Research of Structural Forms and Human-Robot Interaction Control Technologies for Hand Exoskeletons

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Abstract. As a key rehabilitation assistive device, hand exoskeleton plays an important role in helping patients with functional impairments to restore hand function. Although significant progress has been made in some areas of mechanism design, intention prediction and control schemes in recent years, challenges still exist in terms of natural interactivity, control accuracy and structural design. This paper systematically reviews the current research status of structural design and human-computer interaction technology of hand exoskeletons. Based on the structural form, hand exoskeletons are divided into three categories: rigid, flexible and soft, and the technical characteristics and application advantages of each type are analyzed in detail. By analyzing the problems existing in the current hand exoskeleton in terms of natural human-computer interaction, structural design and material application, and control system performance, the future development trend of hand exoskeletons in terms of practicality, lightweight and multi-field application is prospected. The rigid-flexible coupling design concept is innovatively proposed, and the linear drive and airbag control technology are integrated according to different joint characteristics, and the system adaptability is improved through the variable impedance control strategy. The future development direction focuses on optimizing intention recognition with deep learning algorithms, reducing weight and increasing efficiency with new composite materials, and enhancing control real-time performance with multimodal sensing technology, providing theoretical support for the intelligent application of hand exoskeletons in rehabilitation medicine, industrial collaboration and other fields.

INTRODUCTION

At present, the global data on hand dysfunction is becoming increasingly serious. Hand dysfunction not only affects patients' daily activities, but also has a significant impact on their quality of life. Hand exoskeletons interact with human hands through human intention recognition to provide patients with motion assistance or hand function recovery support. Its application in the field of rehabilitation can not only achieve high-intensity and repetitive training tasks, but also promote neural plasticity reconstruction, thereby accelerating the functional recovery of patients. Therefore, hand exoskeleton human-robot interaction is a field with high research value and prospects.

Hand exoskeleton human-robot interaction aims to control the exoskeleton in accordance with the movement characteristics of the human hand by identifying human intentions. Human intentions are converted into precise movements of actuators to help humans perform human-robot collaboration.

This paper systematically sorts out and analyzes the research status and development trends in the field of hand exoskeletons. The technical characteristics and application advantages of various types of exoskeletons are discussed. The problems existing in the current hand exoskeletons in terms of natural human-robot interaction, structural design, material application and control system are analyzed, and its future development direction in terms of intelligence, lightweight and multi-field application is prospected.

RESEARCH PROGRESS

Early rehabilitation robots borrowed from industrial robot technology, with the main goal of fully or partially restoring the manipulation function of disabled users by using robot arms or manipulators. With the development of driving and sensing technologies in the 1990s, hand exoskeletons emerged [1]. In the 21st century, hand rehabilitation robots have developed rapidly, showing a trend of a hundred schools of thought. According to the contact method, they can be summarized as end-contact type and exoskeleton type. In recent years, new components such as series elastic actuators and shape memory alloys have emerged to innovate the driving form of hand exoskeletons [2, 3]. Structurally, exoskeletons are gradually developing from large, bulky, and low-safety designs to small, light, portable, and high-safety human-computer interaction.

The research process of human-computer interaction of hand exoskeletons can be divided into cHRI and pHRI [4]. Physical human-computer interaction (pHRI) is a physical-level two-way interaction process between humans and robots, which directly affects the safety of hand exoskeletons and user experience [5]. Cognitive human-computer interaction (cHRI) is a two-way information interaction process between machines and humans. cHRI mainly studies human intention recognition and control technology [6]. Human-machine interaction, from the formation of human intention to the execution of tasks by the exoskeleton, and then to feedback adjustment, emphasizes the collaboration and real-time adaptability between humans and exoskeletons. Figure 1 shows the process of human-machine interaction, as well as the scope of pHRI and cHRI.

