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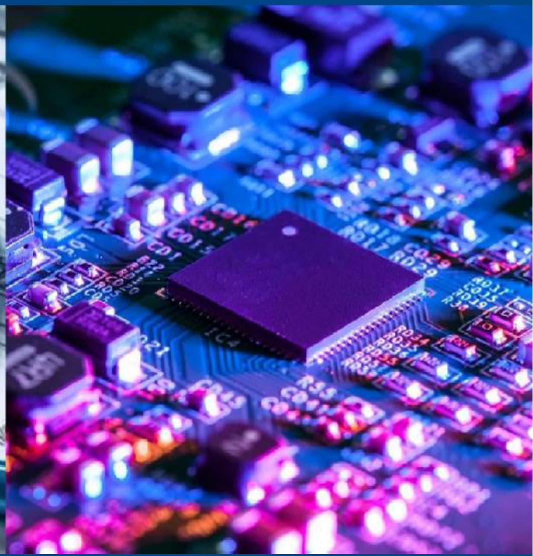

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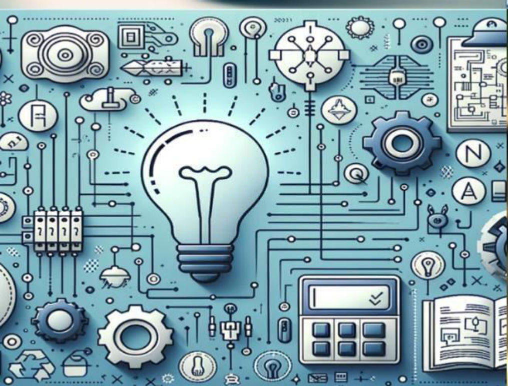

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Review on the Research Status and Development of Medical Rehabilitation Robots

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ABSTRACT: With the accelerating global population aging, the number of patients with physical and cognitive dysfunctions caused by stroke, spinal cord injury, osteoarthrosis and other diseases has been rising year by year. The traditional rehabilitation medical model is faced with prominent predicaments such as uneven resource allocation, limited treatment efficiency and insufficient personalization, which makes it difficult to meet the ever-growing demand for rehabilitation services. As a high-end intelligent equipment integrating multiple disciplines including mechanical engineering, electronic information, biomedicine, artificial intelligence and sensor technology, medical rehabilitation robots can replace or assist rehabilitation therapists to complete the whole-process services such as rehabilitation training, functional assessment and daily nursing. Relying on the core advantages of precision, standardization, high efficiency and personalization, they have become a core force to solve the predicaments of traditional rehabilitation and promote the transformation and upgrading of the rehabilitation medical industry. This paper systematically sorts out the classification and core application fields of medical rehabilitation robots, elaborates on the current research status and industrial layout of this field at home and abroad, deeply analyzes the breakthroughs and existing bottlenecks of its key technologies, and comprehensively discusses the problems and challenges faced by the industrial development. Finally, it looks forward to the future development trends, providing a comprehensive and reliable reference for the subsequent basic research, technological innovation, product development and clinical transformation in the field of medical rehabilitation robots.

I. INTRODUCTION

Rehabilitation medicine is an important part of the modern medical system, and together with preventive medicine and clinical medicine, it forms a complete medical service chain. Its core goal is to help patients with dysfunctions caused by diseases, injuries, aging and other factors restore their physiological functions to the maximum extent, improve their self-care ability, and ultimately return to family and society. In recent years, the global population aging has accelerated. According to the statistics of the World Health Organization (WHO), the proportion of the global population aged 60 and above reached 12.8% in 2023, and it is expected to exceed 22% by 2050 with a total of 2.1 billion. At the same time, the incidence of stroke, spinal cord injury and other diseases remains high, and the huge patient group has spawned an explosive demand for rehabilitation medical services.

Traditional rehabilitation medicine highly relies on the manual operation and experience of therapists. Although a mature system has been formed, it has obvious limitations: first, the shortage and uneven distribution of rehabilitation resources, the long training cycle and high threshold for therapists, especially the prominent shortage in grassroots areas, result in a large number of patients unable to receive standardized treatment; second, the treatment effect depends on experience, and the differences in operation and concept lead to uneven rehabilitation effects, making it difficult to achieve standardization; third, rehabilitation training is boring and repetitive, and patients have poor compliance, which affects the rehabilitation effect; fourth, it is difficult for manual operation to accurately assist in complex rehabilitation

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movements, which is likely to cause secondary injuries; fifth, the treatment efficiency is low, a single therapist can only serve 2-3 patients at the same time, and it is impossible to monitor and adjust the rehabilitation plan in real time.

