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Research progress on lightweight technology of exoskeleton robot

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Abstract. Exoskeleton robots are wearable devices designed to mimic the skeletal mechanisms of insects and humans Enhancing users' body functioning. In recent years, exoskeleton robot has become one of the hot spots in military and medical fields. In the process of exoskeleton robot research and development, how to achieve lightweight exoskeleton robot design is the goal of many research and development teams. Lightweight design is of significant importance in the development of exoskeleton robots since it can increase their efficiency and portability. With the improvement of modern processing technology, the lightweight technology of exoskeleton robot is becoming more and more mature. This paper summarizes the mature and promising lightweight technology of exoskeleton robot at present. In this paper, based on existing exoskeleton robots, the lightweight technology of these robots is analysed and reviewed in terms of their drive devices, power supply, structures and materials, and future development trends of the technology are suggested. This paper offers a reference the lightweight design of exoskeleton robot.

Keywords: exoskeleton robot, lightweight technology, drive device, power supply, material and structure.

1. Introduction

On the basis of bionics, exoskeleton robots are wearable devices with a mechanical structure, which mimics the skeletal structure of insects and humans, representing an important branch of robotics [1]. Exoskeleton robots are generally used in the military and medical industries to improve the weight-bearing capacity and provide motion support. For example, exoskeletons can help soldiers walk for longer distances or carry heavier loads with less physical strength. Moreover, they can be used in rehabilitation to help paralyzed and disabled patients walk. As stroke is highly likely to cause disability, with growing incidence in recent years, more and more research teams are devoted to the development of medical exoskeleton robots [2].

Due to scientific and technological development and breakthroughs, the exoskeleton robot technology has witnessed progress in control techniques and drive techniques. As a consequence, more and more state-of-the-art exoskeleton robots have been developed. At present, relatively advanced rehabilitation therapy exoskeleton robots on the market include the Hybrid Assistive Limbs (HAL) developed by the team headed by Professor Yoshiyuki Sankai from the University of Tsukuba; military exoskeleton robots include the Human Universal Load Carrier (HULC) developed by the company

Lockheed Martin [3]. In the research and development process, such problems as lightweight design gradually emerge. Lightweight design aims to reduce the weight of products as much as possible while ensuring their reliability, structural strength and functions. Due to such factors as material selection and mechanical design, existing exoskeleton robots are rather cumbersome and difficult to wear, and cause mobility inconvenience to users. Lightweight design is of significant importance in the development of exoskeleton robots since it can increase their efficiency and portability. Besides, the weight is greatly associated with the performance, load capability and endurance of exoskeleton robots [4]. Therefore, some research teams have switched their focus to the lightweight design. The lightweight technology is mainly realized in three ways: first, reducing the mass of the drive device and improving its performance; second, decreasing the mass of the battery by improving its performance and increasing its energy density; third, choosing proper materials and optimizing the structure [5]. In this paper, based on existing exoskeleton robots, the lightweight technology of these robots is analysed and reviewed in terms of their drive devices, batteries, structures and materials, and future development trends of the technology are suggested. This paper offers a reference the lightweight design of exoskeleton robot.

2. Drive device

Drive devices of exoskeleton robots make up a significant percentage of whole weight. Therefore, it is feasible to realize the lightweight design by reducing the weight of the drive device. Sufficient research has been done in drive devices by research teams. Common drive devices of exoskeleton robots include motor drives, hydrostatic drives and pneumatic drives.

2.1. Motor drive

The motor drive is a relatively mature drive mode in robotics and has been applied to numerous exoskeleton robots on the market, such as HAL and Roboknee [3]. It boasts high response speed and desirable efficiency, but lacks a relatively high torque, a lightweight design, a low rotation speed and a small size. So, it is generally used in combination with gears and cables [6]. There are mainly two designs for motor drives. The first one is to place a disc motor at the connection point of rotary joints so as to drive the joint rotation through the rotor rotation. However, this drive mode is very cumbersome and it is hard to strike a balance between the weight and the driving force. The second one concerns the linear motion of the electric pushing rod – connect the two ends of the rod to a motor and a joint respectively so as to drive the joint rotation. To realize the lightweight design of motors, DC servomotors have been invented, which have a small size, high precision and a light mass. However, such motors are only applicable to small-sized joints and exoskeleton devices [7]. In addition, the motor drive can easily be overheating due to internal triggers, thus affecting the operation of exoskeleton robots and impairing their sensitivity [8]. Therefore, with the motor weight, size, rotation speed and performance taken into consideration, the lightweight design can only be realized in small-sized exoskeleton robots or joints.