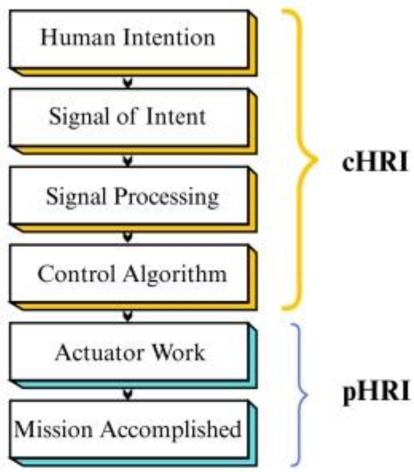

FIGURE 1. Schematic diagram of the HRI process of the exoskeleton device (Picture credit: Original).

Hand exoskeletons can be divided into three categories according to their structural form: rigid, tendon-connected, and soft. This classification is mainly based on their transmission method, material properties, and adaptability to the human body. This article summarizes some typical forms of hand exoskeletons from 2020 to 2025 as shown in Table 1.

TABLE 1. Typical hand exoskeleton devices in recent years

Author	**Years**	**Dofs**	**Mechanical transmission**	**Sensor Type**	**Actuation**	**Material**	**Control Method**
Butzer [7]	2020	15	Flexible	EMG/Bending Angle Sensor	DC	Plastic/Metal	Active
Wang [8]	2020	3	Soft	Force	Pneumatic	Rubber/Plastic	Passive
Ge [9]	2020	7	Soft	Air Pressure	Pneumatic	Fabric/Neoprene	Passive
Li [10]	2020	1	Soft	Flex Sensors/Force	Pneumatic	Fabric/Latex	Passive
Yang [11]	2021	15	Linkage	Position/Force	DC	Plastic/Fabric	Passive
Sun [12]	2021	3	Flexible	EMG/Position	DC	Plastic/Velcro	Active
Feng [13]	2021	5	Soft	EMG/Torque/Force	Pneumatic	Plastic/Fab	Active

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Li [14]	2022	6	Linkage	EMG/Position/Force	DC	Plastic/Metal	Active
Li [15]	2022	5	Linkage	Position/Force	DC	Metal/Neopren	Passive
Dragusanu [16]	2022	7	Flexible	IMU/Force/Position	Linear DC	Plastic/Metal	Active
Tran [17]	2022	5	Flexible	Force	DC	HCR	Passive
Chen [18]	2022	4	Flexible	Position/Force	SEA	Plastic	Passive
Jadhav [19]	2022	5	Soft	Position/Force	Pneumatic	PIB	Passive
Gerez [20]	2022	7	Soft	Vision/Force	Pneumatic	Rubber/Fabric	Active
Lai [21]	2023	1	Linkage	Position/Force	DC	Metal/Velcro	Passive
Michikawa [22]	2023	20	Linkage	Force	Linear DC	Plastic/Fabric	Passive
Sui [23]	2023	15	Flexible	Bending Sensors	SMA	Polyurethane	Passive
Wang [24]	2023	7	Soft	Force/Pressure	Pneumatic	Agilus30	Passive
Liang [25]	2024	5	Linkage	Force	Linear DC	Aluminum Alloy	Passive
Li [26]	2024	5	Flexible	Position/Force	Linear DC	Plastic/Velcro	Passive
Curcio [27]	2024	4	Flexible	EMG/Resistance/Thermal Camera	SMA	Polyurethane	Active
Liu [28]	2024	14	Soft	Aser Distance	Pneumatic	Rubber/Polyethylene	Passive
Hazar [29]	2025	20	Linkage	EMG/IMU	DC	Plastic	Active
Yun [30]	2025	4	Linkage	EMG/Force/Position	-	Plastic	Assessment
Curcio [3]	2025	12	Flexible	SMA Self-Sensing	SMA	Polyurethane	Passive

