Proceedings of the 2nd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/62/20240447

Current research on exoskeletal lower limb rehabilitation robots

Zhihao Wei

Shenyang Institute of Science and Technology, No. 30, Quanyun Second West Road, Hunnan District, Shenyang City, Liaoning Province, 110167, China.

13904281902@163.com

Abstract. Stroke is characterized by a high incidence rate, and walking is one of the essential human functions. Lower limb rehabilitation robots can offer safe and effective walking training to patients with walking impairments caused by conditions such as neural injuries, aiding in their recovery or assisting in walking. For the needs of patients themselves, restoring their physical state and motor function as much as possible is the primary purpose of rehabilitation, and rehabilitation efficiency is an important factor affecting the quality of life of patients after surgery. Research on exoskeleton robots varies both domestically and internationally, each with its own unique characteristics and features. This paper outlines the design of lower limb rehabilitation robots based on gait analysis and control methods. It also provides an overview of the current state of research on lower limb exoskeleton robots in terms of degrees of freedom, actuation methods, and clinical applications. Furthermore, it offers insights into future directions for research on lower limb exoskeleton robots.

Keywords: Stroke, Exoskeleton Robots, Rehabilitation Robots, Rehabilitation Training.

1. Introduction

Stroke is characterized by a high incidence rate, with the ability to walk being one of the functions that patients hope to recover. Rehabilitation training following a stroke affects the adaptability of the motor system, presenting a range of issues such as high intensity and repetitiveness. With the development of robotics and electronic information technology, an increasing number of rehabilitation robots have emerged, saving a substantial amount of human labor. Moreover, these rehabilitation robots are progressively integrating into clinical rehabilitation therapy. Based on their functions, they can be categorized into lower limb rehabilitation robots and upper limb rehabilitation robots. This paper provides an overview of the characteristics and shortcomings of lower limb rehabilitation robots.

2. Exoskeletal Lower Limb Rehabilitation Robots

Research on exoskeleton robots in China started relatively late. However, with continuous innovation from research institutions and enterprises, many new exoskeleton robots with excellent performance and wide-ranging applications have emerged. In 2004, the Hefei Institute of Intelligent Machines of the Chinese Academy of Sciences conducted research, leading to the development of China's first motor-driven exoskeleton robot, which was designed to enhance the speed by modifying the WPAL (Walking Pattern Analysis and Locomotion) and improving its biomechanical model for human motion. The force

© 2024 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/62/20240447

control model was also improved to reduce muscle fatigue [1], marking a new direction for exoskeleton robot research in China. However, it's worth noting that this robot was only tested in the laboratory and not yet applied for practical walking in real-life settings.

2.1. Domestic Lower Limb Exoskeleton Rehabilitation Robots

In 2014, Beijing University of Aeronautics and Astronautics successfully developed the first domestic exoskeleton robot, named AiLegs, capable of enabling paraplegic and hemiplegic patients to wear and walk for rehabilitation purposes (as shown in the figure below). Its primary applications include spinal cord injuries, spinal cord inflammation, cerebral palsy resulting from brain injuries, rehabilitation for patients with hemiplegia due to stroke, post-joint surgery recovery, and muscle weakness. This robot can be used for both active and passive training, supervised by rehabilitation experts or conducted by patients themselves. It employs a biomimetic gait control system that adapts to different pathological features, enabling coordinated and enhanced motor function. Through specialized design, it significantly improves the efficiency of patient rehabilitation. This robot offers precise control, accommodates various disease courses and conditions, and meets individualized exercise needs of patients [2].

In the 2022 Winter Paralympics held in Beijing, AiLegs successfully assisted patients with high-level paraplegia in carrying the torch, allowing patients who were previously unable to care for themselves to participate in the torch relay. The team also developed AiWalker, a novel form of exoskeleton robot, by integrating AiLegs onto a secure mobile platform with four wheels. This design secures the patient's waist for balance control during movement, ensuring safety during training and providing long-term walking rehabilitation on real ground surfaces. It is widely applicable, with a lengthy rehabilitation period, suitable for diseases caused by spinal cord injuries, brain injuries, and lower limb motor impairments due to hemiplegia or complete paralysis. It is also effective for patients with weak early-stage motor function [3]. In 2016, AiLegs and AiWalker were successfully transferred from research to practical application through Beijing Daai Robot Technology Co., Ltd.

