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From Passive Assistance to Neural Integration: A Study on the Technical Evolution of Rehabilitation Robots

Jianye Zeng

School of Future Technology, Dongguan City University, Dongguan, China
18927527891@163.com

Abstract. With the intensifying trend of global population aging, the incidence of neurological diseases such as stroke and spinal cord injury has risen significantly, leading to an increasingly prominent contradiction between the surge in rehabilitation medical demand and the shortage of professional treatment resources. Therefore, developing efficient and accessible rehabilitation assistive devices has become an urgent social need. This paper mainly investigates the evolution trajectory and other key technical mechanisms of rehabilitation robot technology from early passive motion assistance to neural integration models based on biosignals and motion prediction based on machine learning. The research aims to clarify the development history of rehabilitation robot technology, evaluate the clinical effectiveness and existing bottlenecks of current neural integration technology and artificial intelligence-assisted technology in promoting neuroplasticity, and provide a theoretical basis and development direction for building the next generation of rehabilitation systems with adaptive capabilities. This study adopts bibliometric analysis and technical comparison methods to systematically review core patents and academic achievements before 2025; combines typical clinical cases to compare the differences among three generations of technical architectures: passive assistance, active interaction, and neural integration; and comprehensively evaluates the logic and future trends of technical evolution through an interdisciplinary perspective (robotics, neuroscience, rehabilitation medicine).

Keywords: Rehabilitation Robots, Neural Integration, Technical Evolution, Human-Computer Interaction

1. Introduction

The theoretical foundation of rehabilitation robots originates from the Motor Relearning Programme (MRP) proposed by Professors Janet Carr and Roberta Shepherd in the 1980s. With the intensifying global population aging and the rising incidence of stroke and spinal cord injury, developing efficient and accessible rehabilitation assistive devices has become an urgent social need to resolve the contradiction between the surge in rehabilitation medical demand and the shortage of professional treatment resources. Clarifying the technical development history and evaluating existing bottlenecks is crucial for building the next generation of rehabilitation systems with adaptive capabilities. This research differs from a purely technical report; instead, it adopts an interdisciplinary perspective (robotics, neuroscience, rehabilitation medicine) to systematically review core patents and academic achievements before 2025. The research not only focuses on the technology itself but also deeply evaluates the clinical effectiveness of neural integration technology and artificial intelligence-assisted technology in promoting neuroplasticity, and specifically points out the concrete obstacles in the current technology regarding "medical-engineering integration" and industrial implementation, providing a logically clear theoretical basis for technical evolution.

2. Definition and historical coordinates of rehabilitation robots

2.1. Conceptual definition and scope of rehabilitation robots

In the 1980s, Professors Janet Carr and Roberta Shepherd proposed the MRP therapy based on neuroplasticity and motor learning [1]. This theoretical system regards the recovery of function after neurological injury as a relearning process, based on active patient participation, oriented towards functional movements, and emphasizing repeated reinforcement according to scientific methods. Utilizing brain plasticity as an important attribute of cranial nerves, information reconstruction from damaged residual parts and regeneration of non-damaged tissues can restore lost functions through relearning. Since the recovery process depends on repeated input and adjustment of movement patterns, new neural networks or programs are ultimately formed. This leads to varying recovery effects in manual MRP therapy, and the number of relevant practitioners is far less than the demand. Therefore, to solve this series of problems, rehabilitation robots emerged based on the above theoretical mechanisms, aiming to achieve specific neural function training and function recovery. Through high-intensity, repetitive input, they accelerate the promotion of neural remodeling and functional recovery.

2.2. Development of rehabilitation robot technology in the past and recent two decades

2.2.1. Technical exploration of rehabilitation robots before 2006

The first upper limb rehabilitation robot was introduced at the Massachusetts Institute of Technology in 1991, named MIT-Manus [2]. This robot had a relatively simple structure, featuring a five-link mechanical design with 2 degrees of freedom, capable of driving the patient's shoulder and elbow movements. The patient was connected to the mechanical system through a handheld end effector. While the patient performed movement training, MIT-Manus could display movement content and performance results on the screen in real-time.

In 1992, BOLDT JOYCE ANN from the United States first proposed a patent for wearable rehabilitation robots [3]. This patent provided assistance for two modes: active assistance control and passive process control for the wearer, and successfully achieved that the exoskeleton mechanical joints were located outside the human biological joints, but the rotation centers were precisely aligned with the biological joint centers. This solved the problem of harmful forces caused by the mismatch between exoskeleton joints and human joint rotation centers in previous technologies.

