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Structural Analysis and Control Optimization of Finger Exoskeleton Design Modeling

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Abstract:

With the increasing incidence of hand dysfunction caused by stroke, spinal cord injury, and other conditions, finger exoskeletons have emerged as a critical technology in rehabilitation medicine, assistive technology, and human-computer interaction. This paper reviews the structural analysis and control optimization of finger exoskeleton design and modeling. It first elaborates on their application significance in aiding functional recovery for patients, assisting daily activities for people with disabilities, and enhancing human-machine interaction efficiency, while highlighting core challenges such as biomechanical compatibility, motion precision, and control efficiency. Then, it analyzes structural design aspects including mechanical architectures (rigid, soft-rigid hybrid, modular adjustable) and key considerations like biomechanical constraints and wearability. It also discusses control optimization strategies such as trajectory planning, force control, and impedance control. Finally, it identifies current limitations in structure, compatibility, and algorithms, and prospects future directions like sensor network integration and bionic design. This review offers valuable insights to promote the technical advancement and practical application of finger exoskeletons.

Keywords: Finger Exoskeleton; Sensor; Rehabilitation.

1. Introduction

1.1 Research Background and Significance

In today's era of rapid technological development, rehabilitation medicine, assistive technology and human-computer interaction applications are undergoing unprecedented changes. Finger exoskeletons, as a key technology, have received widespread attention. In the field of rehabilitation medicine, finger exoskeletons can provide effective rehabilitation training for patients with hand dysfunction caused by diseases such as stroke and spinal cord injury, helping them restore the movement of their fingers and improve their ability to take care of themselves; in terms of assistive technology, finger exoskeletons can help people with limb disabilities or insufficient strength to complete daily life movements, such as grabbing objects and operating tools, and enhance their ability to live independently; in human-computer interaction applications, finger exoskeletons can accurately capture the movement intentions of human fingers and achieve efficient interaction with machines, for example, playing an important role in scenarios such as virtual reality and remote control. However, finger exoskeleton design faces many challenges. First, biomechanical compatibility is the primary problem. The structure and movement of the exoskeleton must match the biomechanical characteristics of human fingers, otherwise it will cause harm to the human body or affect the use effect; second, the movement accuracy requires the exoskeleton to accurately follow the movement of the fingers to ensure the accuracy of the operation, especially in some precision operation scenarios; third, the control efficiency is related to the response speed and energy consumption of the exoskeleton. Efficient control can improve its user experience and endurance.

This paper aims to focus on the structural design principles, modeling methods and control optimization strategies of finger exoskeletons, covering the latest progress in mechanical design, kinematics and dynamics modeling and intelligent control. Through systematic sorting and analysis of these aspects, it provides a comprehensive reference for relevant researchers and promotes the further development of finger exoskeleton technology.

1.2 Research Content and Chapter Arrangement of This Paper

This paper focuses on the structural analysis and control optimization of finger exoskeleton design modeling.

Chapter 1 is the introduction, which explains the research background and significance, the current status of domestic and international research, and the research content and chapter arrangement of this article.

Chapter 2 discusses the structural design of the finger exoskeleton in detail, including the mechanical architecture and key design considerations.

Chapter 3 focuses on the analysis of control optimization strategies, covering aspects such as trajectory planning and motion control, force and impedance control, etc.

Chapter 4 discusses the current challenges facing finger exoskeletons and future development directions.

Chapter 5 is the conclusion, which summarizes the main research findings, points out research gaps and makes suggestions for future work.

2. Structural Design of Finger Exoskeleton

2.1 Mechanical Architecture

The mechanical structure of finger exoskeletons is mainly divided into rigid exoskeletons, soft-rigid hybrid exoskeletons, and modular adjustable designs. Figure 1 shows two types of commercial hand exoskeletons [1].

