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A comparative study of flexible and rigid hand-oriented exoskeleton robots

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Abstract. The purpose of this paper is to compare and evaluate the performance differences between flexible and rigid hand exoskeletons in terms of functional recovery and assistance in daily activities.Flexible hand exoskeletons are lightweight and soft devices with stretchable materials and flexible mechanisms designed to mimic the flexibility and versatility of natural hand movements.They typically consist of elastic materials, sensors and actuators that enable natural hand movements and provide light strength support.The main advantages of flexible hand exoskeletons are their comfort and flexibility, and their ability to provide personalized assistance for a variety of daily activities and tasks.This form of design is suitable for patients who require mild hand support and dexterity, such as individuals with mildly impaired hand motor function or who need to perform fine motor movements. In contrast, a rigid hand exoskeleton is a more rigid and stable device that uses robust materials and a rigid mechanism designed to provide a greater degree of strength support and stability.They are typically constructed of metal or composite materials, have a high degree of rigidity and stability, and provide strength support through electrical motors or hydraulic systems.The main advantage of a rigid hand exoskeleton is its higher force output and stability for tasks that require higher loads or complex movements.This form of design is suitable for patients who require greater strength support and stability, such as individuals with reduced hand muscle strength or who need to carry heavy loads

Keywords: hand exoskeleton, flexibility, rigid, drive method, rehabilitation robot.

1. Introduction

1.1. Research background

According to the World Health Organization (WHO), stroke is one of the leading causes of death and disability worldwide.More than 130,000 people die from strokes worldwide each year.According to the 2019 Global Burden of Disease Study, stroke is the second leading cause of death worldwide, after heart disease.Stroke is very common in both developed and developing countries, but the morbidity and mortality rates are higher in low-income countries.Meanwhile, China has one of the highest stroke burdens in the world.According to the Chinese Health Statistical Yearbook, stroke is one of the leading causes of death and disability in China, with 80% of stroke survivors suffering from sequelae related to motor impairment that prevent them from taking care of themselves [1].

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Many of these patients choose traditional physiotherapy for their treatment, but there are certain drawbacks to traditional treatment methods.Firstly, the treatment effect is related to the experience and ability of the physiotherapist, the training intensity and efficiency are difficult to guarantee, and the training process lacks clear intensity parameters and objective evaluation of the rehabilitation effect.Secondly, the cost of traditional treatment is generally too high and the form of treatment is not convenient, thus limiting the treatment of some patients [2]. In contrast, the development of hand exoskeleton robots offers new hope for patient rehabilitation.By providing precise motor control and strength support, hand exoskeleton robots can assist patients in hand rehabilitation and promote motor recovery and functional reconstruction.Among hand exoskeleton technologies, flexible and rigid hand exoskeletons are two common design forms that have different characteristics and application areas.

This paper believes that through in -depth research on flexibility and rigid hand bones, it will be able to better understand their advantages and limitations in different application scenarios, and provide useful guidance for future design and development. This is of great significance for improving the quality of life of patients with dysfunction and promoting the development of hand -exoskeleton technology. The results of this study will provide valuable information for medical professionals and R & D personnel to promote further innovation and application of hand exoskeleton technology.

This paper will provide a comprehensive comparison of flexible and rigid hand exoskeletons.We will conduct a comprehensive analysis in terms of structural design, material selection and use experience to evaluate their advantages and disadvantages in different application scenarios.We will consider the following factors: comfort, adaptability, force output, freedom of movement, precision, and maneuverability. By comparing the performance differences between flexible and rigid hand exoskeletons, we will be able to better understand their potential for applications in functional recovery and assisted hand movements.

1.2. Current status of research on hand exoskeleton robots

Research on hand exoskeleton robots has been a hot research topic in recent years due to the large number of stroke patients.Research on rehabilitation therapy through hand exoskeletons originated in Europe and the United States, and CPM rehabilitation therapy was originally proposed by Robert Salter, a Canadian orthopedic surgeon, with CPM (Continuous Passive Motion) machines, which enable the patient's brain to control the movement of the limbs through motor nerves [3].The research on hand exoskeleton robots has also received, the attention of university researchers. Harbin Institute of Technology designed a traumatized finger rehabilitation exoskeleton in 2010. The traumatized finger rehabilitation exoskeleton can perform two rehabilitation modes: bidirectional flexion movement and inward and outward abduction [4]. In 2013, Pologerinosetal et al. of Harvard University made a wearable device for finger rehabilitation based on a pneumatic network (Pneu-Net) type soft body actuator [5]. In 2015, Zhejiang University also designed a finger exoskeleton robot and arranged a thin-film pressure sensor through the inner side of the exoskeleton fingertip so as to capture the contact force between the finger and the exoskeleton [6]. In 2017, Hong Kai Yap et al. at the National University of Singapore fabricated soft rehabilitation gloves made from flexible fabric with an overall lighter mass than the soft actuator made from rubber material [3].Such studies make hand exoskeleton robots lighter and more patient-friendly.

