Development of a finger rehabilitation robot based on sliding slot linkage mechanism

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Abstract. Rehabilitation training for stroke patients is a technical and social problem. A new type of pneumatic finger rehabilitation robot was presented based on sliding slot linkage mechanism. Through the analysis of the biological structure of the human hand, the sliding slot linkage mechanism with characteristics of combination drive, size adjustable and safety protection was developed. The detailed structure and control system of the finger rehabilitation robot were designed. Finite element analysis of the main parts and kinematic simulation of the mechanism were performed to verify the structural strength and motion feature of the finger rehabilitation robot, respectively. Finally, the prototype model of the sliding slot linkage mechanism was fabricated and a series motion tests were conducted. Results indicate that the finger rehabilitation robot is reliable and could satisfy the requirements of finger rehabilitation training.

1. Introduction

With the aging trend of population in China, more and more elderly patients are suffering from a stroke. Stroke could cause movement disorder of patients, such as dysfunction of the finger movement. Rehabilitation training is an effective treatment to restore the function of fingers for stroke patients in addition to pharmacotherapy[1]. Traditionally, the rehabilitation training of patients is mainly accomplished via one-to-one artificial rehabilitation therapy by physiotherapists. However, due to the serious shortage of physiotherapists, this training method can only meet the needs of very few patients, and most patients have had to delay treatment due to lack of effective training. At present, the technology of finger rehabilitation robot provides a way to solve this problem, which could also reduce the cost of rehabilitation training for patients. Finger rehabilitation robot is a mechatronics system composed of actuators, force transfer mechanisms, actuators and control modules. It drives patients’ fingers to carry out movement training by means of manipulator grasps, in order to achieve the effect of rehabilitation training.

Tadano[2] developed an exoskeleton finger rehabilitation robot used pneumatic artificial rubber muscle. Finger flexion and extension exercise training was realized by employing a two-way linkage mechanism, and air bag sensor was used to measure the grip force of patients. Taheri[3] developed the rehabilitation assistant robot "FINGER" in 2014. This robot utilized the principle of exoskeleton linkage mechanism to achieve the stretching and bending training of the index finger and middle finger. Li[4] carried out the development of finger rehabilitation robot by adopting the rope pulling method to separate the driving mechanism from the actuating mechanism, which realizes the adjustment of the motion range of each joint within a certain range.

The finger rehabilitation robots have been developed with different types of mechanical structures,
such as wearable type and exoskeleton type. The prototype with rigid exoskeleton is more simple in structure and higher precision in control. Therefore, this study concentrated on developing an exoskeleton finger rehabilitation robot with link, slider mechanism and adaptive adjustment mechanism. The application of finger rehabilitation robots would provide an advanced, accurate and efficient rehabilitation training means for many patients with dysfunction of finger movement.

2. Methods

2.1. Structure of human hand

The biological structure of the human hand is very complex, and there are 27 degrees of freedom in a human hand. It is important to understand the physiological structure of human hands for designing a safe and reliable rehabilitation training robot that meets the functional requirements. The structure of the human hand was shown in Figure 1. Index finger, middle finger, ring finger and little finger have three knuckles, named distal interphalangeal joint(DIP), proximal interphalangeal joint(PIP) and metacarpophalangeal joints(MCP), respectively.

\[ \theta_{\text{DIP}} = 0.46 \times \theta_{\text{PIP}} + 0.083 \times \theta_{\text{PIP}}^2 \]  

(1)

Where \( \theta_{\text{DIP}} \) is the bending angle of DIP with coupling of PIP, \( \theta_{\text{PIP}} \) is the bending angle of PIP.

2.2. Overall design concept

The essential function of finger rehabilitation robot is to drive the finger joint to bend and spread. Therefore, basic components of finger rehabilitation robot include power producer, drive system, execution units and controller.

As shown in Figure 2, a design concept of sliding slot linkage mechanism was proposed as the drive system of finger rehabilitation robot. This mechanism drives DIP, PIP and MCP to bend flexibility using curved sliding slots, and employs linkage to realize the transmission of driving power. In this research, air cylinders were employed as the power producer. Linkage mechanism was further optimized to satisfy the requirement of the cooperative movement of joints. The dimensions of the sliding slot linkage mechanism were determined by statistics of the average size of human hands, and this mechanism could be adjusted to fit different sizes during work. The overall design diagram of a single mechanism was shown in Figure 3.