In 2015, Shanghai Jiao Tong University developed a novel wearable exoskeleton robot with a focus on bio-inspired design [4]. It employs a hydraulic/electric hybrid mechanism for ankle and hip joints, emphasizing the drive system, and highlights load-bearing capacity in its structural design. This design eliminates the need for balance crutches to maintain body balance and offers automatic height adjustment based on individual differences. To research this exoskeleton robot, an adaptive PID control system was developed to achieve biomimetic lower limb exoskeleton robot motion. Harbin Institute of Technology and Tsinghua University collaborated on intelligent control technology research. In 2016 and 2017, Zhejiang University also manufactured their exoskeleton robots, emphasizing the human-machine interaction sensing system. They reduced the number of joints driven actively by the body, focusing on the hip and knee joints, while the ankle joint passively moved, reducing the need for auxiliary support. Additionally, reinforcement of the exoskeleton robot was necessary to enhance its precision and operational capabilities through breakthrough algorithm applications [5]-[6].

In 2018, Shanghai Siyi Intelligent High-Tech Company introduced the first domestic lower limb soft exoskeleton rehabilitation device, EasyWalkX1, weighing less than 3 kg, without a rigid structural frame. It utilizes an electric motor and linear drive to mimic muscle contractions in humans. The unique drive system allows this robot to assist ankle joint movement in moderately hemiplegic patients. It employs artificial intelligence algorithms to detect the gait pattern that requires assistance and exhibits adaptability during walking in various environments, such as level ground, slopes, and stairs [7]. In 2019, Shenzhen Kenqing Technology Co., Ltd. introduced the "Knight" exoskeleton, which utilizes bilateral assistance to facilitate lower limb exoskeleton movement. It combines a rigid structure with flexible drive mechanisms and weighs only 5 kilograms without a battery. It actively assists the hip and knee joints. In 2020, Wuhan University of Technology and the Chinese Academy of Sciences jointly developed the "Knight Exoskeleton," a lightweight and flexible lower limb support device. It employs a Bowden cable and spring mechanism to provide ankle support and uses a waist-mounted motor to assist leg joint movement, reducing metabolic expenditure [8].

DOI: 10.54254/2755-2721/62/20240447

In recent years, with the deepening of research on exoskeleton robots, wearable exoskeleton devices have been emerging in China. Companies such as Chengdu Buffalo Robot Technology Co., Ltd., developed the AIDER, a personal wearable lower limb exoskeleton robot for ambulation assistance. Shanghai Fourier Intelligent Technology Co., Ltd., developed the FourierX1, another wearable lower limb exoskeleton robot [9]. Maibu Technology Co., Ltd., created the Bear-H1 exoskeleton robot [10], to name a few.



Figure 1. Domestic Lower Limb Exoskeleton Rehabilitation Robots.

2.2. Foreign Lower Limb Exoskeleton Rehabilitation Robots

As shown in Figure 2, the development of foreign exoskeleton robots has progressed rapidly, with extensive exploration and research, resulting in significant advancements. Different classifications have been established based on various aspects of exoskeleton robots, including their force transmission mechanisms, actuation methods, joint interaction locations, and degrees of freedom. Some of the most distinctive exoskeleton robots are illustrated as follows.

Figure (a) represents the ReWalk Rehabilitation Robot developed and manufactured by the Israeli company ReWalk. It is the first comprehensive lower limb rehabilitation robot in China, designed and produced by an Israeli machine manufacturing company. ReWalk is a comprehensive rehabilitation robot that provides lateral assistance and slow walking functions. It features an independently controlled knee joint. By utilizing activation motors, batteries, and computer systems, ReWalk assists individuals, particularly stroke survivors, in walking slowly by directly measuring and calculating subtle changes in trunk motion and body center of gravity. The mechanical design consists of symmetric legs, a waist support, balance crutches, and a backpack, with each mechanical leg having two rotational degrees of freedom corresponding to hip and knee joint flexion and extension movements. Up to now, ReWalk has two different models: ReWalk 6.0 (the walker) and ReWalk 6.0 (the fully recovery model). ReWalk 6.0 helps most paraplegic patients transition from wheelchairs, allowing them to abandon their previous lifestyles and professions, and it adapts to various situations. ReWalk Complete Rehabilitation is tailored to the majority of patients, offering absolute safety, functionality, and optimal joint alignment based on medical imaging and exercise physiology prescriptions for most patients [2].

