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# *Current Development Status and Application Scenarios of Exoskeleton Robot Technology*

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***Abstract.*** Exoskeleton robotics technology is a new kind of wearable bionic device that has been applied in various fields, such as healthcare and industry. However, there are still many development bottlenecks in the technology due to market and core-technology problems. The development history of exoskeleton robot technology, its applications in medical rehabilitation, outdoor walking assistance and industrial production, problems and future development directions of this technology are introduced in this paper. This paper studies the concept of passive exoskeletons and the development of the Hardiman project in the 1960s, and also analyzes the current progress in core technology and the emergence of commercial products. The first is to introduce the technical features of some typical products and compare differences in driving modes, intention recognition, safety and application subjects for exoskeleton robots in different use cases. Finally, this paper will summarize the current problems in technology for cost control, energy supply and human-computer interaction, and look ahead to the future development direction of new materials, integration of artificial intelligence and multi-area expansion

***Keywords:*** exoskeleton robot, human-machine collaboration, intent recognition, Development status, Technical challenges

## 1. Introduction

With the increase in working hours, the frequency of industrial occupational diseases such as lumbar muscle strain is also rising, and more than 15 million people around the world have suffered spinal cord injuries [1]. Exoskeleton robot technology refers to wearable devices that can augment human functions and assist with movement, and research in academia and industry has also been expanding. Lower-limb exoskeleton robots for the recovery of walking function in spinal cord injury patients have been developed to improve their quality of life and rehabilitation results in the medical field [2]. They can help industrial enterprises reduce the amount of manual labour in material handling and logistics operations, thereby easing the physical burden on employees and improving both work efficiency and safety [3]. Although there have been many advances in exoskeleton robot technology, many problems still need to be solved before they can be used widely, such as high research and production costs that restrict their application, short battery life of the current battery technology, and the need to improve the adaptability and control accuracy of human-machine interaction systems [4]. To solve the problems above is to advance the development of this

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technology. Based on the analysis of related studies, this paper offers some theoretical support and practical suggestions for the development and improvement of exoskeleton robot technology.

## 2. The technological development history of exoskeleton robots

### 2.1. Early concepts and military exploration (1890-1970s)

In the 1890s, Russian scholars were the first to put forward the idea of exoskeleton technology and proposed a basic concept for passive exoskeletons: to use external mechanical structures to help people move and reduce the physical burden on them.

[4] The above ideas provided the foundation for the following research. Between 1965 and 1971, General Electric and the US military conducted the Hardiman project to develop the first active full-body exoskeleton in the world. This project employs hydraulic drive technology to achieve a large-load capacity, aiming to amplify human power by 25 times and enable easy lifting of objects weighing up to 340 kg [5]. However, due to the absence of a precise control system, the equipment weighs as much as 680 kg and is difficult to operate precisely; thus, this project has been shelved [5]. Nevertheless, the Hardiman project has led the way in the development of active exoskeletons and provided a valuable reference for later research.

### 2.2. The research focus in the 1980s and 1990s moved to medical rehabilitation.

In the 1980s, the direction of research for exoskeleton technology gradually shifted from the military to medical rehabilitation. The main reason for this change is the urgent need of society to help patients with spinal cord injuries and mobility disorders regain the ability to walk [2, 3]. Therefore, researchers are studying how to use exoskeleton technology to assist patients in recovering some mobility. However, due to the limitations of battery technology and computing power at that time, exoskeleton robots once again stalled in their development in the 1990s. At that time, batteries could not provide enough power, and due to a lack of high-performance computing, complex human-machine interaction control algorithms were not feasible [4].

