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Research on the Development and Structural Design of Medical Five-Finger Dexterous Hands

Qiming Tian

Wuhan Britain-China School, Wuhan, Hubei, 430030, China

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Abstract: Central nervous system injuries from strokes lead to upper limb paralysis in 55% of patients, resulting in severe motor impairments. Medical practice shows that rehabilitation training effectively improves these motor deficits. Traditional rehabilitation methods impose significant economic burdens on society and families. Researchers, both domestically and internationally, have introduced rehabilitation robots, exemplified by the five-finger dexterous hand, to assist patients with their rehabilitation training instead of relying solely on therapists. The five-finger dexterous hand serves as a bionic actuator at the end of robotic arms, playing a crucial role in the development of medical rehabilitation robots. This paper explores the development and structural design of medical five-finger dexterous hands, discusses their current research status, bionic theories, and structural designs. The aim is to provide guidance for the design and development of medical five-finger dexterous hands while also aiding stroke patients in recovering swiftly from illness, thereby enhancing their quality of life and sense of well-being.

1. Introduction

As society ages, the incidence of cerebrovascular diseases, particularly represented by stroke patients, is skyrocketing. The number of patients with hemiplegia from strokes is also increasing, placing a significant burden on families and society. In 2019, there were 100 million stroke patients worldwide, with 6.55 million deaths among 12.2 million newly diagnosed cases, leading to an 11.6% mortality rate, making stroke the second leading cause of death globally [1]. In China, the mortality rate for stroke patients reached 22% in 2018, with a disability rate of 70% to 90%, resulting in varying degrees of hemiplegia. The central nervous system on one side of the brain is damaged in stroke patients, affecting their motor and sensory functions in their limbs [2]. Numerous medical studies indicate that 75% to 83% of patients with lower limb movement disorders can regain some ability, yet 55% of hemiplegic patients continue to face severe mobility challenges in their upper limbs three to six months post-stroke [3]. According to standards for permanent functional impairment, upper limb functions account for more than 60% of overall movement capabilities, with the hands playing a key role. Therefore, hand function rehabilitation is crucial for the recovery of motor function in hemiplegic patients.

Traditional rehabilitation training requires professional therapists to assist patients in completing specific tasks. Through repeated passive stimulation of various parts of the hand, the damaged central nervous system can be rebuilt over time, gradually restoring muscle strength. However, the high costs of rehabilitation impose a significant economic burden on society and families [4]. In recent years, as robotics technology has increasingly integrated with rehabilitation theory, medical dexterous hands have played an ever more important role in clinical rehabilitation and have become a hot topic in rehabilitation research internationally. Dexterous hands controlled by specific language protocols provide greater flexibility and precision compared to traditional rehabilitation methods, effectively addressing patients' needs and enabling customized training programs based on individual conditions [5]. Therefore, researching the clinical application of dexterous hands to enhance hand function in patients is a crucial area of study.

This paper first reviews the research on medical five-finger dexterous hands, detailing their design and historical development. It then examines the biomimetic theory and structural design, focusing on the underlying mechanical principles. On one hand, this study can provide guidance for the design and development of medical dexterous hands; on the other hand, it can enhance their clinical application, offering more efficient and precise rehabilitation training for patients with hand function impairments. This will help stroke patients alleviate their suffering and improve their quality of life and sense of happiness. Additionally, for rehabilitation therapists, this can reduce their workload and improve treatment outcomes, which is highly significant.

2. Research status of medical five-finger dexterous hand

In recent years, the structure of medical five-fingered dexterous hand is diversified. In structure, five-fingered dexterous hand changes from single-fingered to multi-fingered. In the driving mode, the traditional mechanical connecting rod drives to flexible drives. In the control strategy, five-fingered dexterous hand changes from passive control to active control. The development process of hand rehabilitation robot is shown in Figure 1.