The emergence of medical rehabilitation robots provides a new way to solve the above predicaments. As a product of the integration of multiple disciplines, it provides personalized and standardized rehabilitation services for patients through precise mechanical structures, intelligent control algorithms and sensitive perception systems, collects and analyzes rehabilitation data in real time, dynamically optimizes the plan, greatly improves the efficiency and quality of treatment, and reduces the burden on therapists at the same time. With the development of cutting-edge technologies such as artificial intelligence and brain-computer interface, the technical level of rehabilitation robots has been continuously improved, the types of products have become increasingly rich, and the application scenarios have extended from rehabilitation hospitals to nursing homes, families and communities, becoming a new growth point of the rehabilitation medical industry.

Governments of various countries attach great importance to its development. The United States has increased scientific research investment through policies such as the *National Robotics Initiative* and formed a complete industrial chain; Japan, relying on the demand of population aging, focuses on the development of portable and humanized rehabilitation robots with strong international competitiveness; Germany focuses on high precision and clinical adaptability, promoting the research and development of key technologies and standardized development. China has also included it in key documents such as the *14th Five-Year Plan for the Development of Medical Equipment Industry*. In 2025, the National Medical Products Administration optimized the approval process to support technological innovation and clinical transformation.

Based on the recent research results, industrial status and policy orientation at home and abroad, this paper systematically sorts out the classification and application fields of medical rehabilitation robots, elaborates on the research status at home and abroad, analyzes the key technical bottlenecks and industrial challenges, and looks forward to the development trends, providing a reference for the subsequent research and clinical transformation in this field and promoting the healthy and sustainable development of the industry.

II. CLASSIFICATION AND CORE APPLICATION FIELDS OF MEDICAL REHABILITATION ROBOTS

Medical rehabilitation robots can be classified in various ways according to rehabilitation parts, functional purposes, application scenarios, etc. Among them, the classification combining rehabilitation parts with functional purposes is the most in line with clinical needs. Combined with the industrial status and clinical practice, they can be divided into four categories: physical rehabilitation robots, language rehabilitation robots, cognitive rehabilitation robots and nursing rehabilitation robots, covering the whole rehabilitation process. Among them, physical rehabilitation robots are the most mature in research and the most widely used, while the other three categories are gradually developing towards refinement and intellectualization.

2.1 Physical Rehabilitation Robots

Physical rehabilitation robots are targeted at patients with physical dysfunctions caused by stroke, spinal cord injury, osteoarthrosis and other diseases. They provide services such as motor assistance, strength training and gait correction by simulating the physiological movement trajectory of the human body, helping to restore physical functions and reduce muscle spasm. According to the rehabilitation parts, they can be divided into three categories: upper limb, lower limb and trunk rehabilitation robots.

Upper limb rehabilitation robots are used to restore the functions of shoulder, elbow and other upper limb joints of patients, suitable for patients with upper limb hemiplegia, muscular weakness and other symptoms. Their core functions include passive, active, resistance and fine motor training, and the training parameters can be dynamically adjusted according to the rehabilitation stage. In the early stage of rehabilitation, passive training is provided to relieve muscle spasm; in the middle stage, active training is guided to improve muscle strength and coordination; in the later stage, resistance training is carried out to enhance exercise endurance. At present, the research focus is on lightweight, portability and refinement. Some products adopt flexible drive technology, combined with visual navigation and electromyographic signal recognition, to accurately capture patients' motor intentions. For example, the AI-driven upper limb rehabilitation robot developed by the Massachusetts Institute of Technology (MIT) in the United States analyzes patient data through electromyographic and visual sensors to dynamically adjust the training mode; the portable product developed by Tsinghua University in China can be connected with mobile phone APP via Bluetooth to realize remote rehabilitation monitoring at home.

Lower limb rehabilitation robots are used to restore the functions of lower limb joints and gait ability, suitable for patients with stroke, paraplegia and other symptoms, and are a research hotspot. They can be divided into weight-reducing gait training, exoskeleton and portable types. Weight-reducing gait training robots are applied in rehabilitation hospitals to help patients complete gait training through weight-reducing devices; exoskeleton products are easy to wear and flexible in movement, have been industrialized, and can help patients stand and walk; portable products are suitable for families and communities to carry out simple joint and gait training. The exoskeleton lower limb rehabilitation robot developed by Beihang University has reached the international advanced level in performance; the China National Rehabilitation Center has completed the first case of "spinal cord interface + exoskeleton robot" collaborative rehabilitation treatment, helping patients with high paraplegia restore their autonomous activity ability.

Trunk rehabilitation robots are used to restore patients' trunk balance ability and core muscle strength, suitable for patients with stroke, senile balance disorder and other symptoms. Their core functions include posture correction and balance training. They usually adopt seat or support structures, collect trunk posture data through sensors, and dynamically adjust the training platform. For example, the trunk rehabilitation system developed by a German company integrates EMG sensors and IMU to monitor muscle activity and trunk posture in real time; the modular product developed by Southeast University in China can flexibly combine training modules to realize multiple training modes such as sitting and standing postures.