### 2.3. Core technology breakthrough and commercialization (2000 present)

In 2000, the US Defense Advanced Research Projects Agency (DARPA) resumed the development of the Enhanced Human Physical Fitness Exoskeleton project and reached a new level in exoskeleton technology. With the continuous development of materials science, control technology and artificial intelligence, many key technologies have been achieved. The BLEEX system (HULC prototype) developed by the University of California, Berkeley in 2004 weighs only 24 kilograms, and the XOS-2 powered exoskeleton system launched by Raytheon in 2010 weighs 95 kilograms. The actual and perceived weight when carrying heavy objects reaches 17:1, and energy consumption is reduced by 50% [6]. After 2010, the research achievements of the University of California, Berkeley have led to the development of many commercial exoskeleton products, such as eLEGS designed specifically for patients with lower limb paralysis, and Austin, which further optimized the human-machine interaction experience [4]. Afterwards, many representative companies emerged in the international market, such as Cyberdyne (HAL) from Japan, Ekso Bionics from the United States, and ReWalk from Israel. The emergence of these companies played a significant role in promoting the practical application and popularization of exoskeleton technology [4].

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## 3. Analysis of application scenarios of exoskeleton robot technology

### 3.1. Medical rehabilitation and elderly care

In the field of medical rehabilitation, exoskeleton robots, as a new type of wearable biomimetic device, are widely used for walking function recovery training of spinal cord injury patients. Fourier X1 of Fourier Intelligence is a typical representative in this field.

Fourier X1 has a body material of aluminium and carbon fibre-reinforced polymer, is relatively light, and is powered by a high-performance motor for the thigh and knee joints. The 19 sensors are arranged at different joints and on the body of the device to collect all-encompassing biomechanical data for the user, such as stride length, step frequency and plantar pressure. Eleven distributed central processing units (CPUs) are responsible for real-time computation, and they can correctly identify the user's walking intention and adjust the personalised walking path dynamically [7].

A fall-detection device that continuously observes a person's centre of mass and walking patterns to alert caregivers of a fall in case of an accident. It can trigger an automatic shutdown and avoidance mechanism, and also send a distress signal to ensure the safety of users [4]. Some studies have shown that exoskeleton robots can simulate natural walking and provide dynamic support to improve patients' mobility, promote neural function changes, and strengthen muscles [2, 8].

### 3.2. Outdoor walking assistance

An outdoor-use assistive exoskeleton is to help people with reduced mobility walk more easily and reduce their physical strain. Polar Shell by Hypershell is a typical product in this area.

Hypershell polar shells use multimodal sensors (such as inertial measurement units and force sensors) to collect user gait and motion posture data, and then use end-to-end AI algorithms to predict real-time intentions. Finally, the biomimetic motor is driven with millisecond-level synchronous assistance. The advantages of human-machine collaboration as a core technology are obvious. It can achieve a highly intelligent control system, achieve a human-machine gait collaboration rate of up to 97.5%, and provide users with a natural and smooth walking experience [4].

This device can dynamically adjust the assistance level based on real-time conditions, such as automatically increasing the output torque when climbing hills and switching to low-power mode when walking on flat ground, greatly improving the user's walking ability and endurance [8].

### 3.3. Industrial production

Industrial exoskeletons are mainly used to reduce the physical burden on workers during repetitive physical labor. Comau's MATE-XB is a non-powered lumbar exoskeleton specifically designed for handling and logistics operations.

MATE-XB is different from active exoskeletons in that it does not require batteries or motors, but relies on advanced mechanical spring technology to store and release human potential energy. When the user bends down, the exoskeleton absorbs and stores potential energy; When the user stands upright, energy is released, thereby reducing the muscle burden on the lumbar spine. This passive assistance mechanism simplifies the device structure, reduces costs, and maintenance requirements. Research has shown that wearing such exoskeletons for carrying operations can reduce workers' physical exertion by about 30% and increase work efficiency by more than 20% [9]. At the same time, it effectively reduces the risk of occupational diseases such as lumbar spine injuries [8].

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### 3.4. Comparison of technical routes in different application scenarios

In order to present the technological differences of exoskeleton robots in different application scenarios more clearly, this article compares them from four aspects: driving mode, intent recognition, safety, and applicable population, as shown in Table 1.

