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Research on the Design and Control of Finger Exoskeleton Rehabilitation Robot

Mingqin Wen

School of International Education, Beijing University of Chemical Technology, Beijing, 100096, China
2023090137@buct.edu.cn

Abstract:
Finger motor dysfunction caused by nerve injury or musculoskeletal diseases seriously affects the quality of life of patients, while traditional rehabilitation methods lack accuracy and scalability. Although exoskeleton (Exo) robots offer promising solutions, existing designs still face challenges in terms of structural rigidity, control accuracy, and human-computer interaction for finger joint rehabilitation. This paper systematically reviews the finger Exo technology, with a focus on analyzing three key aspects: structural design, driving mechanism, and interaction mode. Through literature comparison and analysis, it is found that the rigid structure has a relatively high torque output (about 10.3 Newtons of grip), but insufficient comfort, while the flexible design improves wear resistance (weight 150-200 grams), but sacrifices load-bearing capacity. Hybrid power solutions and advanced drivers show the potential to bridge these gaps. Human-computer interaction technologies such as Surface electromyography (SEMG) can achieve a motion range of 58.5° for joints, but there is a problem of signal noise. The key research results reveal the trade-offs among various performance indicators: the balance between accuracy (0.2 mm position error) and adaptability, as well as the trade-off between force output (15 N·m torque) and portability. The future development direction emphasizes artificial intelligence-driven control algorithms, modular design, and the use of cost-effective materials to enhance clinical applicability. This study provides a systematic framework for optimizing finger Exo, indicating the need for multidisciplinary innovation to achieve personalized and efficient rehabilitation treatment.

Keywords: Finger Exoskeleton (Exo) Robots, Human-Computer Interaction (HCI), Rehabilitation Trade-offs

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1. Introduction

Fingers play a crucial role in daily life. Their flexible and compact nature enables us to complete various delicate tasks. However, diseases or injuries such as stroke, nerve injury, and muscle atrophy often lead to finger motor dysfunction, seriously affecting patients' self-care ability and quality of life. The traditional rehabilitation training methods mainly rely on the assistance of physical therapists. This approach is not only time-consuming and labor-intensive, but also difficult to achieve personalized and precise rehabilitation training. With the rapid development of robot technology, exo-rehabilitation robots, as a new type of rehabilitation assistance tool, have gradually become a research hotspot in the field of rehabilitation medicine. The Exoskeleton (Exo) rehabilitation robot provides personalized rehabilitation training for patients through mechanical structure and control algorithms. It has the advantages of high efficiency, accuracy, and strong repeatability, and can significantly improve the rehabilitation effect.

The structural design of the finger Exo has a significant impact on the performance and rehabilitation effect of the finger Exo rehabilitation robot. It features a wide range of joint movement and strong load-bearing capacity, and needs to coordinate with other joints of the finger to achieve complex grasping and operational actions. Therefore, the structural design of the finger Exo needs to comprehensively consider multiple factors such as biomechanical characteristics, motion Degree of Freedom (DoF), torque output, patient comfort, and equipment portability.

In recent years, researchers have made remarkable progress in the field of finger Exo rehabilitation robots. Italian scholars Cempini et al. proposed a wearable Exo rehabilitation robotic hand named HX [1]. The index finger module of this Exo has 7 DoF (3 passive and 4 active), and the thumb module has 9 DoF (6 passive and 3 active). Underdrive is achieved through the tendon sheath drive system, and four global movements can be independently controlled. The soft hand orthosis developed by Cornell University uses silicone actuators and combines pneumatic drive and optical curvature sensing [2]. In recent years, researchers have made remarkable progress in the field of finger exo-rehabilitation robots. Italian scholars Cempini et al. proposed a wearable Exo rehabilitation robotic hand named HX [1]. The index finger module of this Exo has 7 DoF (3 passive and 4 active), and the thumb module has 9 DoF (6 passive and 3 active). Underdrive is achieved through the tendon sheath drive system, and four global movements can be independently controlled. The soft hand orthosis developed by Cornell University uses silicone actuators and combines pneumatic drive and optical curvature sensing [2]. It achieves bending through a binary switch (hardening under pressure and low resistance without pressure), and at the same time, it is embedded with the sensing technology of U-shaped plastic optical fibers to monitor the curvature in real time through the loss of optical signals. The experiment shows the force-increasing effect of 1.6 times force amplification. Xi 'an Jiaotong University has designed a hand-assisted Exo based on lasso drive [3]. Three linear motors located on the forearm drive the movement of the five fingers through Bowden lines attached to the palm. Through experiments, this design can cover more than 60% of the range of motion of normal finger joints. At the same time, it can provide more than 14N of interphalangeal driving force, while ensuring that the steady-state error of position is controlled within 0.2mm and the steady-state error of pulling force varies only within 0.6N.

