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REVIEW

Research Progress and Development Trends of Lower Limb Exoskeleton Rehabilitation Robots

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Abstract

Lower limb motor dysfunction arising from a variety of causes is a major public health problem worldwide. The lower limb exoskeleton rehabilitation robot is a wearable biomimetic device used chiefly to restore standing and walking in patients with lower limb motor dysfunction, and it is currently a focus of rehabilitation medicine research. The history of the lower limb exoskeleton rehabilitation robot is reviewed, and the field has achieved a number of breakthroughs and advances in recent years. If the remaining technical problems of portability, intelligence and modularity can be overcome, it will become possible to maximise the rehabilitation of patients with lower limb dysfunction. This paper reviews the key technologies and clinical applications of wearable lower limb exoskeleton rehabilitation robots, and proposes new directions for research and development in this field.

Keywords: exoskeleton robot; lower limb dysfunction; stroke; spinal cord injury; rehabilitation training; human–machine interaction; intelligent; modular

Introduction

In recent years, population ageing has become an increasingly serious problem worldwide, and the number of patients with lower limb motor dysfunction caused by disorders of the locomotor system, cerebrovascular disease and spinal cord injury has risen substantially. Lower limb motor dysfunction seriously affects patients' quality of life, so restoring motor function safely and efficiently is a crucial problem at present[1]. The great majority of patients who lose mobility are confined to a sedentary life or even to bed rest. A lack of exercise in turn increases the risk of secondary health conditions such as cardiovascular and respiratory complications, gastrointestinal and bladder dysfunction, muscle atrophy, obesity, osteoporosis and pressure ulcers, and thus shortens life expectancy[2-6]. Rehabilitation training for patients with lower limb motor dysfunction is therefore a matter that deserves serious attention.

A lower limb exoskeleton robot generally refers to a wearable robot, a synthesis of biomechanics, mechanics, materials science, robotics, bionics, computer science and many other technologies[7]. It was first developed in the military field to meet the requirements of improving combat capability, enhancing soldiers' protection and reducing energy consumption[8]. As technology has advanced and population ageing has become more pronounced, wearable lower limb exoskeleton robots have gradually been applied in rehabilitation medicine. At present they are aimed chiefly at patients' rehabilitation training and can assist with activities of daily living, functional training and gait training. Their structural design proceeds from a biomimetic view of the human body, and they not only protect, support and assist the wearer but are also light in weight, small in volume and portable to wear[9-11].

Combining the Chinese and international literature, this paper reviews the key technologies of lower limb exoskeleton rehabilitation robots and the current state of their clinical application in China and abroad, in the hope of providing a reference for research, development and application in this field.

1 Key technologies

Wearable lower limb exoskeleton robots draw on materials science, robotics, biomechanics, ergonomics, computer science and bionics. They also involve sensor technology, control theory, actuation technology, human–machine interaction technology, information processing and analysis, and artificial intelligence, making them multidisciplinary, high-precision

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technical products. The extensive body of research produced both in China and abroad shows that their development and manufacture rest on the following key technologies.

1.1 Sensing system

The sensing system and the human–machine interaction system are mutually complementary. Achieving human–machine interaction first requires the rapid and accurate identification, analysis and processing of the wearer's movement intention, which is then transmitted to the control system and, through the actuation system, enables the exoskeleton robot to perform the corresponding action. The sensing system includes pressure sensors, angular sensors, electromyographic sensors and others. Lower limb exoskeleton rehabilitation robots mainly use various sensors to collect kinematic and gait information at the user's joints, to analyse the pattern of joint movement over a period of time, and then to apply this back to the corresponding joints of the exoskeleton, thereby completing an individualised joint movement and gait training programme for the user. A single sensor, or a single class of sensor, is not sufficient for a lower limb exoskeleton rehabilitation robot to identify human movement intention with adequate precision. Multimodal signal sensing systems are currently a research focus: by jointly compiling and transmitting the information received from several transducers, they allow the control system to determine the user's movement mode accurately and to deliver the safest, most timely and most appropriate decision. Wang[12] proposed a hybrid control strategy using three sensing methods: (1) electroencephalographic signals to identify the direction of a movement in advance; (2) surface electromyographic signals to identify lower limb movement patterns; and (3) fibre-optic motion capture to provide feedback on position and posture, the three being combined and applied to the exoskeleton system. Real-time, accurate recognition of the user's movement by the sensing system is the precondition for switching between movement modes with high precision and fluidity, and on this basis it helps patients with lower limb motor impairment to carry out rehabilitation training more effectively.