Figure (b) is a relatively intuitive exoskeleton developed for neural interventions, allowing most stroke or systemic disease rehabilitation patients to relearn walking with a more natural gait pattern. The equipment now needed includes robust new features, tools, and software enhancements, which will aid orthopedic surgeons and benefit most patients with a greater investment in initial rehabilitation treatment.

DOI: 10.54254/2755-2721/62/20240447

Figure (c) is the HA Lower Limb Rehabilitation Robot developed and manufactured by the University of Tsukuba in Japan. It is a wearable full lower limb rehabilitation robot developed by the Japanese company Cyberdyne, as depicted. This robot is the world's first wearable technology eligible for medical insurance reimbursement and related equipment. Its aim is to improve, assist, and extend the powerful functions of the body. It can help individuals with lower limb motor function impairments to stand, walk, rise, sit down, and climb stairs. In 2013, it became the world's last rehabilitation robot to receive global third-party certification. On one hand, the HAL robot comprises a wireless router LAN (local area network connection) recovery system, a conventional bicycle powertrain system, detection sensors recovery system (foot acceleration sensors, surface electromyography detection sensors, angle detection sensors), and actuation mechanisms. What's most remarkable is its ability to detect extremely weak signals on the skin's metal surface and control the movement of bones and muscles using turbojet engines. The HAL-5 series of full-body muscle-type soft robots weigh about 23 kg, with the lower limbs weighing 15 kg. The battery life is nearly 2 hours and 40 minutes. The whole-body muscles have 26 degrees of freedom in total, with 8 in each leg actively driven by electric motors. It is available in single-leg and large-size versions and is suitable for most post-stroke sequelae patients and children. It uses motor neurons to receive neural signals from the brain.

Figure (d) depicts the Indego, a relatively lightweight rehabilitation robot developed in collaboration between Vanderbilt University and Parker Hannifin Corporation. It is designed to match the speed and burst force testing of most severely injured patients, endowed with advanced walking capabilities. The Indego Rehabilitation Robot consists of five customized modules: posterior thigh, upper legs on both sides, and lower legs on both sides. Instead of using four brushed DC motors to mount the drivers at the hip and knee joints. This complete recovery system is built on a carbon fiber composite ankle joint and foot orthosis that can stabilize most patients and transfer gravity acceleration to a solid ground. It can provide powerful energy if a rechargeable lithium battery is not selected. In terms of perceiving real intent, the Indego robot receives feedback information on patient posture, tilt angles, and other relevant information detected by sensors, through a dual-core CPU digital signal processor, to determine which actions to perform, and incorporates feedback information from the center of resistance, helping patients walk intelligently.



Figure 2. Foreign Lower Limb Exoskeleton Rehabilitation Robots.

3. Key Technologies

3.1. Human Gait Analysis

Gait refers to the posture of human walking and is influenced by various factors, including anatomical features, physiological structures, physiological functions, motor control abilities, and psychological states. Gait can be used to indirectly assess a person's pathological conditions and characteristics. Gait analysis is a significant area of study within biomechanics and finds extensive applications in disease

DOI: 10.54254/2755-2721/62/20240447

diagnosis and rehabilitation evaluation for humans. Through gait analysis, it becomes possible to analyze the causes of diseases effectively and assist doctors in diagnosing patients' conditions. By diagnosing these conditions, better guidance can be provided for patients in terms of proper upright walking training.

Methods for gait testing include qualitative analysis (visual gait analysis) and quantitative analysis (instrument-based measurement). Nowadays, quantitative analysis is predominant. Quantitative analysis involves observing the walking gait with instruments. Gait analysis systems are categorized into 2D and 3D gait analysis systems.