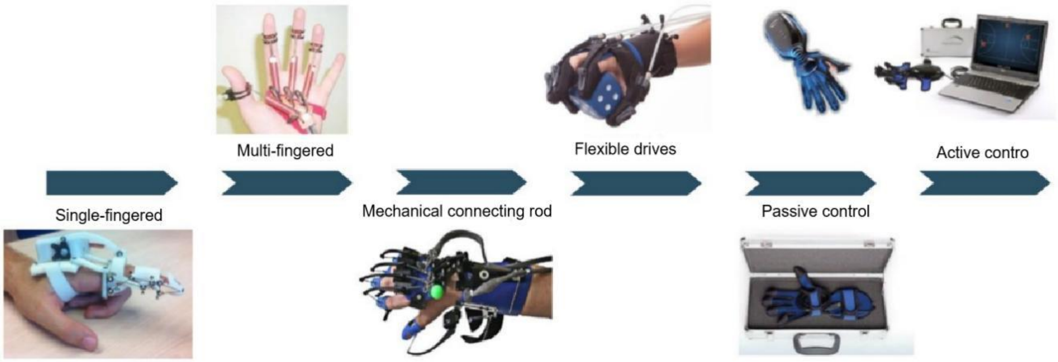

Figure 1: Development of five-fingered dexterous hand

In the early design of medical five-finger dexterous hand, open-loop control was widely used because of its relatively simple and low cost. This control method relies on a pre-designed program to control the five-finger dexterous hand to perform a fixed trajectory rehabilitation action, but cannot perceive the movement intention of the patient during rehabilitation. The Medical engineering Laboratory of Harbin Institute of Technology was established in 2003, and many researchers are involved in the field of rehabilitation equipment. The first generation of dexterous hands can help patients complete continuous passive training by simulating the movement trajectory of the human hand [6]. The open-loop controlled hand rehabilitation device, which is represented by the dexterous hand developed by the medical engineering laboratory of Harbin Institute of Technology, has insufficient control precision, poor comfort and low safety, and is difficult to meet the rehabilitation needs of different patients.

Position control is the most basic and widely used method for controlling medical robotic hands, primarily for patients who cannot move on their own. It's commonly applied in continuous passive motion (CPM) rehabilitation training, where the controller, based on a predetermined training path and using position sensors for feedback, guides the robotic hand to help patients complete specified trajectories, thereby activating muscles and stimulating neurons. In 2009, the Robotics Institute of Beihang University developed a medical robotic hand that uses cable-driven mechanisms along with position and force sensors for closed-loop control [7]. While it effectively controls joint angle errors, this method is only somewhat effective for severely impaired hand patients. Wang Jianhua et. Al [8] designed a medical robotic hand based on position control that can perform actions like arm repositioning, extension, and flexion according to rehabilitation needs. Experimental validation demonstrated that this robotic hand achieved positive rehabilitation outcomes but lacked accurate assessment and feedback mechanisms for patients' hand movements, limiting its adaptability to diverse rehabilitation needs. Guo Tie [9] and colleagues developed a position-controlled medical robotic hand system featuring a mechanical structure, electrical system, and control system that employed a closed-loop control strategy for rehabilitation movements such as arm repositioning, extension, and flexion. Results indicated that this system was effective in rehabilitation. However, while the position feedback control method presented can perform hand rehabilitation tasks, it does not provide real-time assessment or personalized adjustments, failing to fully address the varied needs of patients. Jiang Le [10] and others introduced another position-controlled medical robotic hand system that includes a robotic arm, sensors, and a controller, enabling flexible hand movements to improve rehabilitation outcomes. Experimental results confirmed this system's stability and precision. Nonetheless, the PID control method used, although effective for position control, requires manual PID parameter settings and offers a basic feedback mechanism for hand movements, which does not support personalized adjustments for different patients.

Wang Xiangyu [11] from Harbin Institute of Technology proposed a control method based on active rehabilitation strategies, using parameters like robot motion trajectories and torques to assist patients with hand rehabilitation training. They also set up an experimental platform, which was tested and analyzed with healthy volunteers, validating the effectiveness and feasibility of this control method. However, the paper has shortcomings, including a lack of in-depth exploration of robot control optimization algorithms, a systematic assessment of the robot's applicability, and insufficient detailed quantitative analysis of the experimental results.

In 2020, Liu Hongmei [12] from Shanghai Normal University designed a medical dexterous hand with flexible drives. This system controls the movements of a soft rehabilitation robot by adjusting the stretch of Bowden cables and proposed a position-based impedance control that meets the precise control requirements for interaction forces. However, the impedance parameters are preset, and the impedance controller's parameters cannot be dynamically adjusted in real-time based on environmental stiffness (the degree of stiffness in the patient's finger joints or active movement intentions). Wang Hongbo et. al [13] from Yanshan University also proposed a design for a terminal traction medical dexterous hand, utilizing flexible actuators and sensors to achieve compliant control of the fingers. They introduced an adaptive impedance control method that adjusts the robot's impedance parameters based on the patient's strength and movement conditions. Yet, this method has limitations, as it only considers a single force factor and neglects the influence of other factors.

Reviewing the above literature, early medical dexterous hands mostly employed open-loop control, focusing mainly on passive training, which lacked good human-computer interaction during rehabilitation and raised safety concerns. To address these issues, researchers developed a series of control methods based on closed-loop control. Position control introduced position feedback based on open-loop control; although it improved control accuracy, it still did not enhance human-computer interaction or the patient's active participation in rehabilitation. Fixed-parameter impedance control methods can adjust training trajectories according to the patient's movement intentions, but since parameters like stiffness cannot be dynamically adjusted in real-time based on the environment (patient joint stiffness or movement intentions), the medical dexterous hand cannot exhibit high compliance. Moreover, individual differences can lead to poor universality of the bioelectric signal classification model, limiting its promotion and application in real-world scenarios.