1.2 Control system

The control system of a wearable robot is chiefly responsible for making decisions and determines the performance and function of the exoskeleton robot. Exoskeleton control can be divided into position-based control, force-based interactive control, biosignal-based interactive control and intelligent control[13]. When the feedback that external information and the user's gait information provide to the machine is complex and difficult to interpret, the control system must make a decision. In rehabilitation training, the control system must be accurate, timely, real-time and individualised. Control systems are designed on the principles of responding rapidly to the user's physiological and kinematic information, reducing cost and complexity, reducing gait interference, simplifying the control strategy and lowering the wearer's metabolic cost of walking[14]. Precise control of an exoskeleton rehabilitation robot not only improves training outcomes but also prevents secondary injury to the user.

1.3 Actuation system

The actuation system is the core power source of an exoskeleton robot and, by actuation mode, may be divided into motor actuation, hydraulic actuation and pneumatic actuation[15]. Motor actuation remains the most widely studied: its advantages are a simple structure, high torque, no need for energy conversion and relatively flexible control, while its most serious drawbacks are its bulk, its mass and a generally cumbersome overall build. Hydraulic actuation converts the pressure generated by a hydraulic pump into mechanical energy to provide power. Its advantages include low inertia, a fast response, high reliability, high power density and stable transmission, but because of its high cost, loud noise, environmental pollution and relatively poor transmission efficiency it has received comparatively little attention in China or abroad. Compared with the first two, pneumatic actuation derives its power from air produced by a compressed air supply. Its advantages are small size, low mass, low cost, good compliance, a simple structure and ease of operation. A pneumatically actuated lower limb exoskeleton rehabilitation robot can provide the wearer with efficient, low-energy and low-cost rehabilitation training. Its main drawbacks are low power and unstable control. Although relatively few pneumatic products are in practical use, this mode has considerable potential in the future development of lower limb exoskeleton robots.

1.4 Human–machine interaction system

The human–machine interaction system is a bidirectional communication system that transmits the user's intended movement information to the exoskeleton, where it is converted into power for movement, and simultaneously feeds the exoskeleton's powered movement information back to the user. It falls into two main classes. The first is kinematic information sensing and interaction, which chiefly senses the interaction information between the user and the exoskeleton robot. An exoskeleton rehabilitation robot generally uses several sensors to reflect the user's instantaneous joint angle, angular velocity, human–machine interaction force, movement acceleration and gait pattern, thereby ensuring stability,

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safety and continuity. The second is sensing of, and interaction with, the user's physiological information, chiefly electroencephalographic and electromyographic signals[16]. Electroencephalographic signals are transmitted through a brain–computer interface from the scalp electroencephalogram (EEG)[17]; their advantages are good practicality, fast signal transmission, wide application and good portability. Electromyographic signals are the action potentials of the neuromuscular system commanded by the central nervous system; they arise before skeletal muscle contraction and can therefore reveal the user's movement intention faster than kinematic information[18]. Surface electromyography (sEMG) is usually detected with patch electrodes affixed to the skin surface, which allows muscle activity to be assessed, lower limb movement patterns to be identified and the exoskeleton to be controlled so that it adapts to and corrects the limb's movement[19]. As artificial intelligence has developed, interaction has become more sophisticated and simpler at the same time: a simple gesture, direct speech or even an electroencephalographic signal can serve to interact with the machine. These intelligent and user-friendly modes of interaction all exist to ensure a close fit and coordination between user and exoskeleton robot, and ultimately to achieve the desired rehabilitation outcome.