In 1995, the HAL prototype machine was developed by the Cybernics Research Center at the University of Tsukuba, Japan [4]. As an early exoskeleton power suit, it captured surface biosignals of the skin through sensors and activated the servo system to drive electric motors for rapid action. With HAL's assistance, users could perform normal daily activities while also completing high-difficulty actions such as climbing, grasping, and lifting heavy objects.

At the end of the 20th century, Zhang Xiufeng and others from Tsinghua University in China pioneered the development of an upper limb rehabilitation robot named UECM. This robot consisted of a training mechanical arm and arm support, capable of achieving arm movement training on a 2D plane.

In 2001, the predecessor of ReWalk Robotics applied for a gait movement device patent. Notably, this patent was based on trunk tilt intention recognition control technology. The control unit detected the user's natural forward lean of the body through sensors, analyzing tilt angle, angular velocity, and acceleration, thereby driving the lower limb exoskeleton to execute corresponding gait movements.

In 2004, Professor Yoshiyuki Sankai from the University of Tsukuba, Japan, released HAL-5 and founded Cyberdyne Company. HAL-5 was the first exoskeleton to achieve non-invasive bio-driven "mind control," and as the world's first medically certified rehabilitation exoskeleton, it systematically realized medical-engineering integration design, laying the foundation for subsequent productization.

In 2005, Sanchez and others from the University of California developed a five-degree-of-freedom upper limb rehabilitation robot system called T-WREX, combining Virtual Reality (VR), electromyography, and other technologies, including correctors, grip sensors, and VR software. However, this device had a limited range of motion. Later, the team designed a six-degree-of-freedom pneumatic robot. Compared to T-WREX, it could achieve overall upper limb movement, add grip sensors, and provide greater assistance.

In 2006, Yang and others from Harbin Engineering University developed a four-link series robot based on foreign rehabilitation robot research foundations, capable of simultaneously achieving different mode rehabilitation training for left and right hands. Also in this year, China successively proposed related patent applications, marking China's entry into the initial development stage.

2.2.2. Technical development achievements from 2006 to 2025

In 2007, Rex Bionics from New Zealand developed the Rex support-free independent walking rehabilitation exoskeleton, allowing users to use their hands for work and then engage in other activities.

In 2009, Berkeley Bionics from the United States and Lockheed Martin jointly developed the lightweight design intelligent bionic rehabilitation exoskeleton robot eLEGS using Human Universal Load Carrier (HULC) technology. In the same year, Harbin Institute of Technology in China developed a five-degree-of-freedom exoskeleton robot system that achieved motion control of the affected limb by collecting electromyography signals from the user's healthy side.

In 2011, Berkeley Bionics from the United States changed its name to Ekso Bionics and developed Ekso GT based on eLEGS. Ekso GT was equipped with Variable Assist intelligent software that provided the necessary power to both sides of the patient's body through the control power system, stimulating patient's potential. Shanghai Jiao Tong University in China developed a non-driven six-degree-of-freedom upper limb rehabilitation robot. Equipped with a gravity compensation device, it had no external drive and provided impedance through springs, which had a promoting effect on muscle strength improvement during the hemiplegia recovery period. In the same year, the Chinese Academy of Sciences and the University of Science and Technology of China developed a lower limb exoskeleton robot. This robot set corresponding degrees of freedom at the hip, knee, ankle, and sole of the foot, and was equipped with sensors and encoders at the knee and hip joint positions. After the exoskeleton robot "understood" the user's thoughts, it controlled the corresponding servo motors of the robot to rotate, driving leg movements, thereby helping the user walk.

In 2012, Raytheon Company successfully developed the second-generation exoskeleton robot XOS2. This robot could complete complex actions such as ball juggling. It introduced image processing technology, capturing the patient's limb movement trajectory through cameras, and applied functional electrical stimulation to the patient's muscles, achieving the effects of promoting muscle contraction and optimizing rehabilitation efficacy.

In 2015, ReWalk Robotics from Israel released ReWalk Personal 6.0, which used lighter plastic materials and changed the backpack-style battery compartment to be installed on the hip side, reducing the burden feeling while increasing wearing comfort and gait control capability.

In 2016, Shanghai Fourier Intelligence in China released its exoskeleton prototype robot. This product was based on a self-developed bipedal simulation modular design. In the same year, Jianjiao Technology Company designed an open rehabilitation exoskeleton robot. This platform mainly consisted of two parts: hardware composed of environmental sensors, human body sensors, and a power structure, and software composed of human-computer interaction commands and algorithms and a cloud engine. This open rehabilitation exoskeleton robot had a battery life of at least one week and achieved following walking, climbing slopes and stairs, and self-balancing.