In terms of the structural design of the finger Exo, the research mainly focuses on two major categories: rigid structures and flexible structures. Rigid structures typically employ metallic materials such as aluminum alloys or titanium alloys to offer high rigidity and high load capacity, making them suitable for scenarios that require precise control and high-precision rehabilitation training. However, the drawback of rigid structures is that they are relatively heavy, which may affect the comfort and portability of patients. In contrast, flexible structural designs employ lightweight materials such as carbon fiber or flexible polymers to enhance comfort and portability. Flexible structures adapt to the hand shapes and movement requirements of different patients through their flexibility, but they may be insufficient in terms of load capacity and accuracy. In addition, some new materials, such as shape memory alloys and electroactive polymers, have also shown good application prospects in the structural design of the finger Exo.

This paper adopts the method of literature review to systematically review and analyze the research progress of structure design in finger Exo rehabilitation robots. Through the review of relevant domestic and foreign literatures, the basic principles, driving methods, control strategies of the finger Exo and the research status of human-computer interaction technology were summarized. This article aims to review the research progress of finger Exo rehabilitation robots, explore its application effect in rehabilitation treatment, and analyze the existing problems in the current research and the future development direction.

2. The structural Design of the Exoskeleton of Fingers

2.1 Rigid Structure Design

Rigid structures usually adopt metallic materials, such as aluminum alloys or titanium alloys, to provide high rigidity and high load capacity. For example, the HX (Hand Exoskeleton) is driven by rigid connecting rods and motors, with a degree of freedom of 2+ DOF per finger (including thumb palm-to-palm movement), and can achieve: precise grip: ~ 10.3N (the highest among similar types). However, its wearing weight can reach 499 g, and joint dislocation may cause pain problems [4]. Another similar rigid Exo is Maestro (EMG-driven Exo), which also uses rigid connecting rods for driving. The difference is that it also employs a series elastic driver (SEA) [5]. Zhong Siling et al. from Shanghai Jiao Tong University designed a rigid full-finger functional rehabilitation robot that can perform the functions of most joints [6]. The thumb part is driven by a micro-electric push rod, while a similar six-bar mechanism is used on the other four fingers, with a total of 10 active degrees of freedom.

By comparing the three rigid Exo designs, it can find that this structure can withstand a large torque and is suitable for completing tasks that require high loads. This design is suitable for scenarios that still require precise control and high-precision rehabilitation training. For instance, some Exo devices employ rigid linkage mechanisms, enabling the flexion and extension movements of fingers and providing sufficient torque to complete grasping and operational tasks. However, the drawback of rigid structures is that they are relatively heavy, which may affect the comfort and portability of patients. In addition, the flexibility of rigid structures is poor, which may cause discomfort to the patient's hands during movement.

2.2 Flexible Structure Design

Flexible structures employ lightweight materials such as carbon fiber or flexible polymers to enhance comfort and portability. The flexible Exo composed of fabric gloves such as Exo-Glove and Pneumatic Artificial Muscles (PAMs) has 3 degrees of freedom (DoF) OF (MCP, PIP, DIP coupling) and, the achievable maximum grip force of a single finger is 10 N, while its weight without the air pump is only 200 g [7]. This makes it suitable for stroke rehabilitation training, and it is highly wearable, allowing for smooth use without the need for precise joint alignment. Similar soft rehabilitation gloves designed by Polygerinos and others are composed of silicone/fabric gloves and pneumatic soft actuators. Its degree of freedom (DoF) is: The maximum grip force of a single finger achievable with 3 DoF (coupling of MCP, PIP, and DIP) is 5 N, and the weight without the air pump is 150 g (without the air pump) [8]. It is suitable for low-cost family rehabilitation training and can achieve customized plans.

Through comparison, it can be analyzed that the flexible structure ADAPTS to the hand shapes and movement needs of different patients through its flexibility, reduces discomfort during the movement process, and improves comfort. However, due to the limitations of materials and other factors, flexible structures have limited load-bearing capacity and poor durability. For instance, some flexible exoskeletons are driven by pneumatic or hydraulic means. Although they can provide a certain torque, they may perform poorly in high-load tasks [8].