1.5 Energy system

Whatever new technology is incorporated into the development of a lower limb exoskeleton robot, energy remains an unavoidable and important problem. For a wearable lower limb exoskeleton rehabilitation robot, a research focus in rehabilitation, high energy capacity and long endurance are central, and portability, environmental friendliness and sustainability are also required. The most widely used energy system in lower limb exoskeleton robots is at present the battery–electric motor system. The batteries commonly used are generally lead-acid, rechargeable lithium or fuel cells. The volume, mass, capacity and efficiency of batteries are, however, unavoidable limitations at present[20]. The energy problem may therefore be approached from three directions: (1) designing batteries that are light, long-lasting and highly safe; (2) introducing new energy technologies such as solar power; and (3) reducing the power consumption of the exoskeleton and designing recyclable and sustainable energy systems[21].

2 Clinical applications

2.1 International status

Research on exoskeleton robots began earlier abroad, and can be traced back to the Assisted-walking Device designed by Yagn in 1890. As technology has advanced, exoskeleton robotics has matured, moving from the experimental stage to commercial products and gradually replacing conventional rehabilitation equipment. The progress made in different countries is summarised below.

The wearable robot developed by Parker Hannifin of the United States[22] received FDA approval in 2016; it has a self-weight of 12 kg and an endurance of 1 h, and can assist patients with lower limb dysfunction in intermediate and late-stage rehabilitation. Sensors detect the patient's state of balance and control changes in body position so that the exoskeleton follows the body's movement. Its several modes allow not only switching between sitting, standing and walking but also changes in step length, walking speed and gait[23-25]. Ekso GT™, developed by Ekso Bionics of the United States, has a self-weight of 23 kg and an endurance of 24 h, and can be set to an individualised, natural gait according to the wearer's needs. Such robots focus on the rehabilitation of patients with severe conditions such as stroke and spinal cord injury[26]. SuitX of California has also developed the wearable lower limb exoskeleton robot Phoenix[27], with a self-weight of 12.5 kg and an endurance of 4-8 h; its modular design divides the device into modules for the hip, knee and foot, making it easier to put on, take off and assemble, and allowing the modules to be used singly or combined freely[28]. Harvard University has developed and updated three generations of the Soft Exosuit, a soft wearable lower limb exoskeleton[29]: the first generation was pneumatically actuated, using pneumatic artificial muscles to assist joint torque; the second used soft textile materials and could provide an assisting moment without active actuation; and the third used soft textile straps together with cable–pulley actuation to provide assistance, chiefly improving foot drop[30].

The HAL robot developed by Cyberdyne of Japan has a self-weight of 23 kg and an endurance of 160 min, and has been produced in quantity since receiving global safety certification in 2013[31]. HAL has two systems, biosignal-based voluntary control and autonomous control. The voluntary control system collects the user's electromyographic signals to determine the wearer's intention and thereby controls the exoskeleton's movement; the autonomous control system uses models stored in the system to accomplish simultaneously memorised assisted movement[32]. Kadone et al.[33] assessed the effect of HAL in patients with gait disturbance caused by compressive myelopathy; after completing the HAL training period, patients' gait improved, a near-normal joint trajectory was restored, range of motion was greater, walking was faster and step length increased. Fujita Health University of Japan designed the Wearable Power Assist Locomotor (WPAL), whose distinguishing feature is a pulley track on the inner side and a human–machine interface on the outer side, allowing it to be connected to and used with a wheelchair[34].

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The ReWalk exoskeleton robot developed by ReWalk Robotics of Israel was among the first batch of exoskeletons used in medicine[35]. Its computer control system and sensing technology determine the user's intention to move and then control the exoskeleton robot to adjust so that it is coordinated with the body and completes the rehabilitation training[36]. Professor Awad et al.[37] applied this exoskeleton robot to 44 patients with post-stroke hemiplegia. The results showed that, when used under the guidance of a licensed physiotherapist, the ReStore™ soft robotic exosuit can be used safely and reliably during post-stroke gait rehabilitation. When patients walked on a treadmill and over ground, the exoskeleton could provide targeted assistance with plantarflexion and dorsiflexion in patients with a paretic ankle.

The University of Twente in the Netherlands developed the wearable exoskeleton robot MindWalker; it weighs 28 kg but can assist paraplegic patients in walking, with improved adaptability and comfort[38]. Technaid of Spain developed the Exo-H3 exoskeleton robot, with a self-weight of only 14 kg, a flexible frame and compact drive motors[39]. It drives joint movement chiefly by storing gait data. The product offers Wi-Fi and Bluetooth connectivity, and users can control it from a mobile phone. As well as helping patients with lower limb dysfunction to rehabilitate and walk, it can be used to devise individualised strategies[40].