3. Bionic theory and structural design

3.1 Bionic theory

To achieve the rehabilitation function of a medical five-finger dexterous hand, it's essential to use biomimetic principles to give the dexterous hand a structure, size, workspace, and flexibility similar to that of a human hand. Therefore, it's necessary to study the skeletal anatomy of the human hand as a theoretical basis for the design of finger structures. Additionally, to enable the dexterous hand to mimic human functionality, it's important to investigate the movement characteristics of the human hand.

The hand is a highly developed and complex gripping organ made up of cartilage, ligaments, and nerves, with 19 degrees of freedom and an opposable thumb. The five parts of the fingers work together to perform tasks involving touch, grip, and communication in daily activities. The thumb is the most powerful among the carpometacarpal (CMC) joint and nine independent muscles. The thumb plays a crucial role in the hand's strength and fine motor skills. It has five degrees of freedom, and the force generated during gripping is about a quarter of the maximum force produced when the palm is fully clenched.

The other fingers—the index, middle, ring, and little fingers—each have three joints: the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints. The finger joints can perform complex movements of flexion, extension, abduction, and adduction due to the metacarpophalangeal joints are oval or elliptical. The PIP and MCP joints are key to the hand's gripping function and maintain stability during the movement of the finger joints. The structure of the DIP joint is similar to that of the PIP joint, but due to the unique structure of the DIP joint, there are two concave surfaces between the distal phalanges. The convex surface is not prominent, allowing only slight lateral rotation, as shown in Figure 2.

Figure 2: Composition of hand joints

The primary movements of the hand joints are flexion-extension and abduction-adduction. The flexion-extension occurs around the sagittal axis along the palmar surface, while abduction and adduction occur around the coronal axis. The distal DIP and PIP joints possess a single degree of freedom, providing stability during finger movements. The interaction of ligaments and muscle groups across the joints results in a strong coupling between the DIP and PIP joints. The MCP joints offer two degrees of freedom, allowing the hands to perform intricate tasks and providing adequate cushioning against external forces on the fingers.

3.2 Structural Design

The medical five-finger dexterous hand comprises five main components: finger mechanisms, drive systems, control systems, and sensing. This section discusses the design principles and techniques of the dexterous hand from these five perspectives.

3.2.1 Finger Mechanism Design

The thumb and index finger are crucial for daily hand functions, so dexterous fingers should mimic the dexterity of a human index finger. The degrees of freedom in the fingers are a key indicator of their dexterity, and their design should aim to match the degrees of freedom of a human index finger. Additionally, the coupling ratio between the PIP and DIP joint angles in a human index finger is approximately 3:2. Therefore, the design adopts a coupling scheme where the PIP and DIP joint angles of the finger are designed in a 3:2 ratio, allowing for three joints and three degrees of freedom. This ensures the dexterous fingers are nimble while also reducing the number of finger actuators, simplifying the design and compacting the structure.

3.2.2 Drive Mechanism Design

The main drive methods for the five-finger dexterous hand include pneumatic, hydraulic, motor, and shape memory alloy drives. Pneumatic drives are inefficient, their motion trajectories cannot be controlled, and the air pumps they require take up a lot of space, which hampers the dexterous hand's miniaturization. Hydraulic drives are noisy, prone to leaks, and difficult to maintain. Motor drives are rigid and can easily damage the object being grasped unless flexible components are added. Compared to these drive methods, shape memory alloy drives utilize the property of shape memory alloys, which deform under stress and do not completely return to their original shape after unloading; when externally stimulated, they revert to their original form. This type of drive is powerful, compact, silent, lightweight, and offers gentle movements, making it widely used for driving the fingers of dexterous hands.

3.2.3 Transmission Mechanism Design

The design of the transmission mechanism significantly influences the grasping performance of a dexterous hand by transferring power from the actuator to the system to drive finger movements. When formulating the transmission plan, it's crucial to consider its impact on overall performance. Common methods include linkage, gear, belt, and cable transmission.

Linkage transmission, frequently employed in industrial and commercial settings, combines serial and parallel linkages. This mechanism transmits movement and power through rigid linkages, enabling the grasping of large objects while maintaining a compact structure for enveloping grasps. However, it can be difficult to control over long distances, is prone to bouncing, and offers limited grasping space. Gear transmission is widely used in industrial robots due to its ability to achieve stable transmission ratios, high transfer efficiency, and stronger reliability. However, the weight of the gears increases the overall mass and inertia. Belt transmission has a simple structure and provides smooth operation with a cushioning effect, allowing for power transfer over large distances between axes and multiple axes while being inexpensive, requiring no lubrication, and being easy to maintain. Cable-driven mechanisms are currently the most widely used form of transmission in dexterous hand research, as cables somewhat mimic the tendon structure of a human hand. Cable transmission allows for larger actuators to be placed away from the end effector, reducing the load and inertia at the end, which speeds up the grasping motion. Cables are flexible in arrangement, making them suitable for tight spaces needing multiple degrees of freedom in transmission. However, they do have limitations, such as weak load-bearing capacity, significant variations in pre-tension, and decreased efficiency with heavier loads.