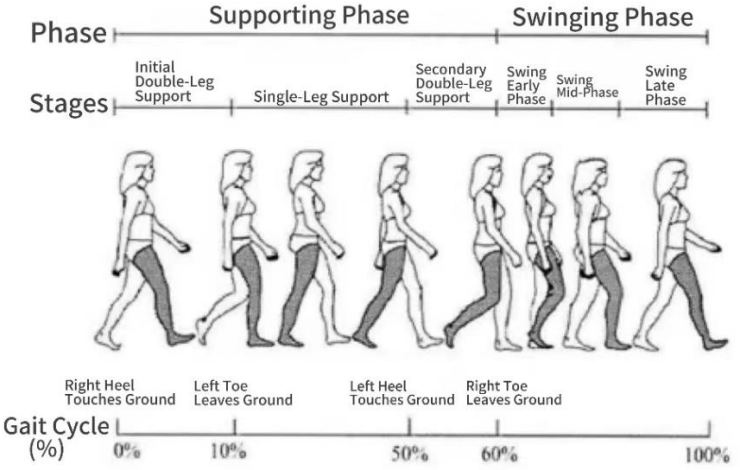

Figure 3. Human Gait Cycle.

3.2. Analysis of Control Methods

Control algorithms are the critical technology governing the operation of lower limb exoskeleton robots. This technology determines the robot's functionality and primary performance. The control system can be divided into three levels: perception, decision-making, and execution. The perception process involves the collection of gait data, patient physiological characteristics, and environmental information through sensors integrated into the lower limb exoskeleton robot. As the data collected by the sensors during rehabilitation training is extensive and noisy, creating uncertainty, control system algorithms need to swiftly and accurately process this data to adapt to different rehabilitation training modes and apply distinct control strategies. The primary means to achieve this involves coordinated movements in the hip, knee, ankle, toes, and muscles. Stability, periodicity, and coordination during the walking process are critical indicators to determine whether the gait is normal. Therefore, gait analysis is widely used in various clinical and non-clinical applications. In clinical applications, gait analysis is employed for rehabilitation assessments and pathological diagnoses. In non-clinical applications, gait analysis is used for monitoring sports, post-injury recovery, and assessing athletic performance. The gait analysis process comprises numerous parameters, including time parameters during walking or other motion, electromyography (EMG) data, kinematic, and kinetic parameters. To enable real-time gait analysis, a range of wearable and non-wearable sensors are used in the design of exoskeleton robots. Wearable sensors include acceleration sensors, gyroscopes, angle sensors, EMG sensors, EEG sensors, and plantar pressure sensors. Non-wearable sensors include ground reaction force (GRF) and motion capture systems. Data acquired from sensors are processed to obtain gait parameters. The relevant technologies encompass classic threshold algorithms based on angular velocity for gait phase detection, muscle-skeletal models that predict motion intentions based on EMG data, and machine learning and deep learning techniques. Based on the above statements, the control algorithms of lower limb exoskeleton robots need to not only meet the requirements of the driving devices but also realize interactive control between the robot and the wearer. The system performance of lower limb exoskeleton robots is directly

DOI: 10.54254/2755-2721/62/20240447

determined by motion strategies. An excellent control strategy is the foundation of coordination between exoskeleton robots and wearable exoskeletons. Control strategies address two main issues: motion completion and control of the entire action. The former mainly deals with data collection and fusion from the robot's information, while the latter encompasses kinematic analysis, control system analysis, design, and dynamic analysis.

1. Direct Force Control Method: This approach uses the idea of force feedback and requires torque sensors to measure the force or torque signals generated during human-machine interaction. These signals are then transmitted to the corresponding joints, where the torque that drives the joints is indirectly obtained through sensors placed between the human body and the exoskeleton robot. This method has some delay, is relatively simple to implement, can adapt to various motion environments, and is self-contained.

2. Control Methods Based on Human Electrophysiological Signals: Among these, the most representative is the HAL series exoskeleton robot. Although it has good human-machine ergonomics, it requires precision in installing sensors as they need to be directly adhered to the surface of the human skin. Additionally, the variations in muscle electrical signals due to differences in individuals cause instability in the sensors during the wearer's movement. This can result in deviations and disconnections, which affect the stability of exoskeleton robot use.

3. Control System Based on Human-Robot Contact Force Information and Sensitivity Amplification: The BLEEX exoskeleton robot is highly representative of this approach. This method utilizes positive and negative feedback to allow sensors to capture the interaction forces between the human and the robot. After amplification and analysis, the robot can grasp the user's motion intentions in real-time. While this algorithm is straightforward, it requires a complex sensor setup and has a high precision requirement for dynamic models. The complex sensor setup results in delayed system responses and applications.