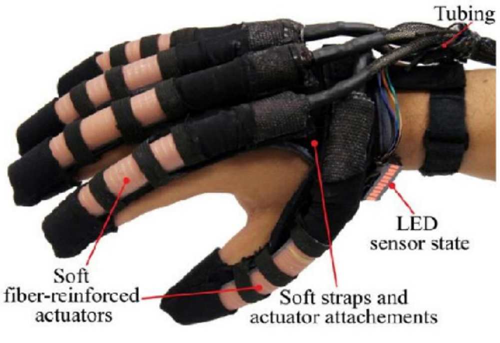

Fig. 1 Commercial hand exoskeleton (a) Rigid pneumatic exoskeleton (b) Fiber-reinforced soft-actuated exoskeleton [1].

Rigid exoskeletons often use serial or parallel mechanisms, and their joint drive configurations are diverse. The serial mechanism is similar to the bone structure of human fingers, with each joint connected in sequence, which can achieve relatively flexible single-degree-of-freedom movement; the parallel mechanism drives the end effector simultaneously through multiple branches, and has the characteristics of high rigidity and strong load-bearing capacity. It is widely used in scenarios that require high precision and large loads. For example, some finger exoskeletons used for industrial assistance use parallel mechanisms to ensure stability when grasping heavy objects. Figure 2 shows the schematic diagram of the multi-segment continuous motion of fingers based on the Tau-jerk guidance strategy [2].

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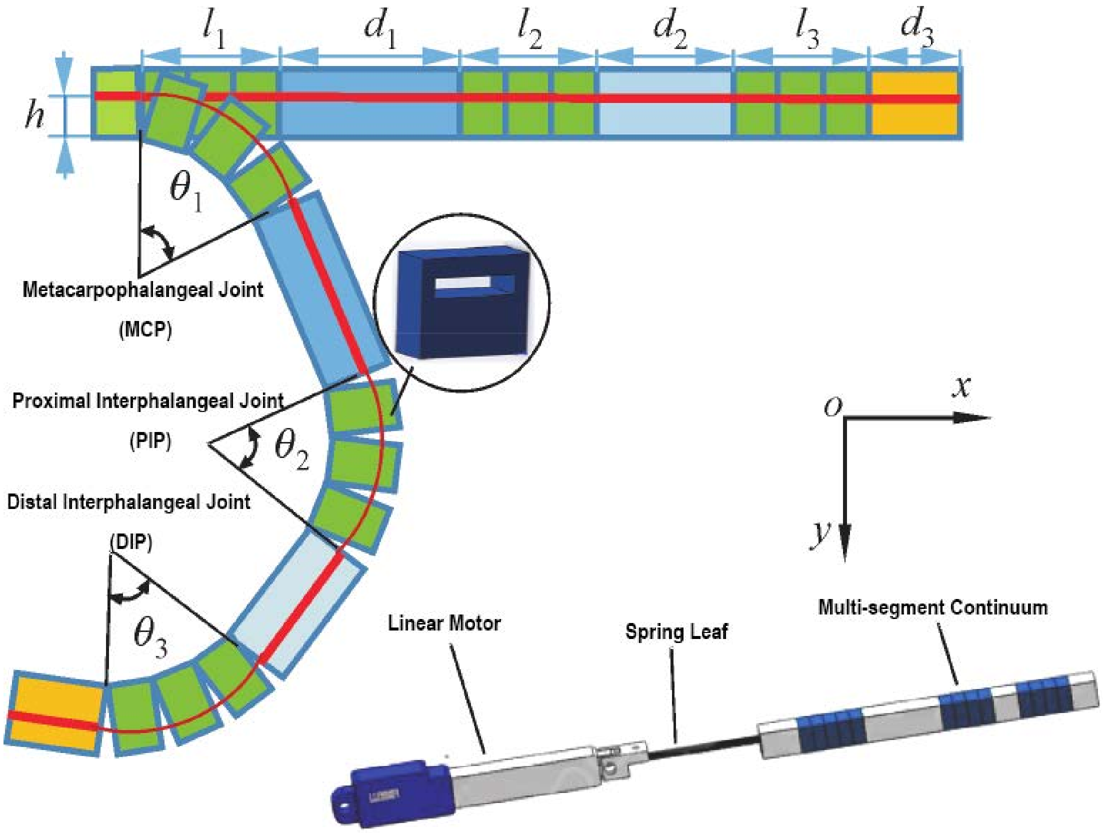