At the beginning of the 21st century, productized hand rehabilitation robots have also emerged, such as the rehabilitation training robot developed by Immersion in the United States and a new wearable exoskeleton rehabilitation device, ExoHand, developed by Festo in Germany [2].

The more cutting-edge research result in China is a flexible hand exoskeleton robot designed by the Shenyang Institute of Automation, Chinese Academy of Sciences, in 2023, through the analysis of the human skeletal muscle drive mechanism, the researchers have optimized the hybrid drive configuration, thus achieving the three-dimensional movement of the human thumb with the minimum number of drives, greatly improving the level of fingertip force [7]. In this study, it was able to help stroke patients to use their own hand joints more flexibly.

2. Rigid hand exoskeleton robot

2.1. Structure and principle of rigid hand exoskeleton robot

A rigid hand exoskeleton robot is a hand rehabilitation robot that transmits drive to the human hand and drives finger movements through rigid components such as linkages, gears, and crank sliders.The mechanical structure of a rigid hand exoskeleton is usually composed of metal or light alloy materials to provide sufficient rigidity and stability.It typically includes finger sleeves, finger joints, and an exoskeleton frame.The finger sleeve is located on the finger and is used to connect the robotic device to the human finger.The knuckles mimic the joint structure of a human finger, providing freedom and range of motion.The exoskeleton frame connects the finger sleeve to the knuckles and supports and protects the mechanical component.

The rigid exoskeleton drive method is roughly divided into motor drive, pneumatic drive and hydraulic drive. The motor drive generally has two options, one is to directly install the disk motor on the rotating joint, using the rotation of the motor rotor to drive the joint rotation. The other is to use electric actuator drive, and connect the two ends of the electric actuator to the exoskeleton with connecting lugs, which converts the rotational motion of the electric motor into the linear motion of the actuator to drive the rotation of the rotating joint.

The principle of air pressure drive and hydraulic drive is similar, through the medium of gas or liquid, and manipulated by a number of control valves, the gas eventually pushes the piston of the cylinder to do linear motion.

Compared to the other two approaches, motor-driven technology is more mature, simple to operate and responsive.Many hand exoskeleton machines choose to be motor driven, such as the iHandRehab, a hand rehabilitation exoskeleton robot designed by Jiting Li et al. However, motor drive has a very big disadvantage, motor drive causes the whole machine to become bulky.To solve this problem, Jiting Li et al. fixed eight motors on a tabletop frame so that the drive is away from the body toprovide force and motion transmitted to the knuckles through the reducer and cable/sheath drive mechanism (see Figure 1) [8].

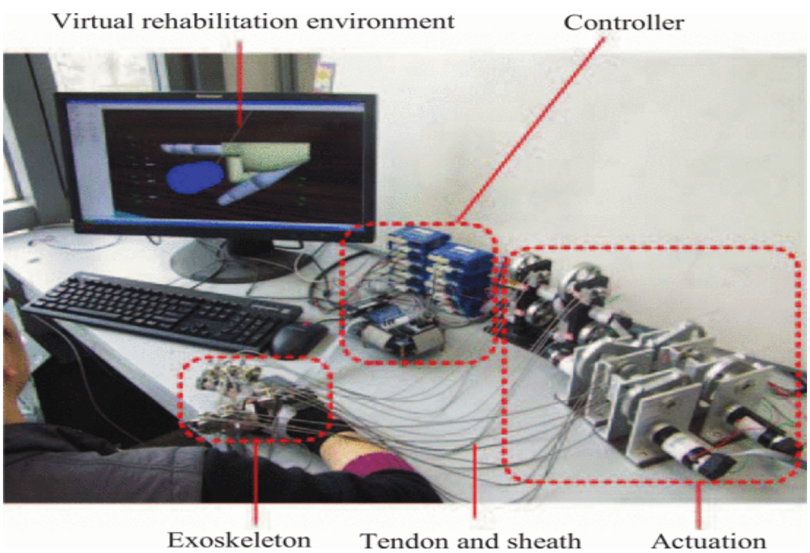

Figure 1. ihandrehab [8].