2.2 Language Rehabilitation Robots

Language rehabilitation robots are targeted at patients with language dysfunctions caused by stroke, traumatic brain injury and other diseases, including aphasia, articulation disorder and other types. They provide services such as language training, pronunciation correction and communication assistance through speech recognition, synthesis, natural language processing and other technologies, helping to restore patients' language expression and understanding abilities.

Their core technology is speech recognition and synthesis, which can accurately collect patients' pronunciation, compare it with standard pronunciation, identify errors and formulate personalized correction plans. The training content includes pronunciation, vocabulary, sentence, dialogue and swallowing training, which are respectively suitable for patients with different types of language disorders. Swallowing training can help patients restore swallowing function and avoid the risk of choking.

In recent years, combined with artificial intelligence and VR technologies, the intelligent level of language rehabilitation robots has been significantly improved. The creation of immersive rehabilitation scenes and gamified design have improved patients' training compliance. For example, the product of Speech Therapy Solutions in the United States has a speech recognition accuracy of over 95%, can correct pronunciation errors in real time, and is widely used in rehabilitation hospitals around the world; the Chinese language rehabilitation robot developed by Southeast University in China optimizes the speech recognition algorithm to adapt to the rules of Chinese pronunciation. Clinical applications show that it can help patients restore basic language expression ability in 3-6 months. In addition, it can provide text input and speech synthesis services for patients with severe aphasia to solve the communication dilemma.

2.3 Cognitive Rehabilitation Robots

Cognitive rehabilitation robots are targeted at patients with cognitive dysfunctions caused by stroke, Alzheimer's disease and other diseases, including memory, attention, thinking ability disorders and other types. They provide services such as cognitive training, functional assessment and assisted memory through artificial intelligence, VR, gamified design and other technologies, helping to restore cognitive functions and delay decline.

Cognitive rehabilitation training is boring and highly repetitive, so the core feature of such robots is gamified design, which integrates training into interesting games to improve patients' compliance. The training content includes memory, attention, logical thinking and other training. Memory training is carried out through memory cards, digital and image memory, etc.; attention training is carried out with the help of visual tracking games, etc.; logical thinking training is realized through digital sorting, jigsaw puzzles and so on.

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Such robots can collect patients' training data, evaluate the recovery of cognitive function combined with AI algorithms, and dynamically adjust the training plan. Some products combine VR technology to create immersive scenes and brain-computer sensors to analyze cognitive status, improving the rehabilitation effect. For example, the AI cognitive rehabilitation robot system developed by the Johns Hopkins University in the United States monitors patients' status through brain-computer and visual sensors, and the rehabilitation speed is 40% faster than traditional methods; the senile cognitive rehabilitation robot developed by the University of Tokyo in Japan has a simple operation interface and is suitable for the living habits of the elderly; the product developed by Beijing Normal University in China optimizes training games and evaluation models to adapt to the cognitive characteristics of patients, achieving good clinical application effects. In addition, it also has an assisted memory function, helping patients remember important matters through voice and text reminders and reducing the burden on their families.

2.4 Nursing Rehabilitation Robots

Nursing rehabilitation robots are targeted at the elderly, the disabled, patients with severe rehabilitation and other groups. Their core functions include daily nursing, position transfer, rehabilitation assistance, health monitoring and so on, reducing the burden on nursing staff and improving patients' quality of life. The research focus is on practicality, humanization and portability, and they can be divided into four categories: transfer, care, massage and severe nursing rehabilitation robots.

Transfer robots are used to help patients with limited mobility realize position transfer, avoid secondary injuries and reduce the physical burden on nursing staff. They adopt hydraulic or electric drive, can adjust the transfer speed and strength, and are suitable for different patients. For example, the nursing transfer robot developed by Toyota in Japan accurately locates patients through intelligent navigation and is easy to operate; the portable product developed by South China University of Technology in China can be folded for storage and is suitable for rehabilitation at home and in communities.

Care robots provide daily care services such as feeding, dressing and washing for patients with limited mobility, integrating visual recognition, speech recognition, mechanical arms and other technologies. The mechanical arms adopt flexible design to avoid injury to patients. For example, the care robot of Panasonic in Japan has a voice interaction function and is suitable for the elderly; the family care robot of Haier in China can learn patients' living habits, provide personalized services and monitor physiological indicators.

Massage rehabilitation robots relieve muscle spasm and promote blood circulation by simulating manual massage techniques, assisting in restoring physical functions. They adopt multi-degree-of-freedom mechanical arms or massage rollers, can accurately locate massage parts and adjust parameters, and some have passive training functions. For example, the full-body massage rehabilitation robot launched by Midea in China combines traditional Chinese medicine techniques, has a high cost performance, and is widely used in families and nursing homes; the local massage product of a German company can relieve muscle spasm in a targeted manner and is suitable for clinical rehabilitation.