Fig. 2 Schematic diagram of multi-segment continuous motion of fingers based on Tau-jerk guidance strategy [2]

The soft-rigid hybrid exoskeleton combines the advantages of flexible materials and compliant mechanisms. Flexible materials such as silicone and elastic polymers have good deformation capabilities and can better adapt to the natural movement of fingers; compliant mechanisms achieve motion transmission through their own elastic deformation, avoiding the friction and gap problems caused by hinge connections in traditional rigid mechanisms. This hybrid structure is widely used in the field of rehabilitation, which can reduce the restraint and pressure on human fingers and improve wearing comfort. Domestic research has made innovations in this area: Zhu Shengchen, et al. designed a multi-segment continuous structure exoskeleton finger function rehabilitation robot driven by a single-layer spring sheet, which has good flexibility and safety, demonstrating the application value of soft-rigid hybrid structures in improving wearing comfort and safety [3].

Modular and adjustable design for different finger sizes and pathological conditions has been a research hotspot in recent years. Through modular design, different modules can be replaced according to the user‘s finger length, thickness and other parameters to meet personalized needs. For patients with rheumatoid arthritis and other diseases that cause finger deformation, the adjustable design can make the exoskeleton fit the fingers better and ensure the effectiveness of rehabilitation training.

In terms of drive technology, domestic researchers have explored diverse solutions. Zuo Kexin, et al. used shape memory alloy (SMA) wire as the driver to develop a hand function rehabilitation robot prototype and conducted relevant performance tests, providing a new idea for lightweight and miniaturized drive design [4]. Internationally, bionic design has become a key direction for structural innovation. Guotao Li et al. proposed a bionic flexible finger exoskeleton based on a double-layer non-parallel spring structure, which has significant improvements in stiffness and load-to-mass ratio, showing the advantages of bionic design in optimizing structural performance [5].

2.2 Key Design Considerations

Several key factors need to be considered during the design of the finger exoskeleton.

Biomechanical constraints are the primary consideration, including the natural range of motion of the fingers, joint kinematics, etc. Each joint of the finger has its own specific range of motion angles, and the exoskeleton must be designed within this range to avoid damage to the joints due to excessive movement. At the same time, it must comply with the laws of joint kinematics to ensure that the movement of the exoskeleton is consistent with the natural movement trajectory of the fingers.

The load-bearing capacity and force transmission efficiency directly affect the practicality of the exoskeleton. The exoskeleton needs to have a certain load-bearing capacity to meet the needs of operations such as grasping objects. The force transmission efficiency is related to the effective use of the output force of the drive device. Efficient force transmission can reduce energy loss and improve the working efficiency of the exoskeleton. For example, when designing the transmission mechanism, the use of efficient transmission methods such as gears and connecting rods can improve the force transmission effect.

Wearability and comfort are also aspects that cannot be ignored. Ergonomic design can make the exoskeleton fit the fingers better and reduce interference during exercise. The choice of materials is crucial. Lightweight materials such as polymers or carbon fiber can not only reduce the weight of the exoskeleton and reduce the burden on the wearer, but also have good strength and durability, suitable for long-term use.

In structural optimization, finite element analysis has become an important tool. Zhang Qiuyue, et al. used the finite element method to perform stress analysis on the key components of the finger rehabilitation exoskeleton robot, providing a basis for structural optimization, which helps to improve the structural stability and service life of the exoskeleton [6].

