Design and Control of Pneumatic Muscle-Driven Robot Arm Based on Bilateral Rehabilitation Training

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Abstract. As a new treatment method, the upper limb rehabilitation training robot can help stroke hemiplegic patients recover their upper limb motor function by providing repetitive exercises and other ways. In this paper, based on the background of bilateral rehabilitation training with pneumatic muscle-driven robot arm containing paw system, the key technology of benevolence is systematically studied, and a set of experimental system is designed to verify the research results in detail. The mechanism design of the humanoid multi-joint double-arm is completed by imitating the human arm. Pneumatic artificial muscles are used to drive the shoulder and elbow joints of the mechanical arm, and stepping motors are used to drive auxiliary motion joints. The designed mechanical arm has both flexibility and compactness in structure. This study provides a useful reference for improving the effectiveness of arm design of upper limb rehabilitation pneumatic muscle-driven robot, and is helpful to broaden the research ideas of upper limb rehabilitation robot.

1. Introduction
With the rapid development of microelectronic technology, sensor technology, control technology and mechanical technology, the application field of robots has gradually expanded from the automotive industry to other fields, and profound changes have taken place in the breadth and depth of application. In the field of modern bionic technology, people hope to produce a kind of robot with similar shape to human beings, namely bionic robot [1]. People do not need this kind of bionic robot to have too high position accuracy and bearing capacity, but they need its mechanical joints to have good compliance. The flexible cable-driven parallel robot has gradually become a new research branch because it combines the advantages of high stiffness, high load capacity and low weight of the parallel structure. Because the flexible cable can only exert one-way tension, it must have redundant force to realize the force closure of the operating arm. As an important means of assisting rehabilitation, upper limb rehabilitation training robot can improve the upper limb rehabilitation effect and pertinence of hemiplegic patients, effectively track the rehabilitation degree of patients after training, and objectively evaluate the rehabilitation effect [2]. Among them, pneumatic actuator has developed from cylinder actuator to the popular pneumatic artificial muscle actuator. Secondly, the robot has developed from a single-arm robot with lower degree of freedom to a double-arm robot with spatial redundancy degree of freedom, and the application potential of the robot has been further developed. The robot system can free the therapist from heavy physical labor, formulate a better rehabilitation
plan for the patient, further improve the rehabilitation efficiency, and has far-reaching significance for the recovery of the patient's motor function.

2. Overall Design of Pneumatic Muscle Driven Robot Arm System

2.1. The design requirements and basic components of the arm system
The biological muscles of the human body are mainly composed of muscle fibers and have the functions of contraction and relaxation, and the muscles output force when contracting. As shown in Figure 1, the muscles of human fingers are mostly concentrated on the arm and transmit force through tendons. The design of pneumatic muscle-driven robot arm system is divided into three main parts: mechanical system design, hardware control system design and software control system design. Pneumatic-driven bionic arms have good flexibility, and the contraction principle of artificial muscles is the same as that of muscle groups when normal people perform flexion and extension movements, which reflects the bionic characteristics to the greatest extent [3]. Figure 2 is a schematic diagram of the relationship among the three, in which the design of the mechanical system is the main part of the whole system, mainly including the selection of each joint drive system of the arm and the design of the corresponding mechanical structure. The design of the hardware control part includes the design of the pneumatic circuit of the robot arm and the design of the control circuit. The design of the pneumatic circuit mainly includes the selection of the control valve corresponding to each joint drive in the arm. Therefore, the shoulder joint can be considered to have three rotational degrees of freedom, and the elbow joint can be flexed and extended.

In addition, the joint joint movement can complete the internal and external rotation of the forearm. Therefore, the elbow joint is considered to have two rotational degrees of freedom. Wrist joints can be extended and flexed, rotated inward and outward. Because pneumatic artificial muscle can provide enough large driving force, it also makes the bionic hand at the end of the grasping reliable and stable, and can complete the design goal [4]. The pneumatic artificial muscle is a closed elastic cavity with single input and output. When compressed air is filled into the pneumatic artificial muscle, the pneumatic artificial muscle contracts in the axial direction and outputs force, and the pneumatic artificial muscle can only output tensile force but not thrust force.
2.2. The design scheme of arm mechanical system