Severe nursing rehabilitation robots are applied in the Intensive Care Unit (ICU), providing services such as position adjustment, lung nursing and passive physical training for severe patients to prevent complications such as pressure sores and lung infections. They have high-precision control and safety protection functions, and can be connected with the hospital's medical system to transmit patient data in real time.

III. RESEARCH STATUS OF MEDICAL REHABILITATION ROBOTS

In recent years, a complete industrial chain of "basic research - technological research and development - product development - clinical application" has been formed in the global field of medical rehabilitation robots. Developed countries abroad (the United States, Japan, Germany, etc.) started early, with mature technology and high industrialization level, occupying the mainstream market; China started late but developed rapidly, achieving technological breakthroughs and localized substitution in some fields, with the market share increasing year by year. South Korea, the United Kingdom, France and other countries have also formed their own characteristic advantages.

3.1 Foreign Research Status

Foreign research on medical rehabilitation robots began in the 1980s. After more than 40 years of development, technological breakthroughs have been achieved in many fields, and a complete R&D and industrial system has been formed. The United States, Japan and Germany are in a leading position in the world with their own characteristics.

3.1.1 The United States

The United States is the most developed country in this field, with a complete R&D system and sufficient scientific research investment. Its research focus is on intelligent, personalized and portable rehabilitation robots, focusing on the integration of cutting-edge technologies and clinical transformation, forming a collaborative innovation model of "research institutions + enterprises + hospitals", and leading in the fields of physical, cognitive rehabilitation robots and brain-computer interface integration.

In the field of upper limb rehabilitation robots, top institutions such as MIT and Stanford University have carried out a lot of research. The flexible drive product developed by MIT combines AI algorithms and multi-sensors to realize precise training and remote rehabilitation; the modular product of Stanford University has a motion control accuracy of 0.1mm and can flexibly combine training modules. In terms of industrialization, enterprises such as Kinova and ReWalk Robotics have launched a variety of products. Kinova's Jaco upper limb rehabilitation robot is applied in more than 50 countries around the world; ReWalk's portable product can realize home rehabilitation monitoring through mobile phone APP.

In the field of lower limb rehabilitation robots, exoskeleton technology is the most mature. ReWalk Robotics' ReWalk exoskeleton robot is the world's first product certified by the FDA, which can help paraplegic patients stand and walk, and is applied in more than 200 medical institutions around the world; Ekso Bionics' Ekso GT exoskeleton robot has an adaptive gait technology and is suitable for patients in different recovery stages. In addition, Hocoma's Lokomat weight-reducing gait training robot has a weight reduction range of 0-100kg and a gait guidance accuracy of 0.5mm, which is widely used in clinical practice.

In the field of cognitive and language rehabilitation robots, the focus is on gamified and intelligent design. The cognitive rehabilitation robot of Boston University combines VR technology to create immersive scenes and dynamically adjust the training plan through brain-computer sensors; the language rehabilitation robot of Speech Therapy Solutions has a speech recognition accuracy of over 95% and provides a full range of training and communication assistance services.

In terms of cutting-edge technology exploration, the brain-computer interface rehabilitation robots developed by MIT, Stanford University and other institutions can identify patients' motor intentions through brain-computer sensors and control the movement of robots, suitable for patients with high paraplegia, and have entered the clinical trial stage; flexible drive technology has made breakthroughs, significantly improving the comfort and safety of products.

3.1.2 Japan

The proportion of the population aged 65 and above in Japan exceeds 29%, with a strong demand for nursing and elderly rehabilitation. Its research focus is on portable, humanized and low-cost rehabilitation robots, focusing on clinical adaptation and marketization, forming a collaborative model of "scientific research + enterprises", with outstanding competitiveness in the fields of nursing and lower limb rehabilitation robots, and having well-known enterprises such as Toyota, Panasonic and Cyberdyne.

In the field of nursing rehabilitation robots, Japan is in a leading position in the world. Toyota's HSR nursing robot can provide daily nursing and rehabilitation assistance services, with intelligent navigation and health monitoring functions. The elderly can control it through voice or touch; Panasonic's nursing transfer robot is driven by hydraulic pressure, with stable lifting, and has folding and weight detection functions. In addition, Panasonic's full-body massage rehabilitation robot simulates manual techniques and is suitable for the elderly and the disabled.

In the field of lower limb rehabilitation robots, the focus is on portability and humanization. The portable product developed by the University of Tsukuba weighs only 5kg and can be connected with mobile phone APP via Bluetooth, suitable for home rehabilitation; Cyberdyne's HAL exoskeleton robot is the world's first clinical application product, certified by the Ministry of Health, Labour and Welfare of Japan, which can assist patients to stand and walk, and is applied in more than 30 countries around the world. Bedridden lower limb rehabilitation robots can help bedridden patients carry out passive training to prevent complications.