The two-handed collaborative rehabilitation hand exoskeleton robot designed by Leonardis et al. uses mechanical structures for joint limitation to ensure the safety of rehabilitation movements, but its hand actuators are similarly too bulky [9].

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In 2017, a wire-controlled hand exoskeleton designed by the Ulsan University of Science and Technology in South Korea was able to achieve linear motors driving each finger individually and each finger exoskeleton joint was a four-link mechanism [10].

In contrast, in the study by Mihai Dragusanu et al. they chose a more ingenious solution by using a differential made of gears to couple the finger exoskeleton [11]. Also, the differential was utilized so that one brake could control two fingers at the same time, thus reducing the number of brakes by half (see Figure 2).

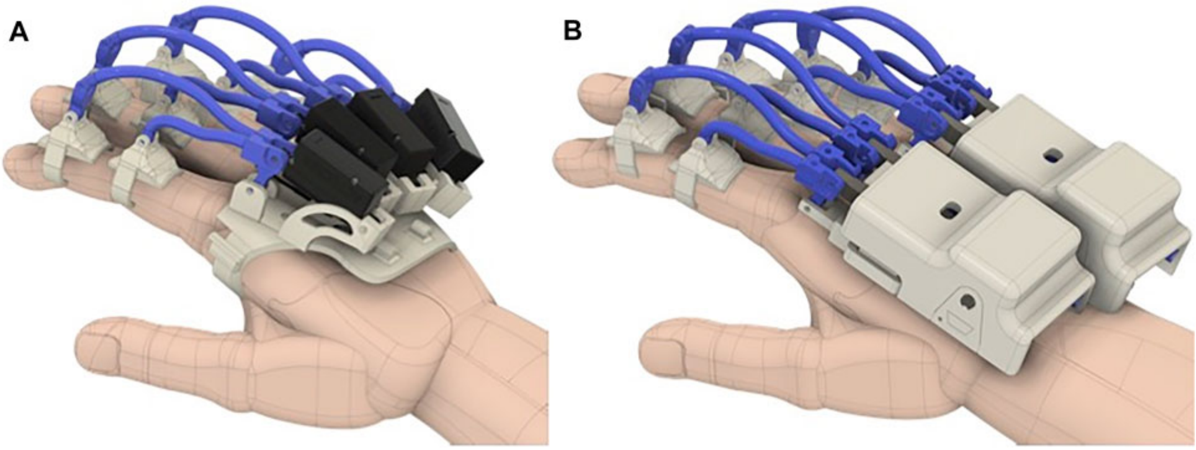

Figure 2. Hand exoskeleton robot coupled via differential [11].

Therefore, the characteristics of the statistical part of rigid hand exoskeleton robot in this paper are shown in Table 1.

Table 1. Characteristics of some rigid hand exoskeleton robots.

Rigid hand exoskeleton robot	DOF	Drive method	Force transmission method	Form Structure	Portability
Trauma finger rehabilitation exoskeleton at Harbin Institute of Technology [4]	——	DC Motor	Gear	Exoskeleton	Portable
iHandRehab[8]	4	Speed Reducing Motor	Cable	Exoskeleton	Fixed
Two-handed synergistic exoskeleton hand [9]	5	Speed Reducing Motor	Connecting Rod	Exoskeleton	Fixed
Linkage exoskeleton hand [10]	10	Speed Reducing Motor	Rope+connecting rod	Exoskeleton	Fixed
Differential exoskeleton [11]	——	Linear brakes	Connecting Rod	Exoskeleton	Portable

2.2. Analysis of the advantages and disadvantages of rigid hand exoskeleton robots

Due to the structural characteristics of the rigid hand exoskeleton robot, it has strong support and stability. The rigid hand exoskeleton robot can provide physical support and stability, so it can reduce the inaccuracy and chattering of hand movements.For stroke patients, it can help them perform some more

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precise movements better.Moreover, the rigid hand exoskeleton can provide a larger force output, which makes up for the weak hand strength of stroke patients.

At the same time, however, the disadvantages of a rigid hand exoskeleton are obvious. Due to his material characteristics, rigid hand exoskeleton robots are usually bulky and large in size, limiting the rehabilitation role in certain environments.Also the larger size and weight may limit the patient's freedom and dexterity.