Southeast University developed QEPLEX, which is chiefly applied to rehabilitation training in patients with unequal muscle strength in the two lower limbs[44]. The Harbin Institute of Technology developed HIT-LEX, which uses a modular design and a quasi-anthropomorphic structure[45], has an endurance of up to 2 h and can support patients walking with a load in complex environments. The Chinese University of Hong Kong developed CUHK-EXO, whose distinguishing feature is a control system designed as an integrated offline and online modification system that can collect and modify data in real time according to conditions in the field before applying it[46].

The Shenzhen Institute of Advanced Technology of the Chinese Academy of Sciences developed the exoskeleton robot Auto-LEE, with as many as 10 degrees of freedom. The exoskeleton not only drives its assisting joints independently but also adopts a modular structural concept directly on the basis of multimodal human–machine interaction. The robot can maintain the user's walking balance without auxiliary support and adds three gait algorithms[47].

2.2 Domestic status

Research in this field began in China later than in Western countries, and early Chinese work on exoskeletons was largely confined to the experimental stage. With the development of science, technology and the economy in China, exoskeleton robotics has gradually approached the international level, and products have been put into production and applied in rehabilitation medicine.

Beijing Ailegs Robotics has developed the wearable exoskeleton Ailegs. The Ailegs robot is designed chiefly to meet the individualised needs of patients after bone and joint surgery and those with spinal cord injury, brain injury, paralysis, stroke or myasthenia[41]. Ailegs can assist patients in recovering a natural gait, training them in a realistic and correct walking posture.

Shanghai Fourier Intelligence has launched the wearable lower limb exoskeleton robot Fourier X2, an upgraded version of Fourier X1[42], used chiefly for assisted walking, rehabilitation training and strengthening motor function. It incorporates multi-sensor fusion technology, a motion control system and a power unit, and can intelligently analyse the user's intention, dynamically adjusting power output according to the external mechanical environment such as movement trajectory and speed. Its core feedback control algorithm can also adjust in real time according to the dynamic environment and the magnitude of force at the contact points.

A wearable robot developed at Zhejiang University uses hydraulic actuation, has a self-weight of only 5.355 kg, requires no auxiliary support and uses the hip and knee as active joints to assist patients in rehabilitation training[43]. It employs a distinctive human–machine interaction system and algorithm, with adaptive fuzzy control improving the exoskeleton's control accuracy and performance.

3 Conclusions and prospects

As population ageing becomes more pronounced, the number of patients with lower limb motor dysfunction continues to rise, and lower limb exoskeleton rehabilitation robots will undoubtedly play an important role in treatment, assisted walking and musculoskeletal rehabilitation. Exoskeletons have made enormous progress in rehabilitation over the past decade. In the light of technological development and the needs of society and the economy, future exoskeleton rehabilitation robots must solve a number of technical problems, including portability when worn, intelligent operation and modular structural design[48-49]. Portability matters for the convenience of the wearer, and most exoskeletons developed to date are relatively heavy and awkward to put on and use. As regards materials, the exoskeleton frame should be designed to be of low density, high strength and good toughness, such as carbon fibre, and some parts can be made by 3D printing. At the same time, as

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energy technology develops, small, efficient and high power-to-weight energy sources should be used to reduce the burden on the wearer.

As artificial intelligence continues to develop, exoskeleton robots should be designed to incorporate it fully so as to reduce the physiotherapist's workload as far as possible. Artificial intelligence is also simple to operate, can intelligently drive and control the exoskeleton, and gives the user a more comfortable experience and more human-centred rehabilitation training. Modular design means dividing the whole exoskeleton robot into modules by region or function; this not only greatly reduces cost but is also more targeted in terms of functional independence. Dividing a complex product and system into modules can improve control precision and is more conducive to subsequent development, use and maintenance[50].

Research and development of lower limb exoskeleton rehabilitation robots should focus on the materials used, modular design, the human–machine interface, cloud data, safety, intelligence, energy efficiency and cost-effectiveness. These are the future research directions that will allow lower limb exoskeleton rehabilitation robots to be used more widely in clinical practice.

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