3. Control Optimization Strategy

3.1 Trajectory Planning and Motion Control

Trajectory planning is the basis of finger exoskeleton control. Its purpose is to generate a smooth and efficient motion trajectory so that the exoskeleton can accurately follow the expected motion path. Common trajectory planning methods include polynomial interpolation and spline curves. The polynomial interpolation method is simple and easy to use, but it may be insufficient in terms of trajectory smoothness; spline curves can achieve smoother trajectories through segmented fitting and are widely used in scenarios such as rehabilitation training that require high motion smoothness. Domestic research has made progress in trajectory planning: He Bo, Xu Guanghua, et al. proposed a finger motion trajectory planning method based on the Tau-jerk guidance strategy, which effectively improves the compatibility between exoskeleton movement and human finger movement [2].

Motion control is to adjust the motion state of the exoskeleton in real time according to the planned trajectory. PID control is a classic motion control algorithm with the characteristics of simple structure and strong robustness. It has been widely used in finger exoskeletons. However, simple PID control does not work well in complex dynamic environments. Therefore, it is often combined with other control methods, such as model predictive control and fuzzy logic algorithm [7] (as shown in Figure 3).

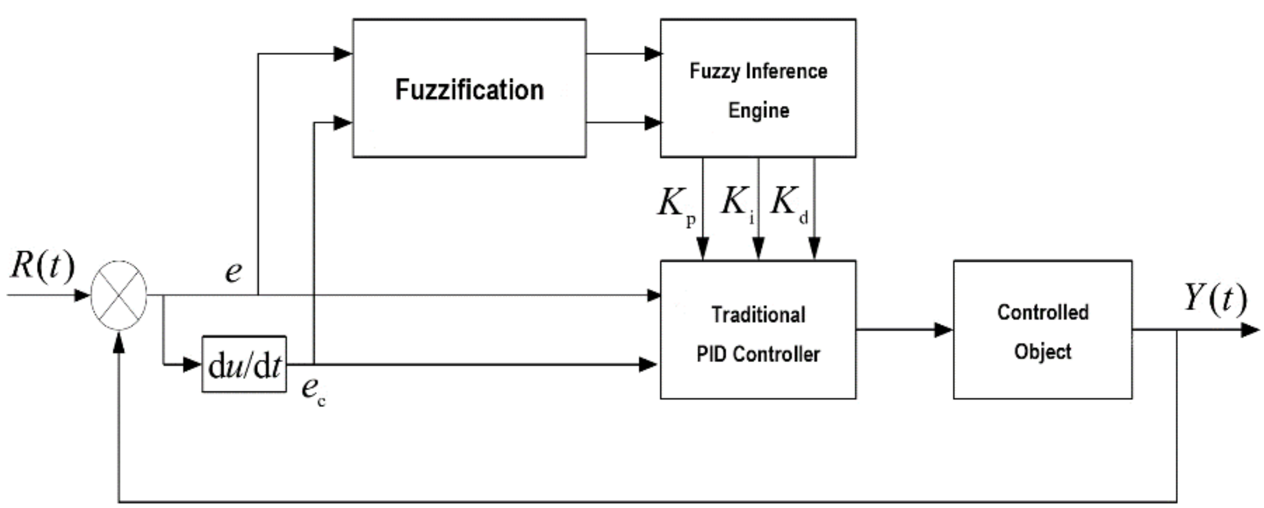

Fig. 3 Fuzzy PID control system structure diagram [7]

Internationally, optimization algorithms have been applied to improve the accuracy of motion mechanisms. Seyyed Mojtaba Varedi-Koulaei et al. used a swarm intelligence optimization algorithm to optimize the design of the Stephenson-II linkage mechanism, and the error was reduced after the optimization design, which provides a reference for improving the precision of exoskeleton motion [8].

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3.2 Force and Impedance Control

Force and impedance control are crucial for the interaction between the finger exoskeleton and the environment. Force control aims to accurately control the force output by the exoskeleton to ensure that it can provide sufficient clamping force when grasping an object without damaging the object. Impedance control adjusts the stiffness and damping characteristics of the exoskeleton to enable it to adapt to changes in the environment. For example, when contacting objects of different hardness, it automatically adjusts its own impedance to ensure the stability of the operation.