In 2017, Maibu Robot from China developed the Maibu BEAR-H1 exoskeleton robot, which had 6 joints with powered bilateral hip, knee, and ankle, plus a hip rotation auxiliary joint. Through multiple sensors and biomechanical model analysis of the patient's gait data and plantar pressure perception, it intelligently adapted correction force and step speed, making rehabilitation training more intelligent and precise.

In 2018, EXO-UL8 was an upper limb rehabilitation exoskeleton system developed by the University of California, USA. Its core advantages lay in high-degree-of-freedom design, flexible admittance control, and an innovative asymmetric dual-arm training mode [5]. It could quantify the rehabilitation process through rich sensor data. However, the system still faced technical challenges in inertia compensation, intention recognition sensitivity for specific actions, and preventing patient dependency. In the same year, Honda from Japan developed the Honda Walking Assist device. Angle sensors perceived hip joint movement, transmitted data to the processor for analysis in real-time, recorded walking parameters, and connected to a mobile APP.

In 2019, China's Fourier Intelligence upgraded the X2 exoskeleton. The upgraded exoskeleton rehabilitation robot adjusted movement angle, speed, and gait trajectory through the patient's movement state and movement intention. The University of Padua in Italy, based on the theoretical basis of combining sensory feedback with motor imagery, designed a hand exoskeleton robot. During hand function rehabilitation, vibration and tactile stimulation methods were used to improve hand grasping training based on motor imagery. However, the relationship between vibration points and action completion rate was not yet clear and required further research. In the same year, the Massachusetts Institute of Technology Boston Branch designed an anthropomorphic soft robotic hand rehabilitation robot characterized by low cost, customizability, and 3D printing. Finger activity range and fingertip force experiments showed that this robot could assist patients in reaching the normal range.

In 2020, Ionut and others from the University of Oradea, Romania, designed an asymmetric underactuated exoskeleton robot system based on the human body structure. After multiple verifications, the researchers pointed out that this robot might also be extended to other fields, such as home environments, industry, aerospace, and other areas.

In 2021, Hangzhou Chengtian Technology Development Co., Ltd. in China developed the UGO series products. This series of robots adopted a combination of mobile framework and exoskeleton for the entire system, adopting three walking training modes: passive mode, active mode, and damping mode. It could maintain safety and stability during the patient's wearing training process. It incorporated more than 50 sensors to perceive the environment, robot, and user, achieving comprehensive protection and intelligent control.

In 2022, Fu Cuiyao from Nanchang University designed a lightweight fully-driven four-degree-of-freedom upper limb rehabilitation robot system. It could switch between left and right-hand modes and adjust joint size. In the same year, Jiao Zongqi and others proposed a nine-degree-of-freedom rehabilitation and life-assist upper limb robot. This robot consisted of a seven-degree-of-freedom working arm and a two-degree-of-freedom suspension arm, conducting rehabilitation training and life assistance separately. In rehabilitation mode, the robot closely matched human body degrees of freedom; in life assistance mode, the two-degree-of-freedom suspension arm could achieve a normal activity range and left-right hand interchange.

In 2024, Wu Tong and others from Beijing Institute of Technology in China proposed a variable impedance control method. They collected the user's electromyography signals as input conditions, recognized movement intention, and obtained movement angles through forest algorithms to conduct rehabilitation training.

3. Challenges and future paths

3.1. Current technical bottlenecks

Rehabilitation robots currently face four major technical bottlenecks: hardware structure, control perception, clinical evaluation, and industrialization costs.

In terms of hardware structure, early and some existing exoskeletons mostly adopted rigid materials such as aviation hard aluminum alloy and titanium alloy, resulting in large volume and heavy weight. Some upper limb rehabilitation robots had limited degrees of freedom, unable to fully simulate complex limb movements, limiting their application scope.

In terms of control and perception, there existed inertia compensation problems as pointed out in EXO-UL8 research. Exoskeleton links still had uncompensated inertia, affecting the compliance of human-computer interaction. Meanwhile, due to limited sensor precision, biosignals (Electroencephalogram EMG/ Electromyogram EEG) had a low signal-to-noise ratio, easily affected by sweat, environment, and individual differences, leading to limited model prediction accuracy. Physical signals such as angle and force, although stable, also had latency. Furthermore, synchronous fusion and real-time processing of multi-source information posed challenges. For example, the US7153242 patent mentioned that tilt sensors had a relatively low signal-to-noise ratio in early technology. Existing systems were mostly based on preset trajectories, lacking adaptive capability to patient dynamic changes. Patients might exhibit "slacking" phenomena, relying on device assistance rather than actively exerting force.