In the field of elderly rehabilitation robots, they are in line with the living habits of the elderly. The cognitive rehabilitation robot of the University of Tokyo has a simple operation interface and a voice companion function to relieve the loneliness of the elderly; the physical rehabilitation robot of Waseda University is small in size and easy to operate, which can carry out basic rehabilitation training and monitor physiological indicators.

3.1.3 Germany

Germany has a profound accumulation in the fields of mechanical engineering and precision manufacturing. Its research focus is on high-precision, intelligent and modular rehabilitation robots, focusing on technical standardization and clinical practicality, with strong competitiveness in the fields of upper limb and lower limb rehabilitation robots, and having research institutions and enterprises such as the Technical University of Munich and Hocoma.

In the field of upper limb rehabilitation robots, the modular product developed by the Technical University of Munich has a motion control accuracy of 0.1mm, combined with multi-sensors, which can dynamically adjust the training mode and complete the rehabilitation assessment; Hocoma's Armeo series upper limb rehabilitation robots adopt weight-reducing devices, can be connected with the hospital's medical system, and are applied in rehabilitation hospitals in more than 40 countries around the world.

In the field of lower limb rehabilitation robots, weight-reducing gait training technology is mature. Hocoma's Lokomat robot is the world's first commercial product, with a gait guidance accuracy of 0.5mm, which can collect gait data in real time and generate evaluation reports, and is applied in more than 500 rehabilitation hospitals around the world; the exoskeleton product of the DFKI Robotics Research Institute combines AI and flexible drive technologies, easy to wear and natural in movement.

In addition, Germany has formulated a complete set of technical, safety and clinical application standards for rehabilitation robots, promoting the large-scale application of products. Data in 2023 shows that rehabilitation robots have helped 30% of the elderly restore their self-care ability, and many rehabilitation hospitals have established clinical application demonstration bases to optimize rehabilitation plans.

3.1.4 Other Countries

South Korea focuses on the R&D of portable and low-cost products, relying on enterprises such as Samsung and Hyundai. Samsung's portable lower limb rehabilitation robot is affordable, applied in families and grassroots rehabilitation institutions, and exported to Southeast Asia; Hyundai's language rehabilitation robot optimizes the Korean speech recognition algorithm to adapt to grassroots needs.

The United Kingdom focuses on the exploration of cutting-edge technologies. The implanted brain-computer interface rehabilitation robot developed by the University of Oxford can directly identify patients' motor intentions, suitable for patients with high paraplegia, and has entered clinical trials; the cognitive rehabilitation robot of the University of Cambridge optimizes the training plan through AI algorithms to improve patients' compliance.

France focuses on the integration of rehabilitation robots and clinical practice. The physical rehabilitation robot for children with cerebral palsy developed by the University of Paris VI adopts flexible drive and gamified design to protect children's bodies and improve training enthusiasm; the cognitive rehabilitation robot for Alzheimer's disease of a certain enterprise combines VR and voice interaction to help patients delay cognitive decline.

3.2 Domestic Research Status

China's research on medical rehabilitation robots began in the 1990s, initially focusing on the introduction and imitation of foreign technologies, with core technologies and components relying on imports and a low level of industrialization. Since the 21st century, driven by policy support and market demand, scientific research institutions such as Tsinghua University and Beihang University have collaborated with local enterprises such as Borui Kang and Tianzhihang, gradually realizing the transformation from "following" to "keeping pace", and leading in some fields, with the localization rate of products and the scope of clinical application continuously improving.

According to the 2024 report of the International Federation of Robotics (IFR), the global market size of medical robots reached 5.2 billion US dollars in 2023, and it is expected to exceed 7 billion US dollars by 2025; China's market size reached 850 million US dollars in 2023, accounting for 16.3% of the global total, and it is expected to exceed 1.7 billion

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US dollars by 2025, accounting for 24.3%, becoming an important growth pole in the global market. By the end of 2023, more than 1,000 rehabilitation hospitals and nursing homes in China have introduced rehabilitation robots, covering 31 provinces, autonomous regions and municipalities directly under the Central Government.

3.2.1 Basic Research and Technological Research and Development

Chinese scientific research institutions have focused on core technical fields such as mechanical design and motion control, made a series of breakthroughs, broken foreign monopolies, and improved core competitiveness.

In the field of upper limb rehabilitation robots, the flexible drive product developed by Tsinghua University combines visual navigation and multi-sensors to realize precise training and remote rehabilitation; the modular product of Harbin Institute of Technology has a motion control accuracy of 0.2mm and a rehabilitation assessment function; the portable product of Shanghai Jiao Tong University has a low cost and can realize home rehabilitation monitoring through mobile phone APP.