2.3 Hybrid Structure Design

The hybrid structure combines the advantages of both rigid and flexible structures, aiming to provide high load capacity and high flexibility to enhance the adaptability and portability of the equipment. For example, the granular obstruction variable stiffness hand rehabilitation robot developed by Thompson-Bean et al. uses Ecoflex 00-30 rubber and granular materials, and realizes passive finger movement through air pressure control, but the output force is insufficient. Li Min et al. from Xi 'an Jiaotong University proposed a Tau-jerk motion planning and Exo structure optimization method. It assists the stretching and bending training of fingers through a rigid-flexible coupling approach and guides the movement of rehabilitation Exo based on the movement patterns of human fingers, which is in line with human movement patterns and safe human-computer interaction [9]. Through comparative analysis, some Exo devices adopt a combination of rigid connecting rods and flexible joints, which not only ensures high load capacity but also improves flexibility [9]. The design of the hybrid structure needs to strike a balance between rigidity and flexibility to meet different rehabilitation needs. However, the way of mixing the two structures increases the design difficulty and maintenance difficulty, and will generate relatively high costs.

2.4 Summary

The structural design of exoskeletons requires comprehensive consideration of multiple factors such as biomechanical characteristics, DoF of movement, torque output, patient comfort, and the portability of the equipment. Rigid structures are suitable for rehabilitation tasks that require high load capacity and high precision, but they are relatively heavy and have poor flexibility. Flexible structures can enhance the comfort and portability of patients, but they may be insufficient in terms of load capacity and accuracy. Hybrid structures combine the advantages of both rigid and flexible structures, capable of providing high load capacity and high flexibility, but their design and maintenance are relatively complex. Future research should further optimize the structural design of Exo to improve its performance and rehabilitation effect.

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3 Drive Mode

3.1 Traditional Driving Mode

Rigid linkage is the traditional driving mechanism used in robot systems and is usually applied in commercial Hand rehabilitation equipment such as Hand of Hope and Reha-Digit [10, 11]. This mechanism is usually composed of metal or 3D-printed rigid rods, forming continuous joints or rods/redundant connecting rods. The spatial motion of the actuator of this mechanism is directly converted into the spatial motion of the joint through rigid transmission. Therefore, the encoder signal, current or torque measured from the actuator directly reflects the corresponding state of the finger, which makes manual control intuitive and clear. Although few research reports on grasping force performance, the rigid connecting rod type shows the highest average precision grasping force (~10.3 N) among all types of drive mechanisms [12]. In addition, pneumatic/hydraulic is also a traditional driving method. Panagiotis Polygerinos et al. proposed a kind of soft robot glove, whose hydraulic drive is accomplished by a multi-stage soft actuator, and this actuator is made of an elastomer with fiber reinforcement [8]. A soft wearable hand Exo, ExoGlove, was proposed [13]. It uses pneumatic actuators with variable stiffness at different positions and can be attached to gloves according to different hand treatment exercises required. For hand grasping, through experiments, ExoGlove can generate a force greater than the minimum force required to lift an object in hand grasping and pinching actions.

3.2 New Driving Mode

Compared with traditional driving methods, motor driving can directly drive joints through servo motors or DC motors or transmit force through tendons/connecting rods. It can achieve high precision, large torque (up to 15N·m), and fast response (<100ms). Such as MANUS Hand Exo (18 DoF, remote motor + Bowden line drive, peak force 15N/ finger) and HEXORR (Single motor-driven multi-finger tendon drive, force control accuracy ±0.5N) [14, 15]. In addition, tendon drive is also a new type of drive method. Its inspiration comes from the mechanism of anatomical finger structure, including the tendons, ligaments, and muscles of the wearable part, pursuing bionic design [16, 17]. Such as Sang Wook Lee et al. designed a driving system. This driving system uses seven DC motors to drive the external tendons to control the movement of the fingers. The tendons are pulled by the motors, and after being buffered by the springs, the fingers are driven to complete precise movements [16]. The average bending Angle of the MCP joint of the hand Exo device designed by Decker et al. is 58.5°, which is higher than that of most devices. However, the cost is that all its DC motors have to be installed on the Exo, making the equipment heavier (454g).

3.3 Summary

The structural design of exoskeletons requires comprehensive consideration of multiple factors such as biomechanical characteristics, DoF of movement, torque output, patient comfort, and portability of the device. Rigid structures are suitable for rehabilitation tasks that require high load-bearing capacity and high precision, but they are relatively heavy and have poor compliance. Flexible structures can enhance patient comfort and portability, but they may be deficient in load-bearing capacity and precision. Hybrid structures combine the advantages of rigid and flexible structures, providing high load-bearing capacity and high compliance, but their design and maintenance are relatively complex. Future research should further optimize the structural design of exoskeletons to improve their performance and rehabilitation effects.

4. Human-Computer Interaction Technology

Human-computer interaction technology is a key component of the finger Exo system, directly affecting the user experience and rehabilitation effect of the equipment. Good human-computer interaction technology can enable patients to control Exo devices more naturally and efficiently, thereby improving the effect of rehabilitation training and patient satisfaction.