4. Predefined Gait Trajectory Control: This is an offline gait trajectory planning control method. This method involves offline planning based on gait data collected while the exoskeleton robot follows the wearer's walking and gait posture analysis. During the walking process, the controller step-by-step reproduces the original gait and adjusts it in real-time according to the system's walking conditions.

Exoskeleton robots have various applications, primarily aimed at assisting and enabling long-distance walking for users, as well as aiding those who are unable to walk independently in a manner that supports lower limb locomotion.

3.3. Degrees of Freedom

Based on the number of active joints in lower limb rehabilitation robots, which relates to the degrees of freedom, they can be classified into lower limb rehabilitation robots with varying degrees of freedom, ranging from 1 to 7.

The joint drive mechanism in lower limb rehabilitation robots is a key factor in improving the effectiveness of lower limb rehabilitation for patients. It has a significant impact on the overall robot's structural design, control strategies, and functionality.

3.4. Drive Mechanisms

3.4.1. Pneumatic Drive. The working principle of pneumatic drive involves compressing air generated from a source to provide power. Scholars from around the world have conducted extensive research on pneumatic-driven lower limb rehabilitation robots. Representative pneumatic-driven systems include PAM and POGO [11-12], EXPO [13-14], and PLLO [15].

A research group from the University of Auckland in New Zealand designed a pneumatic rehabilitation robot driven by servo cylinders. To ensure the continuity of rehabilitation movements, they integrated the POGO system and utilized two degrees of freedom for lateral movement to achieve hip and knee joint extension. This improved the performance of the rehabilitation robot and demonstrated the influence of structural modeling and control strategies on its functionality.

DOI: 10.54254/2755-2721/62/20240447

3.4.2. Electric Drive. The working principle of electric motor drive involves applying the force generated by electric motors to the desired control points. Scholars both domestically and internationally have conducted extensive research on electric motor-driven lower limb rehabilitation robots. Typical examples include ALEX, LOPES, and other lower limb exoskeleton rehabilitation robots developed by Shanghai Jiao Tong University.

Electric motor-driven lower limb rehabilitation robots offer torque control without the need for energy conversion and are highly flexible. Due to the widespread use of low-inertia, high-torque DC and AC servo motors, along with their associated servo drivers, the structural research on electric motor-driven lower limb rehabilitation robots is the most extensive. The focus of this research is on designing a reasonable transmission mechanism and, based on this design, reducing the volume and loss caused by transmission issues while further modifying the structural components related to the rotational angle.

3.4.3. Hydraulic Drive. Hydraulic control systems utilize hydraulic pumps to convert pressure into conserved mechanical energy, providing comprehensive power. Researchers worldwide have studied robots equipped with common hydraulic control systems, although it has only recently been applied to rehabilitation for individuals with disabilities. One of the few robots in this category is the Ekso [15-18] full lower limb rehabilitation robot (formerly known as eLEGS).

Designed by EksoBionics, a legitimate company in the United States, the Ekso lower limb soft exoskeleton rehabilitation robot is a portable device that allows users to select operation modes, such as sitting to standing and standing to moving. Most patients can also use special crutches to transition from a sitting position to a standing one. In general, full lower limb rehabilitation robots often employ hydraulic control systems for joint movements. Their front suspension is an independent MacPherson suspension, providing practical power, fast response, and stable motion. The structure is relatively simple, but it can generate significant noise, is prone to leaks, can lead to environmental pollution, and has lower thermal efficiency than electric motors.

Globally and nationally, there has been relatively less research in the realm of full lower limb rehabilitation with hydraulic control systems. Therefore, research emphasis in hydraulic control systems for full lower limb rehabilitation robots is to design the structure more reasonably, reduce noise, and further improve preventive hydraulic control system leakage control devices, thus enhancing engine thermal efficiency and reducing overall product costs.