In the field of lower limb rehabilitation robots, remarkable achievements have been made, and exoskeleton technology has realized localized substitution. The exoskeleton robot developed by Beihang University weighs only 8kg, with performance equivalent to foreign products and a price of 1/3-1/2 of foreign products, which has passed medical device certification and been applied in clinical practice; the weight-reducing gait training robot of the Institute of Automation of the Chinese Academy of Sciences has a weight reduction range of 0-100kg and a gait guidance accuracy of 0.5mm, which is widely used in rehabilitation hospitals; the China National Rehabilitation Center has completed the first case of "spinal cord interface + exoskeleton robot" collaborative rehabilitation, reaching the world's leading level.

In the field of cognitive and language rehabilitation robots, the focus is on localized adaptation. The language rehabilitation robot of Southeast University optimizes the Chinese speech recognition algorithm with an accuracy of over 92%, achieving good clinical application effects; the cognitive rehabilitation robot of Beijing Normal University combines VR and gamified design to adapt to the cognitive characteristics of patients, and is applied in nursing homes and rehabilitation hospitals.

In the field of nursing rehabilitation robots, the focus is on practicality and low cost. The transfer robot of South China University of Technology has a cost of 1/4 of foreign products and is suitable for grassroots rehabilitation institutions; the massage rehabilitation robots of Haier and Midea combine traditional Chinese medicine techniques, have a high cost performance, and occupy a large domestic market share; the severe nursing robot of the Shenyang Institute of Automation of the Chinese Academy of Sciences can be connected with the hospital system and is suitable for ICU clinical rehabilitation.

3.2.2 Product Development and Clinical Application

The industrialization level of China's rehabilitation robots has been continuously improved. Local enterprises have launched a variety of clinical products, realized localized substitution, and formed a complete product system and clinical application network.

In the field of upper limb rehabilitation robots, products of enterprises such as Borui Kang and Daai Robot have passed medical device certification, with performance equivalent to foreign products and more advantageous prices, applied in more than 200 rehabilitation hospitals across the country; the modular product of Daai Robot can flexibly combine training modules and has a rehabilitation assessment function, which is widely used in clinical practice.

In the field of lower limb rehabilitation robots, exoskeleton and weight-reducing gait training products of enterprises such as Tianzhihang and Borui Kang are widely used in clinical practice. Tianzhihang's exoskeleton robot has achieved a breakthrough in export, sold far to Southeast Asia and Europe; Daai Robot's weight-reducing gait training robot can dynamically adjust training parameters to adapt to different patients, achieving good clinical effects.

In the field of cognitive and language rehabilitation robots, the language rehabilitation robot of Nanjing Weisi Medical optimizes the Chinese recognition algorithm and has a data statistics and analysis function, applied in many language rehabilitation centers across the country; the cognitive rehabilitation robot of Beijing Xinrui Jukang combines VR and gamified design to carry out cognitive training through interesting games, suitable for patients with stroke, Alzheimer's

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disease and other symptoms. In clinical application, it has helped patients significantly improve their memory, attention and other cognitive functions, winning recognition from medical staff and families.

IV. KEY TECHNOLOGIES AND EXISTING BOTTLENECKS OF MEDICAL REHABILITATION ROBOTS

The development of medical rehabilitation robots depends on the integrated breakthrough of multi-disciplinary core technologies. At present, the key technologies are mainly concentrated in four fields: mechanical design and drive, sensor and perception, control algorithm and artificial intelligence, and biomedicine integration. Although remarkable progress has been made, there are still many technical bottlenecks restricting the high-quality development of the industry.

4.1 Development Status of Key Technologies

Mechanical design and drive technology is the foundation of rehabilitation robots, with the core goal of achieving lightweight, flexibility and humanization to adapt to the physiological structure and movement characteristics of the human body. At present, rigid mechanical structures are still widely used, but flexible drive technology is developing rapidly. Adopting flexible materials and drive components to simulate the contraction and relaxation characteristics of human muscles, it improves the comfort and movement naturalness of patients and reduces the risk of secondary injuries. For example, the flexible upper limb rehabilitation robots in the United States and Germany adopt pneumatic flexible drive technology to realize precise and gentle motion assistance; the flexible exoskeleton robot developed by Chinese scientific research institutions adopts flexible rope drive, which greatly reduces the weight and significantly improves the wearing convenience. At the same time, modular design has become an important development direction. Through detachable and combinable modules, it adapts to the needs of different patients and different rehabilitation stages, improving the versatility and economy of products.

Sensor and perception technology is the core to realize the intellectualization and precision of rehabilitation robots, used to collect patients' physiological signals, motion data and environmental information, providing a basis for the adjustment of training plans. At present, commonly used sensors include electromyographic sensors, force sensors, Inertial Measurement Units (IMU), visual sensors, etc. Electromyographic sensors can collect patients' muscle activity signals and capture motor intentions; force sensors are used to detect the acting force in rehabilitation training to avoid injuries caused by excessive force; IMU monitors patients' limb posture and motion trajectory in real time; visual sensors assist in locating patients' limb positions and capturing motion actions through image recognition. Multi-sensor fusion technology is widely used to integrate and analyze data from different types of sensors, improving the accuracy and comprehensiveness of data collection. For example, the combination of electromyographic sensors and visual sensors can more accurately identify patients' motor intentions and realize precise guidance of active rehabilitation training.