4.1 sEMG Signal Control

sEMG is one of the most commonly used human-computer interaction technologies in finger Exo. sEMG signals predict the movement intentions of patients by detecting the electrical signals of their muscles, thereby achieving active rehabilitation training. The advantages of this technology lie in its non-invasiveness, ease of implementation and high signal resolution, which can directly reflect the patient's movement intention and improve the patient's participation and rehabilitation effect [18]. However, sEMG signals also have some drawbacks. For instance, in the study by Liu et al., due to muscle spasms, the autonomous electromyogram activities were contaminated by involuntary muscle contractions [19].

4.2 Voice Control and Visual Feedback

Voice control and visual feedback technologies have also been applied in some designs of Finger exoskeletons, further enhancing the naturalness and effectiveness of human-computer interaction. Considering that some patients have severe discomfort in their hands and have difficulty completing rehabilitation movements, voice control can be used when the patient's hand function is limited. For example, in the FLEXotendon GloveT-II proposed by P. Tans, the voice control it adopts is more compact and only requires a smart phone for on-board signal processing. And a microcontroller with Bluetooth Low Energy (BLE) function is required to control the motor [20]. Visual feedback technology helps patients better control Exo devices and improve the effect of rehabilitation training by providing real-time visual information [21].

4.3 Summary

The human-computer interaction technology of finger exoskeletons is the key to improving the user experience of the equipment and the rehabilitation effect. sEMG is currently the most widely used human-computer interaction technology. Voice control and visual feedback technologies have further enhanced the naturalness and effectiveness of human-computer interaction. Future research should further optimize these technologies, improve the accuracy and efficiency of signal processing, and at the same time reduce the complexity and cost of the system, so as to promote the development and application of finger exoskeletons technology.

5. Discussion

5.1 The Challenges and Problems of the Current Research

The main challenges of the current research cover multiple dimensions. The first one is the anatomical and functional complexity. The human hand has 15 joints and 20 DoF. Due to factors such as its structure and materials, the existing exoskeletons lack sufficient support for fine movements (such as palmar interaction and rolling), and thus cannot fully achieve the Dof consistent with the functions of the human hand [9]. Secondly, there are bottlenecks in sensing and control. The reasons are the lack of force/torque feedback, insufficient application of advanced algorithms such as impedance control, which limits the effect of rehabilitation training. In addition, the biological signals (such as sEMG) are noisy, have a low recognition rate for spasticity patients, and the graphical interface (GUI) requires additional attention from users [5]. Next comes the issue of safety and comfort that users are very concerned about. For instance, rigid structures are prone to causing secondary injuries, while soft materials have problems such as low force transmission efficiency and joint alignment issues [6]. The lack of assessment and standardization is also a major challenge at the current stage. There is a lack of unified standards for relevant functional tests, and most studies are only verified by healthy subjects, thus lacking authority [7]. In terms of the cost in the popularization stage, customized design is costly, and lightweight materials (such as carbon fiber) and drive technologies (such as artificial muscles) have not yet been widely adopted [6].

5.2 Future Development Directions and Trends

Future technological innovations may focus on the following aspects: The first is the application of new materials such as shape memory alloys and electroactive polymers, which possess both lightweight and high-load capabilities, and are expected to address the limitations of existing structures [9]. In addition, in terms of control algorithms, it is expected to combine the currently popular artificial intelligence and machine learning technologies to optimize control strategies. Then, in terms of the integration of human-computer interaction technologies, it is not limited to the single interaction strategy mentioned above. Instead, sEMG, EEG, voice control, visual feedback and other technologies should be combined to enhance the naturalness and efficiency of interaction [22]. Finally, different hand sizes and disability degrees can be matched according to the individualized needs of different patients. Modular design can be added to improve the universality and scalability of the equipment [23].

6. Conclusion

This paper systematically reviews the design and control research of finger joint-assisted motion rehabilitation robots, with a focus on analyzing the research progress in structural design, driving mode, and human-computer interaction technology. Rigid structures are suitable for high-load and high-precision tasks, but their weight and comfort are limited. Flexible structures are lightweight and comfortable, but have insufficient load capacity. The hybrid structure attempts to combine the advantages of both. Among the driving methods, motor drive has high precision but limited load capacity, while hydraulic drive has strong load capacity but a complex system. Human-computer interaction technologies such as sEMG offer the possibility of natural control, but signal processing technologies still need to be optimized. Then it is discovered that future research should focus on optimizing structural design, exploring new driving methods and human-computer interaction technologies, and reducing equipment costs to promote popularization and benefit more patients.

Finger joint rehabilitation robots represent a promising field that requires multidisciplinary collaboration and innovation to provide patients with more efficient and comfortable rehabilitation solutions.

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