Pneumatic muscle-driven robot arm system is a typical mechatronic device, so its design should not only meet the above requirements, but also meet the general principles of mechanical design, such as compact structure, flexibility and reliability, sufficient strength and rigidity, etc. Moreover, its movement is directly controlled by the central nervous system of human beings, and it can realize various actions or coordinate actions according to human will. It is a multi-input-multi-output system that can complete multiple functions [5]. The robot arm consists of forearm, wrist and paw. The wrist has two degrees of freedom of rotation and pitch, and the paw has two fingers. The detailed design includes: big arm, elbow joint, small arm, wrist joint, hand, elbow joint flexion and extension drive mechanism, wrist joint flexion and extension drive mechanism, wrist joint spin drive mechanism and finger flexion and extension drive mechanism, wherein the elbow joint flexion and extension drive mechanism is installed in the big arm to provide power for elbow joint flexion and extension; When inflating pneumatic artificial muscle from one end, the silicone tube expands like a balloon, but when the silicone tube which is relatively easy to deform meets the braided mesh tube which is relatively difficult to deform, the radial expansion of the silicone tube is hindered by the braided mesh and begins to convert into axial contraction. Rotating joint is the connecting part of the joint robot, which is called joint for short. It not only connects the mechanisms of the robot but also transmits the rotary motion between the mechanisms. In order to make the joint rotate, a driver is needed to provide energy for it.

2.3. Design of arm control system

Figure 3 is a block diagram of the hardware control system of the robot arm. As can be seen from the diagram, the hardware control system consists of a computer, a data acquisition card, and pneumatic valve, a driver and a sensor. Therefore, the design of the hardware control system is mainly the selection of control valves and sensors, as well as the configuration of analog input and output conversion interfaces and digital input and output interfaces. The shoulder joint of the humanoid arm preliminarily designed has two independent rotational degrees of freedom. The rotation in each direction is driven by motors respectively and rotates around the vertical axis and the coronal axis. The shoulder joint is driven by two motors in the design process, and other parts of the bionic arm are driven by pneumatic artificial muscles.

![Figure 3. Block diagram of hardware control system](image_url)

In the measurement, one end of the pneumatic artificial muscle is fixed, and the other end is fixed on the measuring slider of the displacement sensor. The air pressure entering the artificial muscle is regulated by the pressure regulating valve, so that the pneumatic artificial muscle is contracted from the natural length to the minimum length, and then the pressure is reduced [6]. Pressure proportional valves are used to input continuous electrical signals and convert them into continuous gas pressure signals for output. Currently, the following three proportional valves are commonly used for pressure control of pneumatic muscles: Digital proportional control valve, pneumatic servo valve, electric proportional control valve. The selected two motors are provided with encoders and torque sensors, and each rotating shaft is provided with a rotary encoder arranged to measure the real-time rotation angle, wherein the spin freedom degree of the shoulder joint is a coupling motion, and the two motors need to move simultaneously. The flexion and extension movement of shoulder joint is driven by a
single motor, each motor is equipped with a driver, and the signals of the driver and encoder are connected to the industrial control computer.

3. Research on Stiffness Regulation of Pneumatic Muscle Driven Joint

3.1. The driving principle of pneumatic muscle
There are many kinds of pneumatic muscles, but no matter what kind of pneumatic muscle structure, when it inflates, it will inevitably lead to an increase in volume and a decrease in length, and its output force will decrease with the decrease in length [7]. According to the design scheme, the shoulder joint can realize two kinds of rotational movements, and its rotational axes are perpendicular to each other. Considering the overall needs of the humanoid arm, the shoulder joint should be compact in structure, stable in operation, and the parameters such as strength and range of motion should meet the requirements. The motor and reducer set are driven by a series of gear sets to realize the rotation of the shoulder joint around the coronal axis and generate the rotation of the shoulder joint around the vertical axis.

Pneumatic artificial muscle is the driver of tandem double-joint dexterous finger, which is responsible for providing the power for finger rotation. Then tendon applies torque to finger joint, converting the linear motion of pneumatic artificial muscle into joint rotation. It can be considered that it is impossible to completely simulate and reproduce the complex movements of the above joints and is of no practical significance from the perspective of the technologies that may be applied in current projects. From the perspective of engineering application, a humanoid robot arm can only realize specific movement under specific tasks [8]. Because there are many uncertain factors, such as elasticity, viscoelasticity, thickness of pneumatic muscle tube wall, end radian, friction between fiber webs, friction between outer fiber and rubber inner tube, etc. Each motor has a Hall sensor assembled and adjusted, which can measure the rotation data of the motor in real time, and the output shaft is connected with the torque sensor through a coupling. In the control process, a specific input affects other outputs. On the contrary, other specific control inputs also affect the output of the input. This phenomenon is called coupling.