Linkage

Linkage exoskeletons are usually made of hard materials such as metal or hard plastic, and use gears, connecting rods, or joint mechanisms to achieve precise force transmission. Yang et al. proposed a portable hand rehabilitation exoskeleton device based on a gear rack mechanism [11]. The device adopts a modular design and a real-time feedback system. By using a circuitous joint to match the rotation center of the finger, secondary injuries are avoided. At the same time, it can adapt to fingers of different sizes and ensure the safety of rehabilitation training. The study developed an Android-based interactive system, which improved the patient's rehabilitation participation through a virtual reality environment, innovatively introduced force cognition functions, and used the Gaussian process regression (GPR) model to achieve accurate collision detection and force feedback control. However, when implementing force feedback and collision detection, there are still certain technical challenges due to the nonlinear characteristics of the Bowden cable. These innovations provide new research ideas for the field of hand rehabilitation exoskeletons, especially breakthroughs in portability, interactivity, and intelligent control. The Linkage exoskeleton has the characteristics of high strength and high precision, can accurately control finger movements and provide large output forces, and therefore performs well in scenarios requiring high load capacity. However, the disadvantages of rigid exoskeletons are also very significant. Their heavy weight and volume may affect the wearing comfort. At the same time, the rigid structure has poor adaptability to the natural movement of the hands and can easily cause joint dislocation or discomfort.

Flexible

Flexible exoskeletons achieve motion control through flexible materials and flexible transmission mechanisms. This design makes up for the shortcomings of rigid exoskeletons to a certain extent, can better fit the shape of the hand, and provides higher comfort and adaptability. Based on a deep understanding of the need for hand rehabilitation, Curcio et al. proposed an innovative hand rehabilitation exoskeleton device based on shape memory alloy (SMA) drive [27]. This method adopts a design that combines a modular polyurethane ring structure with an elastic steel sheet. Directly installing the SMA actuator close to the finger, significantly improves the shortcomings of traditional exoskeletons in terms of portability and adaptability. The study proposed three analytical models of different complexity, from rigid body kinematics to a composite model considering finger sliding, which provides a theoretical basis for exoskeleton design optimization. It also implemented a self-sensing control strategy based on resistance change, which can achieve closed-loop control without additional sensors. The innovative thermal insulation design ensures operational safety during the SMA drive. Experimental results show that the device can effectively reduce the user's muscle activity intensity by about 50%, showing a good rehabilitation assistance effect. Flexible exoskeletons are usually used in scenarios that require lightness and flexibility, such as daily assistance and mild rehabilitation training. Due to the mechanical properties of flexible materials, their output force and control accuracy are usually low, making it difficult to meet the needs of high-intensity tasks. In addition, flexible transmission systems may have problems such as friction loss, nonlinear control, and material fatigue.

Soft

Soft exoskeletons use pneumatic, hydraulic or shape memory alloy drive methods and are based on soft materials such as silicone or fabric. They can achieve motion control through deformation or pressure changes. Gerez et al. proposed an innovative hybrid soft robotic exoskeleton glove design based on the biomechanical characteristics of human hand grasping [20]. This solution combines the tendon drive system with the soft inflatable structure for the first time, and enhances the grasping stability through the inflatable ring array and telescopic thumb structure, providing a new technical path for the design of soft exoskeletons. The research team integrated a visual recognition system in the palm and developed a semi-autonomous shared control solution based on object recognition, which significantly lowered the threshold of use and avoided the operational limitations of traditional exoskeleton gloves that rely on EMG sensors or mechanical buttons. Soft exoskeletons have extremely high flexibility and adaptability, and can fit the natural movement of the hand well. They are particularly suitable for scenarios that require complex interactions or fine operations, such as rehabilitation assistance and tactile feedback applications in virtual reality. The design of soft exoskeletons also faces many challenges, such as the complexity of the drive system, the difficulty of nonlinear control, and insufficient output force. Pneumatic or hydraulic drive methods may require external equipment support, affecting their portability and ease of use.