On the other hand, the cost of rigid hand exoskeletons is generally high, not only in the manufacturing process, but also in maintenance costs after use, which can put some pressure on the patient's financial situation.

In addition, the rigid hand exoskeleton tends to interfere with the hand and cause strong friction during movement, thus causing secondary injuries to the patient's hand.

3. Flexible hand exoskeleton robot

3.1. Structure and principle of flexible hand exoskeleton robot

Flexible hand exoskeleton robots have been a popular direction of research in recent years. Flexible hand exoskeleton robots use soft materials, such as elastic fabrics, airbags or elastomers, to ensure a close fit between the robot and the human hand and to provide a comfortable wearing sensation.Based on this, sensors are used to obtain information about the posture, strength and movement of the user's hand.The sensors monitor the range of motion of the finger joints, the force distribution between the fingers, and the acceleration and angular velocity of the hand.Meanwhile, actuators in the robot are responsible for providing force and power to assist the patient's hand movements.These actuators are similar to rigid exoskeleton robots usually consisting of electric motors, pneumatic components or hydraulic systems.

Currently, in order to make exoskeleton robots more lightweight and convenient, it is now more popular to use springs to provide provide the necessary fingertip forces, i.e., finger flexion and extension.To make the hand exoskeleton more lightweight Vaheh Nazari et al. chose to use a 3-layer sliding spring (see Figure 3) to mimic the flexion and extension of human fingers when designing the hand exoskeleton robot [12].

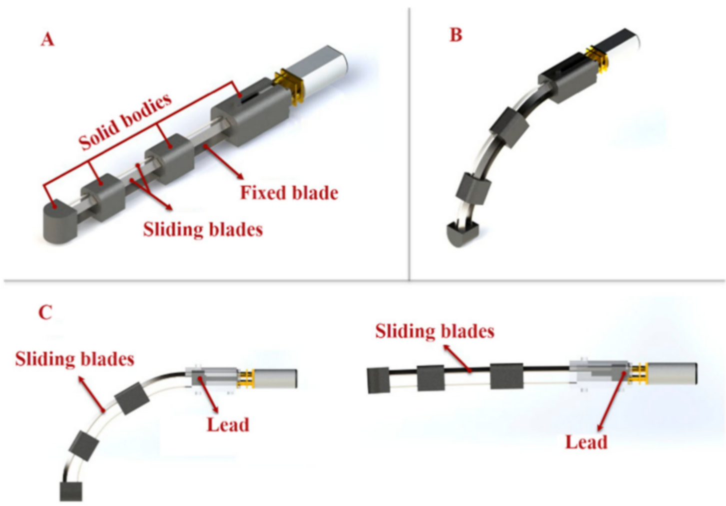

Figure 3. Finger exoskeleton robot consisting of 3 layers of springs [12].

Since the little finger only plays a supporting role in life, in 2016 Park et al. designed a three-fingered exoskeleton robot that conducts force through a cord [13].

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Kang et al. designed a wearable finger robot with a silicone material that can better fit the human hand and can adapt to different sizes of hands [14].

The flexible exoskeleton has two special actuation methods, which are pull wire actuation, shape memory alloy (SMA) actuation.

Pull cord drives are characterized by the fact that the cords transmitting the tension are able to withstand high tension in the direction of the drive length, but are less stiff in other directions and can be bent and folded into arbitrary shapes.As a result, they can be arranged on the hand in different transmission paths and fit well into the complex geometry of the patient's hand.However, this type of drive is a complex device and therefore it is more difficult to control.

SMA drive, on the other hand, relies on the characteristic that memory alloys are easily deformed by external forces, so it has a degree of passive flexibility and is prone to elastic deformation.But by giving it heat it will return to its original shape, thus generating a driving force in the deformation path.The disadvantages of this type of drive are also evident in that it requires a harsh temperature environment for its operation [2].

A summary of some of the flexible hand exoskeleton properties in this paper is shown in Table 2.

Table 2. Characteristics of some flexible hand exoskeletons in this paper.

Flexible hand exoskeleton robot	DOF	Drive method	Force transmission method	Form Structure	Portability
Soft drive exoskeleton hand [5]	——	Air Pumps	Highly elastic rubber material	Exoskeleton	Portable
Triple sliding spring exoskeleton hand [12]	5	DC Motor	Stainless steel spring bars	Exoskeleton	Portable
Three-finger exoskeleton [13]	3	Speed Reducing Motor	Rope	Gloves	Fixed
Exo-Glove Poly[14]	3	Speed Reducing Motor	Rope	Gloves	Fixed

3.2. Analysis of the advantages and disadvantages of flexible hand exoskeleton robots

First of all, the flexible hand exoskeleton robot is made of soft materials and designed to fit well with the human hand, providing a comfortable wearing sensation and reducing discomfort to the user's hand.Moreover, because of its material properties, the flexible hand exoskeleton robot is flexible enough to adapt to different hand forms and movement needs, providing personalized support.