The combination of PID + model predictive control performs well in force and impedance control. PID control is responsible for quickly tracking force instructions, while model predictive control optimizes PID parameters based on the dynamic characteristics of the system and future force requirements to improve control accuracy and robustness. In rehabilitation training, through force and impedance control, the exoskeleton can provide patients with appropriate auxiliary force to help them complete specific movements while avoiding injuries to patients due to excessive force.

In terms of improving control adaptability, Zhonghan Chen et al. designed and optimized an index finger exoskeleton robot with an underactuated mechanism, and improved the control performance by combining genetic algorithms [9]; Rui Qian et al. improved the adaptability of the index finger rehabilitation exoskeleton by adding sensors and improving the structure, which provides new ideas for enhancing the control effect of exoskeletons in complex environments [10].

4. Challenges and Future Directions

4.1 Current Limitations

Current finger exoskeletons have many limitations. In terms of structure, the wearing comfort of rigid exoskeletons needs to be improved, while the load-bearing capacity and control accuracy of flexible exoskeletons are relatively low. In terms of biomechanical compatibility, it is difficult to achieve a perfect match between the exoskeleton and different individual fingers, especially for patients with deformed or dysfunctional fingers.

In terms of control, existing control algorithms lack real-time and robustness when dealing with complex dynamic environments and individual differences. For example, when the user‘s movement intention changes suddenly, the exoskeleton‘s response may be delayed, affecting the user experience. In addition, the measurement accuracy and reliability of the sensor will also limit the control effect. Force/torque sensors, inertial measurement units, etc., are susceptible to interference in complex environments.

4.2 Emerging Trends

Integrated sensor networks are an important development direction for the future. By installing force/torque sensors, inertial measurement units, etc., on finger exoskeletons, real-time monitoring of the motion state and interaction force of human fingers can be achieved, providing accurate feedback information for control algorithms. Real-time feedback enables the exoskeleton to quickly adjust motion and force output, improving control accuracy and safety.

Bionic design and development is committed to simulating the flexibility and adaptability of human fingers [11]. By studying the anatomical structure and movement mechanism of human fingers, an exoskeleton structure that is more in line with biomechanical characteristics is designed. For example, by imitating the multi-degree-of-freedom movement of finger joints and adopting a new drive method and transmission mechanism, the exoskeleton has higher flexibility and range of motion.

The hybrid control framework that integrates model-driven and data-driven control is an emerging trend in the field of control. The model-driven approach is based on the mathematical model of the system and has a strong theoretical basis; the data-driven approach optimizes the control strategy by learning from a large amount of data and can better cope with the uncertainty and complexity of the system. The hybrid control framework combines the advantages of both and can improve the control performance and adaptability of the exoskeleton.

5. Conclusion

This paper systematically reviews the structural analysis and control optimization of finger exoskeleton design modeling. In terms of structural design, rigid exoskeletons, soft/rigid hybrid exoskeletons, and modular adjustable designs each have their own characteristics, with domestic and foreign studies showing innovations in drive technology (such as SMA), bionic structure design, and finite element-based structural optimization. The key design needs to consider biomechanical constraints, load-bearing capacity and force transmission efficiency, as well as wearability and comfort. In terms of control optimization strategy, the application of trajectory planning methods (such as Tau-jerk guidance strategy), motion control algorithms (such as fuzzy PID), and optimization algorithms (such as swarm intelligence optimization) improves the performance of the exoskeleton, while force and impedance control enhance the interaction stability between the exoskeleton and the environment.

Current research still has gaps in the precise matching of biomechanical compatibility, the real-time and robustness of control algorithms, and the integration and reliability of sensors.

Future work can be carried out in the following aspects: in-depth research on the biomechanical properties of human fingers, establishing a more accurate model, and improving the biomechanical compatibility of the exoskeleton; developing more advanced control algorithms, combining artificial intelligence, machine learning and other technologies to improve the real-time and robustness of control; optimizing the layout and performance of sensors, improving measurement accuracy and anti-interference ability, and achieving more accurate real-time feedback.

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