3.2. Test and analysis of pneumatic muscle drive characteristics
The test object is two kinds of pneumatic muscles used in this subject, one is for wrist pitch joint, and the specification is 25mm × 30mm; the other is for finger joints, with a specification of 10mm × 150mm. Table 1 shows the values of three basic parameters of two kinds of pneumatic muscles in different states. Contraction state refers to the state where inflation pressure is 0.5MPa, relaxation state refers to the state where inflation pressure is zero when load is zero, and initial state refers to the state where inflation pressure is zero when load is maximum. The arm includes shoulder joint, elbow joint and wrist joint with 5 degrees of freedom.

| Table 1. Three basic parameters of pneumatic muscle |
|-----------------|---------------|--------|---|
| Pneumatic muscle type | state      | Effective shrinkage length(mm) | Radius(mm) | Weaving angle |
|-----------------|---------------|--------|---|
| 25mm × 300mm    | Contraction state | 130    | 15.6 | 53° |
|                 | Diastolic state   | 156    | 14   | 40° |
|                 | Initial state     | 195    | 5.3  | 23° |
| 10mm × 150mm    | Contraction state | 50     | 5.8  | 50° |
|                 | Initial state     | 73     | 3.7  | 25° |

The output force of the basic pneumatic muscle model is quite different from the actual measured output force. The reason for this is that in the derivation of the basic model, it is assumed that the system has no energy loss and energy storage, that is, it is assumed that the energy of compressed gas
is completely converted into mechanical energy during the expansion and contraction of pneumatic muscles. Another reason for the large difference between the output force of the model and the actual output force is that the pneumatic muscle does not conform to the second basic assumption, that is, the pneumatic muscle is not infinite in length, so its two end faces take the shape of a quadric surface during contraction. Figure 4 below.

![Graph](image)

**Figure 4.** Basic model value and experimental value of pneumatic muscle with diameter of 25 mm

According to the coordinate transformation matrix of the connecting rod, the change matrix from wrist joint to shoulder joint can be calculated, and the exact substitution value can be calculated by MATLAB. According to the average motion speed required by the end, the control points of the end trajectory are calculated equally according to the sampling time interval on the given trajectory. The pressure stabilizing valve is used to adjust the gas pressure input to the pneumatic muscle, the tension sensor is used to measure the tension generated by the pneumatic muscle, and the pressure sensor is used to measure the inflation pressure of the pneumatic muscle. In which the positive and negative elements indicate the direction of the force applied by the tendon represented by the column number to the joint represented by the row number. There is a large hysteresis in the process of stretching and shortening pneumatic muscles, because in the process of gradually stretching pneumatic muscles, the direction of friction is the same as the direction of output force, while in the process of gradually shortening pneumatic muscles, the direction of friction is opposite to the direction of output force.

4. **Research on Position Control of Pneumatic Muscle Driven Joint**

4.1. **Joint control method**

The dynamic response characteristics of the joint are usually given by the step response experimental results. In order to maximize the range of joint rotation angle and have moderate rigidity, if no special statement is made in the future, the initial input pressure $P_0 = 0.25 MPa$ and initial contraction rate $\varepsilon_0 = 0.16$ [9] of the two pneumatic muscles are generally defaulted. The initial position of each joint is a natural initial position, namely 0, and the movable range of each joint is different according to the design requirements, and the matrix can reflect the relationship between shoulder, elbow and wrist parts of the humanoid arm. However, due to the strong compressibility of gas and the fact that actual gas cannot be completely treated as ideal gas, it is difficult to accurately describe the flow rate of gas.
through high-speed on-off valves with equations. Due to friction and other factors, the actual detected output torque of the robot has certain amplitude and phase errors with expectation, but the overall force servo performance is better. The input pressures of the two are changed to \( P_0 + \Delta P \) and \( P_0 - \Delta P \) respectively, and the change process of joint angle is recorded at the same time. In order to study the dynamic response characteristics of joints under different loads, several square stainless steel loads with different weights are processed. The natural state of bionic arm is set as the initial state, i.e. the initial joint rotation angles of shoulder joint, elbow joint and wrist joint are all 0 degrees, and the rotation angles in the flexion and extension directions of shoulder joint are respectively given as 90 degrees. The pose of the end is obtained in real time by using this forward position solution method, and then the trajectory of the end is obtained according to the trajectory planning method, which is compared with the set trajectory to verify the effect of position control.