4. Current Status of Clinical Research and Clinical Applications

The use of lower limb exoskeleton rehabilitation robots for treatment has proven highly effective in improving functional disabilities in patients with lower limb impairments, particularly in the context of physiological therapy. Taking Lokomat as an example, Hebei United University's School of Rehabilitation Medicine randomly divided 40 post-stroke patients into two groups: under equivalent conditions, the control group received conventional rehabilitation treatment. The Lokomat group received robotic drug treatment aimed at achieving full lower limb recovery [19]. The final data from the database were obtained. The results indicated that in the Lokomat group, most patients who received drug treatment demonstrated significant improvements in step length, width, running and walking speed, as well as enhanced balance abilities. Similarly, the Department of Integrative Medicine at Shanghai First People's Hospital reported on acute myocardial infarction cases. They divided 60 patients with limb motor function disabilities into two groups: under what circumstances should drug treatment be administered? Under the exact same specific conditions, the control group received conventional rehabilitation treatment, while the robot group received comprehensive rehabilitation training using a lower limb rehabilitation robot jointly developed and produced by Shanghai Jiao Tong University's Institute of Robotics and Biology [20]. Finally, a composite score based on the Fugl-Meyer scale, including lower limb mobility, body coordination, movement speed, and overall functionality, showed significant improvements in the robotic group, with values noticeably higher than those of the control group. Each index corresponds to specific assessments.

DOI: 10.54254/2755-2721/62/20240447

5. Development Trends and Prospects

This article provides an overview of exoskeleton robots, and the research in exoskeleton robot technology encompasses multiple disciplines. Due to limitations in personal time, resources, and expertise, there are various aspects of the research related to this article that require further development. There are still some shortcomings and deficiencies in the current research. Therefore, it is suggested that future research should focus on the following areas:

1. Structural Design, Whole-Body Statics and Kinematics Analysis of Lower Limb Exoskeleton Robots: While this article addresses the reliability of overall system stress and motion, it does not perform further optimization on specific components. The system still needs additional verification of the reliability and comfort of its components.

2. Stability Assessment Based on Zero Moment Point (ZMP) and Gait Analysis: This article optimizes gait parameters using genetic algorithms under idealized conditions. Future developments in lower limb exoskeleton robots offer significant potential to make them more flexible, comfortable, and effective in mimicking the walking patterns and gaits of normal individuals. Therefore, further efforts and research are needed to innovate and experiment with lower limb exoskeleton robots.

3. Modular Design of Lower Limb Rehabilitation Robots: It is essential to conduct research into modular lower limb rehabilitation robots that cater to the specific needs of individual patients. This approach allows for targeted rehabilitation training according to different patient requirements, reducing fatigue in non-targeted areas during the rehabilitation process. This, in turn, helps patients focus their energy on the areas that require rehabilitation.

In conclusion, the field of exoskeleton robots holds great promise, and addressing these research areas can significantly contribute to the development and improvement of lower limb exoskeleton technology. Continued experimentation, innovation, and modular design will play a vital role in advancing this field and making exoskeletons more accessible and beneficial for a broader range of patients.

6. Conclusion

Due to the significant issue of an aging population in China, the demand for assistive lower limb rehabilitation robots is on the rise. The current state of exoskeleton robot research varies both domestically and internationally. Exoskeleton robots developed by Beijing University of Aeronautics and Astronautics, such as the AiDong wearable rehabilitation exoskeleton, have shown remarkable capabilities in assisting individuals with spinal cord injuries, spinal cord inflammation, and other problems arising from brain injuries. Numerous technology companies, including Fourier, and others, have also invented their unique exoskeleton robots. Internationally, many outstanding exoskeleton robots have been developed, such as the ReWalk rehabilitation robot and its accompanying accessories, as well as intuitive exoskeletons designed for neural intervention to assist patients in regaining the ability to walk with a more natural gait. This article has also analyzed the key technologies behind exoskeleton robots. By focusing on the analysis of human gait, it emphasizes the importance of gait analysis in the context of human locomotion. The various methods of gait analysis have also been discussed. Control methods are crucial in determining the functionality and performance of lower limb exoskeleton robots and involve a range of sensors needed for lower limb walking. The number of degrees of freedom is another key factor in determining the flexibility of exoskeleton robots. The choice of drive mechanisms includes pneumatic, electric, and hydraulic drives. An analysis of the current state of clinical research reveals that lower limb exoskeleton rehabilitation robots can significantly aid in restoring walking capabilities and assisting individuals in walking upright. It is believed that in the future, by further optimizing the structural design, whole-body statics, and kinematics of lower limb exoskeleton robots and innovating for greater wearer comfort, these robots can become even more accessible and beneficial to patients. It is also anticipated that, in the near future, lower limb exoskeleton robots will find more widespread and convenient applications in assisting more people in their journey to recovery and improved health.