2.2. Hydrostatic drive

Hydraulic system mainly comprises a hydraulic drive unit, a hydraulic power unit and connecting tubes [9]. At present, the hydraulic system has such shortcomings as overheating hydraulic power system, large size and mass, leakage and high energy consumption due to technical weaknesses and component limitations [10]. The hydrostatic drive is a drive mode with a rather complicated but compact structure. When the power is the same, it is often smaller and lighter compared with other modes. Therefore, numerous research teams are committed to developing compact hydraulic engines, like the compact hydraulic power unit developed by the research team from the American company Parker [9]. Some seek to reduce the weight of hydraulic motors by changing raw materials of the hydraulic system components, from traditional metal to advanced composite materials. Herbert Haenchen Company has made improvements and developed hydraulic cylinders made from carbon fibre composite materials, lowering the mass by 25%-30% compared with the traditional metal ones [11]. The weight of the robot HYDROID has decreased to 10kg from 38kg by utilizing a lightweight hydraulic brake and choosing carbon fibre composite materials as body materials of the hydraulic cylinder [12].

2.3. Pneumatic drive

Similar to the hydrostatic drive, the pneumatic drive utilizes compressed air acting on a piston inside a cylinder to move a load along a linear path and drive the joint rotation. Its biggest advantage lies in a relatively light mass. Besides, by using the air as raw materials, the pneumatic drive has lower costs, higher cost-effectiveness, greater safety and compliance in comparison with the motor drive [6]. Now new pneumatic drives have been developed and applied to the new-generation artificial exoskeleton robots, such as pneumatic artificial muscles. McKibben pneumatic artificial muscles are relatively mature, which are driven by pressure difference [13]. The main component is a hollow pipe, with one end connected to a bladder for transporting high-pressure air, and another to a drive rod. Compared with traditional rigid cylinders, it is lighter and has higher compliance. However, precise control and dynamical models are still tricky problems in the pneumatic drive research [13]. Given that the pressure inside the pipe and the force produced as well as the model contraction length exhibit non-linear relations, precise control of the model can only be realized through massive calculation. Therefore, the crux of a new pneumatic drive dynamical model lies in the dynamical model. The pneumatic drive is an essential approach to developing lightweight exoskeleton robots, as well as a hot issue in the future lightweight technology of exoskeleton robots.

3. Power supply

The lightweight design of exoskeleton robots can also be realized by decreasing the weight of their power supply. Existing exoskeleton robots are mainly equipped with such power supply devices as storage batteries, Li-ion batteries, cable supply, photovoltaic batteries, and advanced-composite-materials-based batteries. The performance of power supply devices greatly influences the performance, endurance and sensitivity of robots. Therefore, reducing the power supply weight of exoskeleton robots while maintaining its performance has become a research hotspot. Another way of realizing the lightweight design of exoskeleton robots is to separate battery devices from the main body of the robots.

3.1. Automatic tracking device

The battery devices of exoskeleton robots are rather heavy. Separating them from the main body of the robots by placing them on an automatic tracking device is a feasible variant to realize the lightweight design. Though this can reduce the weight of the robots, the dexterity of automatic tracking devices remains a tricky problem to be addressed [14].

3.2. Battery efficiency enhancement

3.2.1. Storage battery. The energy stored in storage batteries, the energy conversion rate and efficiency are relatively low. Experiments show that the mass energy density of storage batteries is 50-70wh/g, merely one third to one fifth that of Li-ion batteries. Thus, the lightweight technology of exoskeleton robots rarely utilizes storage batteries. However, some robots are still equipped with such batteries because their price is much lower than that of Li-ion batteries.

3.2.2. Li-ion battery. Experiments show that, compared with traditional Li-ion batteries, polymer Li-ion batteries have higher energy density, lower self-discharge rate, greater environmental friendliness and no memory effect, while traditional Li-ion batteries have lower efficiency and energy conversion rate. Therefore, most of the research teams usually choose to use compound and polymer Li-ion batteries with middle and high energy density. The safety of Li-ion batteries needs to be improved, but it is increasing due to better processing technology and battery protection board [15]. Besides, the mass energy density of Li-ion batteries is 200-260wh/g, three to five times that of storage batteries. So, Li-ion batteries are more suitable for the lightweight technology of energy-storage devices. Their volume energy density is 1.5 times that of storage batteries. When the energy capacity is the same, Li-ion batteries have smaller sizes than storage batteries and better apply to the lightweight technology of exoskeleton robots.