In the current rehabilitation robot field, there was a general lack of clear standardized evaluation standards, making rehabilitation effects difficult to feedback through intuitive data. Meanwhile, products had low levels of clinical evidence. For example, clinical research evidence for application in the acute phase of stroke was still insufficient, mostly small-sample observational studies, lacking large-scale multi-center randomized controlled trials. Furthermore, related products lacked strict safety definitions and real-time safety monitoring and incident alarm systems.

Current prices were generally between 100,000 to 150,000 US dollars. Hardware complexity, expensive materials, and difficulty in mass production hindered large-scale marketization. Meanwhile, the number of patent applications from universities and research institutes exceeded those from enterprises, but the degree of technology industrialization was low, and domestic innovation subjects had insufficient layout in the international market.

3.2. Social and ethical obstacles

In addition to technical-level problems, there were also some social and ethical issues that we had not yet resolved. High equipment costs, treatment fees, and the lack of standardization of rehabilitation robot treatment charges internationally made rehabilitation robots difficult to include in medical insurance or popularize to the grassroots level. This might lead to only a few people being able to enjoy advanced technology, exacerbating inequality in medical resource distribution. Meanwhile, in the absence of strict safety definitions and monitoring systems, once an accident occurred, the attribution of responsibility (physician, manufacturer, or patient) was still unclear. Multi-modal data collection (such as brain electricity, myoelectricity, movement data), patient privacy data protection, and ethical use were also potential issues.

3.3. Possible research directions for the next ten years

In terms of material structure, carbon fiber, titanium alloy, and new plastic materials should be adopted to optimize structural topology, reducing overall mass and size.

In terms of drive methods, pneumatic muscles, cable drive, and variable stiffness compliant actuators should be applied to reduce rotational inertia, improving wearing comfort and human-computer interaction compliance.

In terms of control and perception, with the development of artificial intelligence technology, the advantages of combining physical signals and biosignals (EMG+EEG+force sensation) should be utilized. Deep learning algorithms (such as fuzzy neural networks) should be used to improve the accuracy and real-time performance of movement intention recognition. Variable impedance, variable admittance, and adaptive control strategies should be developed, enabling robots to dynamically adjust assistance intensity according to the patient's rehabilitation process, achieving "assistance on demand." Meanwhile, the technical fusion of brain-computer interfaces and rehabilitation robots should be explored. Non-invasive BCI algorithms should be optimized to improve signal recognition rates, achieving more precise "mind control" and promoting neural remodeling.

Exploration will also be conducted in rehabilitation environments. Future robots will not only focus on motor function but will also combine Virtual Reality (VR) and Augmented Reality (AR) technologies to simultaneously train patients' brain cognitive abilities and stimulate damaged nerve recovery. Voice recognition and emotion perception functions should be added to create a positive and relaxed atmosphere, improving patient compliance and enthusiasm. Or, with the development of communication technology and portable devices, rehabilitation will extend to homes and communities, achieving remote and online centralized management, reducing treatment costs.

The clinical effects of equipment use also require more high-quality multi-center clinical studies to be conducted, quantitative evaluation standards and safety monitoring systems to be formulated, and promoting technology iteration.

4. Conclusion

Reviewing the full text, this paper mainly explored the evolution trajectory and key mechanisms of rehabilitation robot technology from early passive motion assistance to neural integration models based on biosignals and motion prediction based on machine learning. The research aimed to clarify the technical development history, evaluate the clinical effectiveness and bottlenecks of existing technology in promoting neuroplasticity, and provide theoretical basis for building the next generation of rehabilitation systems with adaptive capabilities.

After experiencing three generations of transformation: "passive assistance, active interaction, neural integration," the core lies in continuously improving the compliance of human-computer interaction and the accuracy of intention recognition. Currently, it faces four major bottlenecks: cumbersome hardware structure, insufficient control perception, lack of clinical evaluation, and high industrialization costs. Meanwhile, high costs lead to unequal distribution of medical resources, and ethical issues such as responsibility attribution and privacy protection have not yet been resolved.

Although this paper fully analyzed rehabilitation robots and the fields involved, the discussion on social and ethical obstacles was relatively brief, without deeply proposing specific ethical framework suggestions or solutions for responsibility division.

In future research, directions that need to be explored include: adopting carbon fiber, cable drive, and variable stiffness compliant actuators to reduce rotational inertia and improve wearing comfort and human-computer interaction compliance; combining physical signals and biosignals, utilizing deep learning algorithms such as fuzzy neural networks; optimizing non-invasive brain-computer interfaces to improve signal recognition rates and achieve more precise "mind control" to more effectively promote neural remodeling.

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