ERGONOMIC DESIGN

The hand mainly includes the wrist joint, metacarpophalangeal joint (MCP), proximal interphalangeal joint (PIP), and distal interphalangeal joint (DIP) as shown in Figure 2. The MCP joint is an elliptical or condylar joint with an oval-elliptical articular surface. It is biaxial and can achieve flexion/extension (f/e) and abduction/adduction (a/a) movements. The PIP joint and the DIP joint are both bicondylar joints with a biovoid articular surface. Their main movement is (f/e), with a relatively small range of motion, and they are mainly used for fine finger movements.

The movements of the PIP and DIP joints are coupled, that is, when the PIP joint flexes or extends, the DIP joint will also move accordingly. This coupling relationship is crucial for the precise movement of the fingers and helps to complete complex movements such as grasping and pinching.3.1.2 Innovative method of cycle current suppression:

Hand kinematic analysis mainly studies parameters such as angle, velocity, trajectory, and acceleration during hand movement. Measurement equipment includes X-ray, magnetic resonance imaging (MRI), goniometer, electric goniometer, and three-dimensional motion analysis system. Ahmadi et al. combined the entire spike activity (ESA) as the input signal with the quasi-recurrent neural network (QRNN) decoding algorithm and replaced the traditional BMI method through long-term experimental verification. A comprehensive performance evaluation was used to obtain the final decoding results, showing better stability and accuracy in the hand motion decoding of the braincomputer interface [31]. Jarque-Bou et al. used larger-scale calibration data to improve hand kinematic modeling research and proposed a comprehensive dataset containing 77 subjects and 40 hand movements [32]. This dataset collects 22 sensor data through the CyberGloveII data glove and uses post-processing calibration methods to solve the sensor nonlinearity problem. It can accurately record and analyze complex hand movements including isometric and isotonic hand configurations, basic wrist movements, and daily grasping, providing important data support for research in many fields such as robotics, 3D modeling, rehabilitation medicine, and neuroscience.

In the design of hand exoskeletons, the optimization of ergonomics is crucial. Through in-depth research on hand anatomy and biomechanics, designers are able to develop exoskeleton devices that conform to the natural movement patterns of the human body. The use of lightweight materials and advanced sensing technology can effectively reduce the weight of the device and improve user comfort while ensuring accurate capture and feedback of hand movements.

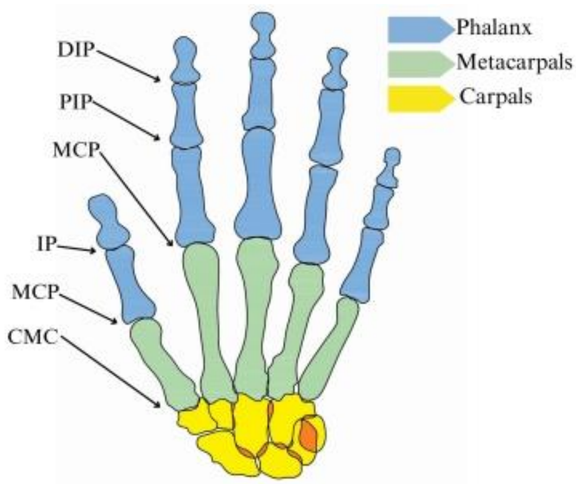

FIGURE 2. Simple diagram of the hand structure (Picture credit: Original).

EXISTING DEFICIENCIES

In recent years, significant achievements have been made in the field of hand exoskeleton human-computer interaction, but there are still many problems to be solved:

The Problem of Insufficient Naturalness in HRI

In practical applications, hand exoskeletons need to work closely with the human body, such as rehabilitation training, daily assistance, industrial collaboration, and other scenarios. Compared with traditional mechanical equipment, the main challenge of natural human-computer interaction lies in the complexity of human movement. The human hand has a high degree of flexibility and precision, and the strength, speed, and trajectory of different movements vary, which increases the difficulty of control. In actual use, individual differences of users and environmental changes will further increase the difficulty of interaction.