DOI: 10.54254/2755-2721/62/20240447

References

[1] Fang, Y. (2009). Research on dynamic analysis and control of the wearable power assist robot [Doctoral dissertation]. University of Science and Technology of China.

[2] Shuai, M. (2018). A biped lower-limb exoskeleton rehabilitation robot (CN3048224985) [Patent]. September 18, 2018.

[3] Wang, Z. B., Chen, S. J., Yang, Q., et al. (2021). Progress in clinical rehabilitation of lower extremity exoskeleton robot. Chinese Journal of Rehabilitation Medicine, 36(6), 761-765.

[4] Miao, Y. J. (2015). Research on the mechanical performance design of an innovative lower extremity exoskeleton [Doctoral dissertation]. Shanghai Jiao Tong University.

[5] Zhang, C. (2016). Research on lower limbs powered exoskeleton robot [Doctoral dissertation]. Harbin Institute of Technology.

[6] Jin, X. L. (2017). Control system research of hydraulic driven lower limb exoskeleton in swing phase [Doctoral dissertation]. Zhejiang University.

[7] Zhao, X. G., Tan, X. W., Zhang, B. (2020). Development of soft lower extremity exoskeleton and its key technologies: A survey. Robot, 42(3), 365-384.

[8] Liuwang, Z. Y., Zheng, Y. H., Sun, J. Q., et al. (2021). Design and performance experiment of a lightweight flexible lower-limb exoskeleton. Robot, 43(4), 433-442.

[9] Buffalo Robot Technology (Chengdu) Co., Ltd. (2019). Buffalo Rehabilitation Robot Product Introduction [Webpage]. http://www.buffalo-robot.com/show-25-35-1.html

[10] Shanghai Fourier Intelligent Technology Co., Ltd. (2019). Fourier X2 Product Introduction [Webpage]. http://www.fftai.com/product/X2.php. Li, J., Zhu, L. Y., Gou, X. F. (2018). Survey on exoskeleton lower limbs rehabilitation robot and key technologies. Chinese Medical Equipment Journal, 39(8), 95-100.

[11] Reinkensmeyer, D. J., Aoyagi, D., Emken, J. L., et al. (2006). Tools for understanding and optimizing robotic gait training. Journal of Rehabilitation Research & Development, 43(5), 657-670.

[12] Hussain, S., Xie, S. Q., Jamwal, P. K. (2013). Robust nonlinear control of an intrinsically compliant robotic gait training orthosis. IEEE Transactions on Systems, Man & Cybernetics, 43(43), 655-665.

[13] Kong, K., Jeon, D. (2006). Design and control of an exoskeleton for the elderly and patients. IEEE/ASME Transactions on Mechatronics, 11(4), 428-432.

[14] Carse, B., Meadows, B., Bowers, R., et al. (2013). Affordable clinical gait analysis: an assessment of the marker tracking accuracy of a new low-cost optical 3D motion analysis system. Physiotherapy, 99(4), 347-351.

[15] Ekso Bionics. (2012, September 2). Ekso Lower limb rehabilitation robot [Webpage]. http://www.eksobionics.com/ekso

[16] Berkeley Bionics. (2009, February 26). Human Universal Load Carrier [Webpage]. http://bleex.me.berkeley.edu/research/exoskeleton/hulc/

[17] Chu, A. (2005). Design of the Berkeley lower extremity exoskeleton (BLEEX) [Doctoral dissertation]. University of California, Berkeley.

[18] Ghan, J., Kazerooni, H. (2006). System identification for the Berkeley lower extremity exoskeleton (BLEEX). In IEEE International Conference on Robotics and Automation Orlando (pp. 3477-3484).

[19] Zhao, Y. N., Hao, Z. W., Li, J. M., et al. (2012). The effect of Lokomat lower limb gait training rehabilitation robot on balance function and walking ability in hemiplegic patients after ischemic stroke. Chinese Journal of Rehabilitation Medicine, 27(11), 1015-1020.

[20] Feng, X. X., Bai, Y. H., Xu, Y. M., et al. (2014). Effectiveness of lower limb exoskeletons rehabilitation robot in improving lower limb function of stroke patients. Chinese Journal of Rehabilitation, 29(2), 86-88.