Control algorithm and artificial intelligence technology are the core driving forces for the intelligent upgrading of rehabilitation robots, used to process perception data, control mechanical movement and optimize rehabilitation plans. In terms of control algorithms, the traditional PID control algorithm is still in application, but advanced algorithms such as adaptive control, fuzzy control and sliding mode control are gradually popularized, which can dynamically adjust control parameters according to patients' rehabilitation status and motion data to realize personalized motion control. The integrated application of artificial intelligence technology has greatly improved the intelligent level of rehabilitation robots. Machine learning algorithms can mine rehabilitation rules by analyzing patients' training data and automatically optimize rehabilitation training plans; deep learning algorithms are used for speech recognition and image recognition to improve the pronunciation recognition accuracy of language rehabilitation robots and the scene recognition ability of cognitive rehabilitation robots; reinforcement learning algorithms allow robots to continuously adjust training strategies through interactive feedback with patients to adapt to individual differences of patients. In addition, as a cutting-edge direction, brain-computer interface technology realizes the direct interaction between brain neural signals and robots, providing a new rehabilitation path for patients with severe dysfunctions such as high paraplegia, and has currently entered the clinical trial stage.

Biomedical integration technology is the key for rehabilitation robots to achieve clinical adaptation. It combines the knowledge of rehabilitation medicine, biomechanics, human anatomy and other disciplines with engineering technology to ensure that the motion trajectory and training intensity of robots conform to the laws of human physiology and the requirements of rehabilitation medicine. For example, through biomechanical analysis, optimize the motion trajectory of robots, simulate the normal physiological movement of the human body, and improve the rehabilitation effect; combine the staged treatment concept of rehabilitation medicine, design training modes and parameters for different rehabilitation stages to realize the standardization and personalization of rehabilitation training. At the same time, rehabilitation assessment technology is integrated with biomedicine. By collecting patients' physiological data and training data, combined with the rehabilitation medicine assessment standards, it automatically generates rehabilitation assessment reports, providing a scientific basis for doctors to formulate and adjust rehabilitation plans.

4.2 Existing Technical Bottlenecks

Flexible drive technology is still imperfect. At present, the strength, durability and stability of flexible materials are insufficient, and wear and aging are prone to occur after long-term use, affecting the service life of products; the control accuracy of flexible drive is low, making it difficult to achieve precise control of complex and fine movements, especially in fine motor rehabilitation training, which cannot meet clinical needs. In addition, the high cost of flexible robots restricts their market promotion and popularization, making it difficult to adapt to the needs of grassroots rehabilitation institutions and ordinary families.

Sensor and perception technology has shortcomings. High-end sensors rely on imports, and the accuracy, sensitivity and stability of domestic sensors are quite different from the international advanced level, resulting in insufficient accuracy of data collection and affecting the optimization effect of rehabilitation plans; multi-sensor fusion technology still needs to be improved, there are problems such as redundancy and conflict in data from different sensors, the data processing efficiency is low, and it is difficult to achieve real-time and precise perception; the lack of perception technology for special patients (such as patients with skin sensitivity and limb deformity) makes it impossible to accurately collect their physiological signals and motion data, with poor adaptability.

The integration depth of control algorithm and artificial intelligence is insufficient. At present, the AI application of rehabilitation robots is mostly in the primary stage, the generalization ability of machine learning algorithms is weak, making it difficult to adapt to the individual differences of patients of different ages, different conditions and different rehabilitation stages; the automatic optimization ability of rehabilitation plans is limited, mostly relying on manual adjustment by doctors, and it is impossible to realize fully autonomous personalized rehabilitation; brain-computer interface technology still faces many challenges, the non-implantable brain-computer interface has low signal collection accuracy and poor anti-interference ability, the implantable brain-computer interface has insufficient safety, invasiveness and long-term stability, and the high cost makes it difficult to achieve clinical popularization.

The integration of biomedicine is not in-depth enough. The design of rehabilitation robots is not closely combined with the clinical needs of rehabilitation medicine. The motion trajectory and training mode of some products do not conform to the laws of clinical rehabilitation, resulting in poor rehabilitation effects; rehabilitation assessment technology is not perfect, focusing on motor function assessment, lacking a comprehensive assessment of cognitive function, language function and psychological state, and unable to fully reflect the rehabilitation status of patients; the insufficient collaborative innovation between different disciplines and the insufficient communication and cooperation between engineering and technical personnel and rehabilitation medical experts lead to the disconnection between product R&D and clinical needs.