3. Design of finger rehabilitation robot

3.1. Structural design of the sliding slot linkage mechanism

The detailed structure of the of the sliding slot linkage mechanism was shown in Figure 4. The structure of this mechanism mainly contains three pairs of slots and slide rails, expansion links, drive
levers, shift lever, and some size adjusting devices. This structure could be adapted to index finger, middle finger, ring finger and little finger for rehabilitation training. For the thumb finger, it has only two revolute joints, so the structure of the sliding slot linkage mechanism for thumb can be simplified to two pairs of slots and slide rails based on the mechanism in Figure 4.

Figure 3. Overall mechanism design
Figure 4. Structure of sliding slot linkage mechanism

Structures of slots and slide rails were designed in arc shape, and the bending of the joint depends on the shaft of the rail sliding in the slot. The rotation range of the sliding rails was designed according to the rotation angle of the finger mentioned above. In order to balance the driving power and reducing impact, an expansion link was designed using rod, spring and shaft. The spring on it can absorb the impact force of the driving source, so this structure could prevent excessive force from transmitting to the finger joints. The drive lever on the mechanism can regulate force and stroke, and the spring installed on it could get rid of the dead point of this mechanism. The shift lever was utilized to convert the drive mode of DIP and PIP to meet the users’ requirements of multiple forms of rehabilitation training. Meanwhile, size adjusting devices, including the regulating link and the regulating cover, were developed to fit different finger sizes. Under the drive of air cylinders, the motion of the joints would vary from extended, to slight bending, half bending and full bending, as shown in Figure 5.

Figure 5. Motion of the mechanism
Figure 6. Overall system of finger rehabilitation robot

3.2. Structure of finger rehabilitation robot and control system
Based on the sliding slot linkage mechanism of each finger, a support platform was designed to fix each mechanism. Three air cylinders were installed at the back of the sliding slot linkage mechanism as driving power. Micro vacuum pump was employed to provide compressed air. The three-position four-way valve was used to control the switch between the cylinders to achieve required movements of fingers. Compensated flow control valve was to adjust the air flow to control the speed of finger rehabilitation training device. The two-position four-way reversing valves were used to control the action of each cylinder. The action of the valves was controlled by singlechip by preset program which is suitable for finger rehabilitation training. The overall system of the finger rehabilitation robot was shown in Figure 6.
4. Reliability verification of the mechanism

4.1. Finite element analysis of the main parts

The material of the main structures is aluminium alloy 6061. The maximal driving force of each cylinder is 20N. Finite element analysis for main structures of the finger rehabilitation robot was performed to verify the strength and stiffness of the main parts. The stress analysis result was shown in Figure 7. From the finite element analysis results, the higher stresses are mainly distributed in the joint parts. The maximal stress of the slot is 12.9MPa, and all the maximum stresses of the parts are much lower than allowable stress.

4.2. Kinematics analysis of the sliding slot linkage mechanism

Kinematics analysis of the sliding slot linkage mechanism was conducted to further understand its motion characteristics. The velocity, acceleration and displacement curves at the middle fingertip were shown in Figure 8. Figure 8 (a) is the motion characteristics of the fingertip with the coupling drive of all the cylinders, and Figure 8 (b) and Figure 8 (c) are the motion characteristics driven by cylinder of MCP and PIP, respectively. The motion curves with one single drive, Figure 8(b) and (c), are more gentle compared with the coupling drive(Figure 8(a)). Therefore, this mechanism could meet the requirements of multiple working speed for users.
4.3. Model test
A prototype model of the sliding slot linkage mechanism was fabricated via 3D printing with TPS resin. Figure 9 shows a series motion tests between extended and bending, and there is no interference or fracture of the parts happened. During testing, each slot and slide rail rotated smoothly to match the bending of the MCP, PIP, and DIP of the finger. The result indicates that the sliding slot linkage mechanism developed in this study is suitable for rehabilitation training of the finger rehabilitation robot.

5. Conclusions
With the increasing of patients with dysfunction of the finger movement, the finger rehabilitation robot system is proposed to assist patients with rehabilitation training. This paper developed a new type of pneumatic finger rehabilitation robot with mechanism innovation. Through a series of verification by simulation and testing, this robot has the advantages of reliable structure, stable movement and multiple training functions. The finger rehabilitation robot could satisfy the requirements of finger rehabilitation training.

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