Secondly, compared to traditional rigid exoskeleton robots, flexible hand exoskeleton robots are usually lighter and more portable, enabling users to use them in different environments and scenarios.

At the same time, however, the characteristics of flexible materials and structures may lead to limitations in providing force and support for flexible hand exoskeleton robots.Compared to rigid exoskeleton robots, flexible hand exoskeleton robots may have lower force output and load-bearing capacity.

And the lack of mechanical structure due to the deformation and elasticity of flexible materials leads to inaccurate motion transfer and high control difficulty.At present, researchers at home and abroad mainly use sensors to collect motion data to achieve closed-loop control of the system and improve the accuracy of motion [15].

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4. Comparative analysis of rigid and flexible hand exoskeleton robots

4.1. Comparison of structures and applications

Due to the different material properties of the two exoskeleton robots, they have some significant differences in structure and working principle.Flexible exoskeleton robots have a more flexible structure and are able to adapt and coordinate better with human limbs.A rigid hand exoskeleton robot is built with a strong metal or rigid material, usually with a rigid frame and joints.It has a more rigid structure and therefore provides higher strength and support.

Due to their structural differences, they have different areas of expertise in the hand rehabilitation process.Flexible exoskeleton robots mainly specialize in providing assistive strength and support to help patients increase their dexterity and range of motion.Thus it can help patients to do some dexterity tasks in daily life.While rigid hand exoskeleton robots are better at providing strength support to assist patients to perform some grasping, pinching, holding and other movements.

4.2. Comparison of advantages and disadvantages

The evaluation of the advantages and disadvantages of a hand exoskeleton robot should be based on comfort, wear resistance, braking degrees of freedom, maximum force, accuracy, and maneuverability.From this paper, it can be seen that the advantages and disadvantages of both flexible and rigid hand exoskeleton robots are relatively obvious.

In terms of comfort and wear resistance, the flexible hand exoskeleton robot fits the human hand better, and the material is more flexible and less likely to cause secondary injuries due to rehabilitation exercises during patient use.

In terms of braking degrees of freedom, rigid hand exoskeleton robots have relatively limited activity space due to the limitation of rigid materials, while flexible hand exoskeleton robots are more adaptable to different degrees of freedom for rehabilitation movements.

In terms of maximum force, the rigid hand exoskeleton robot is clearly superior. The robust material and rigid mechanism design enable the rigid hand exoskeleton to provide a greater degree of force support and to withstand larger loads and perform complex movements.On the contrary, the flexible hand exoskeleton robot has less force output than the rigid hand exoskeleton robot due to the limitation of elastic material.

In terms of accuracy and maneuverability, the rigid structure of rigid hand exoskeleton robots usually has higher stiffness and rigidity, allowing for more precise motion control and manipulation for tasks that require high precision operation.In contrast, the flexible structure of flexible hand exoskeleton robots is more prone to deformation and shaking compared to the rigid structure, which may reduce the stability and accuracy of the robot.

Thus, the advantages and disadvantages of flexible and rigid hand exoskeleton robots are summarized in Table 3.

Table 3. Summary of advantages and disadvantages of flexible and rigid hand exoskeleton robots.

Type	Comfort and wear resistance	Braking freedom	Maximum force	Accuracy and maneuverability
Flexible hand exoskeleton robot	√	√	×	×
Rigid hand exoskeleton robot	×	×	√	√

5. Conclusion

As seen from the research trends in recent years, flexible exoskeleton robots are developing very rapidly due to the consideration of patient comfort and the diversity of rehabilitation movements.The traditional rigid hand exoskeletons also focus more on flexibility and lightweight design to provide more natural movements and higher comfort. At the same time, in order to adapt to the hand characteristics of different people, personalized and customized design will become the trend of future development in order to provide better user experience and treatment results. Of course, for the development prospects of hand exoskeleton robots, this paper argues that researchers should focus on combining the advantages of flexible and rigid hand exoskeletons in the future, which can have both better comfort and larger braking degrees of freedom, but also have certain strength support and precision, and the maneuverability of patients when using them can be significantly improved.

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