V. PROBLEMS AND CHALLENGES FACED BY THE DEVELOPMENT OF MEDICAL REHABILITATION ROBOT INDUSTRY

In addition to technical bottlenecks, the medical rehabilitation robot industry is hindered by multiple non-technical challenges that impede its large-scale and high-quality development, demanding joint efforts from governments, research institutions, enterprises and medical institutions for resolution. In terms of policy supervision, the global regulatory system is flawed: China has issued supportive policies but suffers from unclear classification of rehabilitation robots, lengthy approval processes, inadequate post-marketing long-term monitoring, and an incomplete medical insurance reimbursement mechanism, which pushes up R&D costs and limits market demand, while inconsistent international regulatory standards increase enterprises' cross-border circulation and certification costs. Clinical transformation is plagued by low efficiency due to the phenomenon of "prioritizing R&D over clinical practice", with some research results decoupled from clinical needs, a lack of unified verification and evaluation standards, insufficient integration of robotic and manual rehabilitation, inadequate professional training for therapists, and low patient acceptance and compliance. Market promotion is obstructed by high product prices caused by imported core components, limited application scenarios concentrated in large medical institutions, an imperfect after-sales service network especially in grassroots areas, and an irregular market competition order with inferior imitation products disrupting the industry. The industry is

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also severely short of interdisciplinary compound talents: universities offer single-discipline programs lacking integrated training, school-enterprise collaboration and practical bases are insufficient, technical personnel and rehabilitation therapists lack effective cooperation due to professional knowledge gaps, and the loss of high-end talents to developed countries further exacerbates the talent predicament.

VI. FUTURE DEVELOPMENT TRENDS OF MEDICAL REHABILITATION ROBOTS

Driven by cutting-edge technological progress, evolving market demand and policy guidance, medical rehabilitation robots will advance toward intelligence, flexibility, personalization, portability and multi-scenario application, with in-depth interdisciplinary integration and collaborative innovation becoming the core driving force for industrial upgrading. Intelligence will be further enhanced through the deep integration of artificial intelligence, big data and brain-computer interface (BCI) technologies, enabling robots to achieve autonomous learning, adaptive personalized rehabilitation plans, and clinical popularization of BCI with improved accuracy and reduced costs, while seamless connection with hospital medical systems and cloud platforms will build an integrated "online + offline" rehabilitation service model. Flexibility and humanization will become mainstream in design: breakthroughs in flexible drive technology will shift robots from rigid to flexible structures with optimized modular and lightweight design, and human-centered upgrades will feature user-friendly interfaces for special groups, gamified and immersive training modes, and emotional interaction functions to boost patient compliance. Personalized rehabilitation services will cover the entire patient journey, with real-time dynamic adjustment of training plans based on multi-sensor data and in-depth collaboration with manual rehabilitation, alongside the development of customized robots for specific patient groups. Application scenarios will expand from large hospitals to grassroots medical institutions, nursing homes and families, with home rehabilitation emerging as a key growth point and robots extending to rehabilitation prevention, driving the shift from "disease rehabilitation" to "health maintenance". Moreover, interdisciplinary integration will be strengthened to form a closed-loop system of R&D, clinical verification, product optimization and market promotion, and international collaboration will be deepened for joint cutting-edge research and unified regulatory standards, facilitating the coordinated development of the global industry.

VII. CONCLUSION

As a high-end intelligent device integrating multiple disciplines, medical rehabilitation robots are a core force in addressing the predicaments of traditional rehabilitation medicine and promoting the transformation and upgrading of the rehabilitation medical industry, providing high-quality and convenient rehabilitation services for patients with dysfunctions in physical, language, cognitive and nursing rehabilitation through their advantages of precision, standardization, high efficiency and personalization. The global medical rehabilitation robot industry is developing rapidly: developed countries such as the US, Japan and Germany, with an early start, mature technologies and a complete R&D and industrial system, lead in cutting-edge technology exploration and clinical application, while China, though starting late, has achieved a shift from "following" to "keeping pace" and even "leading" in some fields under policy support and the joint efforts of research institutions and enterprises, with continuous breakthroughs in core technologies, rising localization rates, expanding clinical applications, and emerging as an important growth pole in the global market. Despite facing multiple challenges including technical bottlenecks in flexible drive and high-end sensors, an imperfect policy supervision system, low clinical transformation efficiency, market promotion obstacles and a shortage of compound talents, the industry is poised for healthy and sustainable development with the continuous breakthrough of cutting-edge technologies such as artificial intelligence and BCI, and the joint efforts of governments, research institutions, enterprises and medical institutions. These efforts will address industrial bottlenecks, improve regulatory systems, standardize market competition, and expand the talent team, enabling the widespread popularization of medical rehabilitation robots at the grassroots level and in families, providing stronger support for the progress of rehabilitation medicine, helping more patients with dysfunctions restore physiological functions, improve quality of life, and ultimately achieve the goal of returning to family and society.

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