In the future, the ability of the device to recognize and respond to human movements can be improved by improving the intention recognition algorithm and sensor system. Or a more advanced variable impedance control strategy can be adopted to adjust the stiffness and damping of the device in real time to achieve a more natural human-computer interaction experience. Long et al. proposed an online sparse algorithm based on Gaussian process regression to learn human motion intention (HMI) from physical human-computer interaction signals [33]. This method drives the exoskeleton through a fuzzy-PID control strategy and demonstrates the potential for precise motion assistance in complex environments. However, the computational complexity of this method on large-scale data sets is still a problem. How to optimize the algorithm to improve real-time performance and accuracy is an important direction for future research.

Problems with Structural Design and Material Limitations

Existing designs of hand exoskeletons mainly focus on rigid structures and simple soft structures, and there is relatively little research on composite structures that have both rigid and flexible characteristics. This leads to problems such as excessive weight or insufficient force output in practical applications of hand exoskeletons. Even in mainstream designs, there are some special problems, such as the excessive size of the drive system and unreasonable sensor layout, which also require targeted solutions.

Elastic actuators provide a solution to improve force control and interactive safety. Calanca et al. proposed an exoskeleton design based on low-inertia electromagnetic motors, which improved the robustness and performance of force control by reducing the motor inertia, thereby reducing the sensitivity to wearer impedance changes [34]. Keppler et al. studied elastic structure preservation (ESP) control in elastic joint robots, and achieved excellent positioning accuracy and compliance with environmental contact by combining non-colocated integral actions [35]. The design of elastic actuators needs to consider the durability of materials, energy efficiency, and compatibility with the human body to ensure the reliability and comfort of the equipment in long-term use.

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The design of underactuated grippers can achieve complex grasping actions while reducing the number of actuators. Birglen et al. proposed a method to analyze the force capability of underactuated fingers. This method can effectively study the grasping stability of different underactuated mechanisms by introducing a matrix to describe the relationship between the input torque of the finger actuator and the contact force of the knuckles [36]. Shan et al. studied soft robot fingers that utilize the fin effect and estimated the contact force generated by the fingers when grasping objects of arbitrary shapes by establishing a kinematic statics model [37]. Through adaptive analysis, the gripper can automatically adjust the grasping strategy according to the shape and material of the object, thereby improving the stability and flexibility of grasping.

This paper proposes a rigid-flexible coupling hand exoskeleton structure. For joints with low degrees of freedom such as DIP and PIP, controlling them by wire drive is an efficient solution as shown in Figure 3. This design achieves the linkage bending and extension of multiple joints through a single drive source, significantly reducing the number of motors and the weight of the equipment, while also avoiding the manufacturing difficulties and maintenance problems that may be caused by complex mechanical structures.

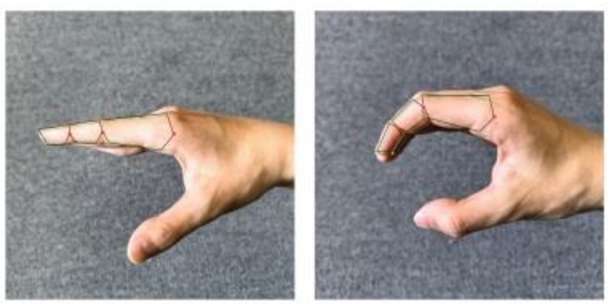

FIGURE 3. Concept of a Cable-Driven Finger Exoskeleton Structure (Photo credit: Original).

For MCP with high degrees of freedom, rigid mechanisms may limit its natural motion trajectory. Therefore, a flexible airbag structure can be introduced into the design to control the multi-degree-of-freedom motion of the MCP joint by inflation and deflation. This design not only improves the wearing comfort of the user but also provides new possibilities for the flexible control of hand exoskeletons.