Table 1. Comparison of exoskeleton robot technology routes in different application scenarios

| Comparative dimension | Medical rehabilitation (such as Fourier X1) | Outdoor walking assistance (such as Hypershell) | Industrial production (such as MATE-XB) |
|---|---|---|---|
| Drive type | Active drive (high-performance motor) | Active drive (biomimetic motor) | Passive drive (mechanical spring) |
| Intent recognition | Multi-sensor fusion and real-time CPU computation | Real-time end-to-end algorithm prediction | Passive response of mechanical structure |
| Safety | Fall warning, automatic shutdown, distress signal | Intelligent assistance strategy ensures comfort | Ergonomic design ensures comfort |
| Target audience | People with limited mobility or lower limb paralysis | Need outdoor walkers | Workers engaged in handling and logistics |

## 4. Challenges and development trends of exoskeleton robotics technology

### 4.1. Main technical challenges

In terms of cost control, exoskeleton robots involve interdisciplinary technologies, such as the development and manufacturing of core components such as high-performance sensors and precision actuators, which have high costs. At the same time, the application of lightweight materials such as carbon fiber has also driven up product pricing and limited its popularity in the medical and industrial fields [4].

Most existing active exoskeletons rely on battery technology, but due to the limitation of battery energy density, their endurance is difficult to meet the requirements for long-term operation. In addition, the battery pack and drive motor attached to the exoskeleton significantly increase the end mass of the lower limbs, which alters the natural gait dynamics of the wearer and leads to a non-linear increase in hip joint torque demand during swing. When the inertial load caused by the self-weight of the device offsets or even exceeds the mechanical positive work it provides, the actual net metabolic energy consumption of the wearer during walking will actually increase, thus falling into the 'energy-saving paradox'.

At the level of human-computer interaction, the adaptability and control accuracy of exoskeleton robots still face severe challenges. Human body movement has a high degree of nonlinearity and individual differences, which puts extremely high demands on the intention recognition of the system. Although the introduction of surface electromyography (sEMG) signals or kinematic sensors can capture motion precursors, there is inevitably a millisecond-level phase lag in the complete process from signal acquisition and feature extraction to actuator response. This control lag can lead to the inability of the exoskeleton's torque output to perfectly synchronize with human joint movements, resulting in human-machine adversarial forces that hinder movement at the human-machine coupling interface. This not only increases the wearer's metabolic energy consumption, but also affects the naturalness and safety of multi-joint coordinated motion [4].

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### 4.2. Future development trends

In the application of new materials, high-performance composite materials such as carbon fiber reinforced polymer (CFRP) and titanium alloy, with their lightweight and high-strength characteristics, will become the mainstream materials for exoskeleton manufacturing, which can reduce equipment weight, improve durability, and compensate for the shortcomings caused by battery weight. Moreover, the application of smart materials such as shape memory alloys (SMA) will also enhance the adaptive ability of exoskeletons [10].

In terms of artificial intelligence, introducing machine learning and deep learning algorithms into exoskeleton robots can more accurately predict user intentions and adjust strategies in real time. Application of reinforcement learning algorithms in control strategy optimization to achieve personalized rehabilitation training goals and improve user experience [11].

At the same time, exoskeleton technology has applications in medical and industrial fields, and is now expanding to military, aerospace, sports training, and other directions. For example, improving the load-bearing capacity of soldiers in the military, reducing muscle atrophy in astronauts in aerospace, and helping athletes improve posture and reduce injury risks in sports training [2, 8].

## 5. Conclusion

Despite the vast technological prospects, achieving large-scale adoption still requires facing severe challenges in terms of cost, energy, and human-computer interaction. The commercialization process of different application scenarios will show significant differentiation. The industrial production scenario, with its high repeatability of actions, structured environment, and high tolerance for passive technology, is highly likely to be the first to achieve large-scale commercialization and become a breakthrough in the popularization of exoskeleton technology; However, the medical rehabilitation scene is still severely constrained by the safety and accuracy of human-machine coupling algorithms due to its direct relationship with the patient's life safety. Its technical threshold and verification cycle will be much longer than in other fields.

In the future, with the lightweight application of new materials such as carbon fiber and the deep integration of artificial intelligence algorithms, exoskeleton robots are expected to further expand into multiple fields such as military, aerospace, and sports training after solving energy consumption and interaction problems. Continuously promoting the research and differentiated development of exoskeleton robot technology has important practical significance and strategic value for improving social production efficiency and enhancing human quality of life.

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