4.2. PID control method of joint
The traditional model-based control method is realized by designing the controller according to the mathematical model of the controlled object and the performance index required by the control system, and performing mathematical analysis and description on the control law [10]. The rotation angle of the shoulder joint in the spin direction is 30 degrees, the rotation angle of the elbow joint in the flexion and extension direction is 30 degrees, the rotation angle of the wrist joint in the flexion and extension direction is 10 degrees, and the rotation angle of the wrist joint in the spin direction is 20 degrees. The actual mass flow of the high-speed on-off valve should be multiplied by a factor, i.e. duty cycle. The response frequency of the high-speed on-off valve is very high, up to 100Hz, and the response delay time is 7 ms. Set the end of the robot to move to a circle with a radius of 8mm at a speed of 1.6mm/s, and then track the circle track at a speed of 1 mm/s. During the movement, the end encounters environmental constraints, stops at the constraint surface, and the contact force of the end to the constraint surface should be controllable. For this reason, this paper firstly adopts PID control method based on no model to control the joint position, and PID controller parameter adjustment is convenient. Each finger has two degrees of freedom and is driven by six pneumatic artificial muscles, and moves in an under actuated manner, wherein the thumb is driven by two pneumatic artificial muscles, and the other four fingers are respectively driven by one pneumatic muscle. Whether pneumatic artificial muscle is inflated or deflated, the mass flow rate is not only related to the inflation duty ratio of the high-speed on-off valve, but also related to the gas pressure in the pneumatic artificial muscle cavity. The mass flow rate of gas flowing through the high-speed switch during charging and discharging of pneumatic artificial muscle is a non-linear function of the gas pressure and duty ratio in the pneumatic artificial muscle cavity.

4.3. The basic principle of PID control
The control research of double-arm operation force or torque is mainly to study the operation algorithm of the target and optimize the control force. During inflation, the pneumatic artificial muscle contracts axially and expands radially. Under the condition of ignoring the expansion and contraction of pneumatic artificial muscle woven fibers, the axial contraction rate of pneumatic artificial muscle is equivalent to the diameter expansion rate. In addition, the volume of the pneumatic artificial muscle cavity is proportional to the product of the square sum of the diameter and the axial length. Reflects the change trend and change rate of the deviation signal, and can introduce an effective early correction signal into the system before the deviation signal becomes too large, thus accelerating the operation speed of the system and reducing the adjustment time. Figure 5 is a principle block diagram of an analog PID control system. As can be seen from Figure 5, the control system consists of two parts: an analog PID controller and a controlled object. In the figure: \( t \) is the given value of the system, \( y(t) \) is the actual output value of the system, \( e(t) \) is the given value: \( t \) the deviation from the actual output value \( y(t) \) is taken as the input value of the PID controller, and \( u(t) \) is the output value of the PID controller. The linear combination of \( (t):\)
In the formula, $K_p$ is a proportional constant, $T_I$ is an integral time constant, and $T_D$ is a differential time constant. The three constants $K_p$, $T_I$, and $T_D$ are multiplied by the integral value of $e(t)$, $e(t)$, and the differential value of $e(t)$, respectively, to form three control links of the control system.

The change rate of cavity air pressure of pneumatic artificial muscle is a nonlinear function of gas mass flow rate, cavity air pressure and volume change rate. Considering that the volume change of the cavity is small relative to the volume of the cavity, this item is ignored. Therefore, the length of the double-joint finger connecting rod is close to the structural parameters of the adult finger, and considering the mechanical structural parameters of the photoelectric rotary encoder, the finger thickness is larger than that of the adult finger. The bionic hand has 10 degrees of freedom, each finger can realize the rotation movement of the proximal knuckle and the middle knuckle, and the whole movement of the five fingers can realize the action of grasping daily articles.

5. Summary

Based on bilateral rehabilitation training, this paper mainly studies the precise position control of double-joint dexterous finger system driven by pneumatic artificial muscle. Using intelligent PID control algorithm, the error of single control PMA is within 0.2 mm and the end error is within 0.4 mm. In the aspect of structure design, the driving mode of each joint, the installation position of the driving mechanism and the driving mode are considered. In order to show the flexibility of the whole self-defense arm, besides shoulder joint, elbow joint, wrist joint and bionic hand are all driven by wire rope. The output torque of the joint is derived in detail by using the improved model of pneumatic muscle. A method of indirectly measuring joint stiffness by using joint static measurement parameters is proposed. The hybrid drive dual manipulator based on pneumatic artificial muscle and stepping motor has both flexibility and compactness in structure. To explore a new path for the application of pneumatic artificial muscle.

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