However, the combined design of wire drive and airbag control may show certain limitations when adapting to complex grasping movements, and the accuracy and response speed of airbag control also need to be further improved. Future research can improve these shortcomings by combining multimodal sensor technology and smart materials such as shape memory alloys. In the long-term use of the system, fatigue failure of the wire drive and air leakage of airbags may affect the reliability of the device. It is recommended to introduce redundant structures or self-healing materials in the design to improve durability.

Problem of Insufficient Control System Performance

Control system performance refers to the ability of the device to accurately respond to user intentions and provide precise assistance. For some specific application scenarios, such as fine manipulation, rehabilitation training, remote control, etc., the control accuracy requirements of the hand exoskeleton are very high, and it is necessary to be able to achieve millimeter-level position accuracy and precise force feedback. The current problem of insufficient control system performance is mainly reflected in two aspects: first, the accuracy of intention recognition is not enough, and the user's movement intention cannot be accurately captured; second, the control response is not timely enough, and there is a delay in complex movements, which affects the user experience.

In view of the problem of insufficient performance of hand exoskeleton control system, the future development direction can be carried out from two aspects: improving algorithms and optimizing hardware systems. For algorithm improvement, more advanced deep learning methods and adaptive control strategies can be explored to improve the accuracy of intention recognition and the real-time performance of control. Although the current variable impedance control and under-actuated design have made progress in reducing system complexity, variable impedance control enables the device to provide adaptive force feedback according to the user's action requirements by adjusting the stiffness and damping of the exoskeleton in real time. This control strategy dynamically adjusts the mechanical impedance to adapt to different task requirements and user characteristics, thereby improving the flexibility and safety of robot-human interaction. Kronander et al. pointed out that variable impedance control can flexibly adjust the dynamic relationship between external force and robot motion during task execution, thereby enhancing the stability and responsiveness of the system [38]. Ma et al. further proposed a terrain-dependent variable admittance model based on real-time force perception, which can dynamically adjust the desired joint trajectory in the interaction between the amputee-prosthesis system and the environment, thereby enhancing the dynamic interaction capability of the system [39]. These studies show that variable impedance control plays a key role in improving the adaptability and user comfort of exoskeleton equipment.

In terms of hardware, higher-performance processors and sensor systems can be used to improve the efficiency of signal acquisition and processing, and achieve faster and more precise control responses.

CONCLUSION

In recent years, hand-exoskeleton human-computer interaction technology has made significant progress. From the perspective of structural design, three major technical routes have been formed: rigid, flexible, and soft. Each type of design has its unique advantages and application scenarios. In terms of core technology, key technologies such as intent recognition, variable impedance control, and multi-degree-of-freedom design have made continuous breakthroughs, providing strong support for improving equipment performance. However, hand exoskeletons are still facing problems such as insufficient naturalness of human-computer interaction, limitations of structural design and materials, and the need to improve the performance of the control system. In particular, in practical applications, the weight, volume, wearing comfort, and long-term reliability of the equipment still need to be further improved and optimized. In this paper, the advantages and limitations of these methods in different application scenarios are discussed. For example, low-frequency modulation techniques reduce switching losses but require more complex control strategies. Modular design can effectively reduce losses, but it is still a challenge to implement in large-scale systems. Cycle current control has a significant effect in reducing power loss, especially for MMC.

In the future, on the technical level, improving the accuracy of intention recognition through advanced algorithms such as deep learning, developing new composite materials to optimize structural design, and using multimodal sensing to improve control performance will become important research directions. Of particular note is the rigid-flexible coupling design concept. This new design scheme that combines wire drive and airbag control is expected to significantly improve the lightweight level and user experience of the equipment while ensuring the function is realized. As related technologies continue to mature, hand exoskeletons will provide better rehabilitation assistance support for more patients with functional disorders and promote the development of human-machine collaboration technology to a higher level.

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