3.2.4 Control Technology

Robotic hands need precise control to perform tasks like grasping, holding, and placing. Analyzing human hand dexterity through basic principles and mathematical methods provides a scientific foundation for planning and controlling multi-finger operations in robots. Fine manipulation requires planning the robotic arm's trajectory and actions based on the target task and environment, considering factors like obstacle avoidance, movement smoothness, and energy efficiency to safely and effectively navigate complex settings.

3.2.5 Perception Technology

Perception technology in robotic dexterous hands can be categorized into internal and external perception. Internal perception involves measuring movement parameters such as position, speed, and acceleration, while external perception gathers information about the environment through sensors like force, visual, tactile, and temperature/humidity sensors. The complexity of external information heightens detection challenges. These sensors offer accurate feedback on hand position, posture, object location, and applied force. However, replicating the complex and flexible structure of human skin while ensuring high perception functionality remains difficult. Consequently, research on electronic skin is increasingly important in dexterous hand perception technology.

4. Conclusion

In summary, the development of medical five-finger dexterous hands is showing a steady growth trend. At the same time, the demand in the market is pushing forward the research and development of these dexterous hands. By using bionics to mimic and study the characteristics of biological systems that adapt well to their environment, are highly effective, and have reasonable structures, dexterous hands are getting closer to human hands. In future developments, the dexterity of these hands will increase, becoming more human-like in size, shape, and control. The integration of drive control systems will be higher, and the structure and sensing will become more refined. Perception functions such as position, force, and touch will see substantial improvements. The incorporation of AI algorithms will make dexterous hands more precise and convenient, while advancements in machinery will provide strong hardware support for dexterous gripping. Moreover, the application of five-fingered dexterous hands isn't limited to the healthcare sector; in fields like aerospace and scientific research, their development will gradually replace human hands in a range of activities, enabling more delicate and higher-risk operations. In short, as the end effector for robots interacting with their environment, the research and development of dexterous hands will greatly enhance human life and will continue to be a hot research topic in the future robotics field.

References

[1] GBD 2019 Stroke Collaborators. Global, regional, and national burden of stroke and its risk factors, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019[J]. Lancet Neurol. 2021; 20 (10): 795-820.

[2] Chinese Cardiovascular Health and Disease Report Compilation Group. Summary of China Cardiovascular Health and Disease Report 2020. Chinese Journal of Circulation, 2013, 36: 562-586.

[3] Zhang T. Chinese Stroke Rehabilitation Treatment Guidelines (2011 Complete edition)[J]. Chinese Rehabilitation

Theory and Practice, 2012, 18(04):301-318.
[4] Chen Yi, Gao Qiang. Research progress of rehabilitation of motor dysfunction after stroke [J]. West China Medicine, 2022, 37(05):757-764.
[5] Kong Fanlei. Design of late hand rehabilitation training system for stroke patients [D]. Donghua University, 2022.
[6] Wang Peng. Research on functional rehabilitation manipulator system for finger trauma [D]. Harbin Institute of Technology, 2009.
[7] Wang S, Li J, Zheng R. Active and passive control algorithm for an exoskeleton with bowden cable transmission for hand rehabilitation[C]//2010 IEEE International Conference on Robotics and Biomimetics. IEEE, 2010: 75-79.
[8] Wang Jianhua, Yang Fucai, Yang Guoqiang. Design of a robotic rehabilitation robot based on Position control [J]. Chinese Journal of Scientific Instrument, 2018, 39(10): 2165-2172.
[9] Guo Tie, Chen Guanghua, Wang Lei. Hand rehabilitation robot system based on position control [J]. Control Engineering, 2019, 26(2): 258-263.
[10] Jiang Le, Li Xiaofeng, Xiao Hongchang. Design and experimental research of hand rehabilitation robot based on position control [J]. Journal of Biomedical Engineering, 2019, 36(1): 46-53.
[11] Wang Xiangyu. Control and Experimental research of hand exoskeleton robot based on Active rehabilitation strategy [D]. Harbin Institute of Technology, 2015.
[12] Liu Hongmei. Research and Implementation of the Control System of the Flexible Driving Hand Function Rehabilitation Robot [D]. Shanghai Normal University, 2020
[13] Wang Hongbo, Yan Yongfeng, Wang Xincheng, et al. Design and compliance control method of end-traction finger rehabilitation Robot [J]. Chinese Journal of Science and Technology, 2019, 15(07):743-749.