3.2.3. Cable supply. Cable supply is generally used in large high-power exoskeleton robots that move within a specified range, like those in rehabilitation centers. Although it restricts the convenience and scope of operation, it significantly diminishes the influence of battery devices on the weight of the robots. The LOKOMAT robot, developed by University of Zurich and Hocoma, is powered by cables that receive electricity from a centralized indoor power supply. Its lightweight design eliminates the impact of battery weight, but it can only operate within the confines of a room [16]. Assuming a robot's operation scope is not a consideration, cable supply can be a highly efficient lightweight technology option for exoskeleton robots.

4. Material and structure

Lightweight materials and structural optimization are also effective means to realize the lightweight design of exoskeleton robots. The structure of exoskeleton robots is required to be highly durable so as to ensure the safety of users. Therefore, these robots have a high requirement for structural strength. Aluminum alloy, magnesium alloy, carbon fibre reinforced plastic (CFRP), titanium alloy and composite materials are commonly used to make exoskeleton robots. In addition to lightweight materials, structural optimization is also an effective approach to realizing the lightweight design. Applying topology optimization method and adopting differentiated design solutions is an effective means of reducing their weight.

4.1. Lightweight materials

4.1.1. Aluminum alloy and magnesium alloy. Aluminum alloy outperforms traditional steel and iron materials in terms of weight. Moreover, it has lower costs and its density is far lower than that of ferroalloy. Aerospace aluminum is a common material used in exoskeleton robots, but it may not be able to meet the structural strength requirements of certain parts. At present, magnesium alloy is the lightest metal composite material with a lower density than aluminum alloy, greatly increasing the dexterity of robots. However, similar to aluminum alloy, its strength can hardly meet the requirements of exoskeleton robots operating in a highly demanding environment.

4.1.2. Titanium alloy. Titanium alloy, a high-strength metal material with excellent corrosion resistance and low-temperature performance, can be used in complex working environments. However, the processing difficulty and manufacturing cost of titanium alloy are much higher in comparison with other metals. Therefore, it is usually used to make key parts of exoskeleton robots so as to improve their quality and prolong their service life.

4.1.3. Carbon-fibre material. Carbon fibre, a kind of special material made of carbon, is a kind of highly-processed composite non-metal material. Carbon fibre composite material has high strength and low density. Its strength is higher than that of aluminum alloy, magnesium alloy and titanium alloy mentioned before. The density of carbon fibre epoxy resin composite material can be as low as $1.5 g/cm^3$, making it a good option to realize the lightweight design of exoskeleton robots. The manufacturing cost of carbon fibre composite material is lower than that of titanium alloy, while still higher than that of aluminum alloy and magnesium alloy. Therefore, carbon fibre composite material is generally used to make those high-end exoskeleton robots, but can hardly be used in the mass production of civilian ones. The University of Sheffield has developed a robot machine tool composed of lightweight carbon fibre, enabling it to be easily transported and installed by just two people [17].

4.2. Lightweight structure

Structural optimization includes size optimization, shape optimization and topology optimization. Size optimization refers to the process of optimizing the dimensions of a product to achieve a lightweight design, while maintaining other parameters such as materials and topological shape unchanged. Shape optimization relates to the optimization of the boundary of a product, such as chamfer design. Compared with the other two types of structural optimization, topology optimization is considered the most promising method in terms of lightweight design. It involves designing a material distribution layout based on product constraints so as to achieve the best possible performance. This way a lightweight design can be achieved while ensuring the strength of exoskeleton robots.

However, high design freedom is required for products designed through topology optimization, so traditional manufacturing processes may not be able to produce product models directly, often requiring manual post-processing.

As computer technology advances, 3D printing has become increasingly mature and solved the post-processing problem to a large extent, making the application of topology optimization increasingly widespread. It can be seen that a combination of the lightweight design and new techniques is necessary. Hollow or cellular structures can be used in non-critical or low load-bearing parts of exoskeleton robots to significantly reduce their weight. For example, the Atlas robot designed by Boston Dynamics is produced using 3D printing technology, with its leg components formed into hollow structures to achieve lightweight design [18].

5. Conclusion

Although considerable effort has been devoted to the field of exoskeleton robots in recent decades, most finished variants remain in the experimental stage and have not been widely applied due to issues such as inconvenience in use, high cost, large mass, and low reliability. Therefore, lightweight design has become a primary task for many research teams as one of the most effective methods to improve robot performance and comfort while lowering costs. Currently, there are four common and promising ways to achieve the lightweight design: lightweight drive devices, lightweight batteries, lightweight materials, and lightweight structures. Additionally, advancements in related techniques such as 3D printing technology are also crucial to the development of lightweight technology. At present, the structural design and material improvement of exoskeleton robots are the two most promising solutions, and their development cannot be separated from the progress of related technology. In the future, the exoskeleton robot will gradually realize lightweight design to make it easier for users to carry and wear, so that the exoskeleton robot will make greater contributions to human beings.

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