly and should have a soft and sufficient contact area as large as possible to improve comfort and safety. For paralyzed patients or the elderly, the lower limb strength is insufficient, has to be provided with adequate interactions. But for the exoskeleton robot that providing load supporting capacity and following the motion of human body, the smaller is the human/robot interaction, the better the effect will be [74].

5. CONCLUSION

This paper summarizes the requirements for the mechanical structure and control system of the LEERs and gives a review on the current research focuses of various research institutions. The core of the mechanical structure is the anthropomorphic features, that is, this robot should not only make the length adjustable, but also meets the require-

Fig. (6). Walking assistance lower limb exoskeleton, IHMC mobility assist exoskeleton, Lower-limb power-assist exoskeleton, HAL-3, WPAL(Wearable Power-Assist Locomotor), ATLAS, lower body exoskeleton, knee-ankle-foot robot, alex, ortholeg, walking supporting exoskeleton(wse), robotic exoskeleton.

ments of degrees of freedom of human body's motion. In addition, sensitive sensors and reliable control system decide the function and productiveness of the robots. Design schemes of some research institutes' exoskeleton robots are presented in Table **2** and Fig. (**6**).

Besides, the contradiction between high energy consumption of exoskeleton robot and small amount of energy supply is a chief limiting factor in the development of exoskeleton robots. The improvement of energy and motor technology will open up a rising application for exoskeleton robots. The

Table 2. The design of every institute's exoskeleton robot.

Number	Institute (Country)	Name	Use	Degree of Freedom	Actuator and Output Force	Sensors	Control Algorithm
1	Yonsei University(South Korea)	Walking assistance lower limb exoskeleton	Patients with lower limb paralysis	Hip:A-U-U Knee:A Ankle:U-U-U	200W Brushless DC motor+harmonic reducer Hip joint torque:79.3Nm Knee joint torque:42.2Nm	Angle sensor, Force sensor, Plantar contact sensor, Inclinometer	CoP stability control, Kinematics analysis
2	Florida Institute for Human and Machine Cognition(America)	IHMC mobility assist exoskeleton	Paralysis patients	Hip:A-A-U Knee:A Ankle:U-U-U	RSEA:Moog BN34-25EU-02 brushless motor+harmonic reducer(100:1) Output torque:80Nm	Optical rotary encoder, Linear encoder,Foot switch	Position control, Force/torque control
3	Saga University (Japan)	Lower-limb power-assist exoskeleton	Lower extremity weakness daily use	Hip:A-N-N Knee:A Ankle:U-N-N	Maxon DC motor	Encoder, Force sensor, EMG sensor, Laser ranging sensor, plantar contact sensor	ZMP stability control, Conscious recognition based on EMG signal, Ability to perceive to environment
4	University of Tsukuba(Japan)	HAL-3	Patients with lower limb paralysis	Hip:A-U-U Knee:A Ankle:U-U-U	DC servo motor+harmonic reducer	Plantar pressure sensor, Angle sensor, Gyroscope	Conscious recognition based on plantar pressure and torso angle
5	Nagoya University(Japan)	WPAL(Wearable Power-Assist Locomotor)	Patients with lower limb paralysis	Hip:A-N-N Knee:A Ankle:A-N-N	DC servo motor	Three axis angular acceleration sensor, Plantar pressure sensor, Encoder	Swing phase step trajectory control of lower limb
6	Centre for Automation and Robotics(Spain)	ATLAS	Quadriplegic patients	Hip:A-N-N Knee:A Ankle:U-N-N	Brushless Maxon motor+ harmonic reducer Peak torque:57Nm Average torque:32Nm	Plantar pressure distribution sensor, Angle sensor	CoP stability control, Conscious recognition
7	University of Salford(UK)	Lower Body Exoskeleton	Patients with lower limb paralysis	Hip:A-A-U Knee:A Ankle:A-N-N	Pneumatic muscle actuator (pMAs) Torque:60Nm	EMG sensor	The design of actuator
8	National University of Singapore	Knee-Ankle-Foot Robot	Rehabilitation robot	Knee:A Ankle:A-N-N	Maxon DC brushless motor +reducer+ screw nut Maximum output force:700N	EMG sensor, Angle sensor, Force sensor, Acceleration sensor	The design of actuator, Gait phase classification

Table 2. contd…

Number	Institute (Country)	Name	Use	Degree of Freedom	Actuator and Output Force	Sensors	Control Algorithm
9	University of Delaware(America)	ALEX	Stroke patients	Hip:A-U-U Knee:A Ankle:U-U-N	Linear actuator Peak torque:50Nm	Encoder,Force-torque sensor, Foot switch	Human-robot coordination
10	Rio Grande do Sul Federal University(Brazil)	Ortholeg	Spinal cord injury patients	Hip:A-N-N Knee:A Ankle:U-N-N	24V/150WDC motor+planetary gear reducer + screw nut	Encoder	Brain wave control
11	Necmttin Erbakan University(Turkey)	Walking supporting exoskeleton(WSE)	Disabled people	Hip:A-U-U Knee:A Ankle:U-U-U	24V/100WDC servo moto+reducer(100:1)	Plantar pressure sensor, Holzer effect sensor	Design of mechanical structure
12	Carlos Ⅲ University(Spain)	Robotic exoskeleton	patients	Hip:A-N-N Knee:A Ankle:A-N-N	Hip:24V/90W Maxon DC motor+ harmonic reducer(100:1) Maximum continuous torque:39Nm Knee, ankle:24V/70WMaxon DC motor+ harmonic reducer (160:1) Maximum continuous torque:20.8Nm	Inclinometer, Force sensor,IMU sensor	Trajectory control

Hip joint degrees of freedom sequence: flexion/extension, ab/ad-duction, rotation
Ankle joint degrees of freedom sequence: plantar/dorsal flexion, in/e-version, pro/supi-nation
A-actuated, U-unactuated, N-no DoF

exoskeleton robots are existed to assist normal people, not only the patients, so the coordinate movements between robots and human will attract increasing attention. The difficulty to sense human actions and adaptation to human body should be settled.

We believe that in the near future, the exoskeleton robots can walk into our lives, help the elderly and patients to complete the daily life activities and rehabilitation training, reduce the labor intensity on workers, and improve the soldier's capability of carrying load and going to battle.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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