Design and Simulation Modeling of Antagonistic Bionic Joint Driven by Pneumatic Artificial Muscle

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Abstract: Pneumatic artificial muscle is widely concerned by researchers because of its simple structure, convenient installation, no crawling phenomenon, high power/dead weight ratio, good flexibility, similar to biological muscle movement and other characteristics. In this paper, two pneumatic artificial muscles are used to drive the bionic joint control system in the form of antagonistic structure. Based on the principle of antagonistic joint movement of human body, two pneumatic artificial muscles were used to control and drive joint rotation with antagonistic structure. The dynamic equations of air inlet and exhaust, the mass flow equation of inflow and outflow proportional pressure valve and the dynamic equation of driving joint were used as the nonlinear dynamic mathematical models for the control system of elbow joint rehabilitation driven by antagonistic pneumatic artificial muscle. Finally, Simulink simulation and experimental verification are carried out to prove the correctness of the established model.

Keywords: *Antagonistic type; Pneumatic artificial muscle; Nonlinear dynamic mathematical model; MATLAB simulation*

I. PREFACE

Pneumatic artificial muscle, also known as pneumatic rubber actuator, is a new kind of actuator which has attracted wide attention abroad in recent years. With good flexibility, light weight, easy to use and other advantages. Pneumatic artificial muscle is very suitable for medical treatment, nursing, biomedicine and other fields, and has a good application prospect[1]. See Figure 1 for its physical picture.

Fig.1 Physical picture of pneumatic artificial muscle

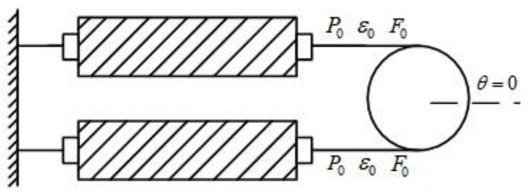
Although pneumatic artificial muscle has many unique advantages, due to the inherent rubber elastic force of the inner rubber sleeve and the existence of friction between the outer fiber braided net and the rubber sleeve, coupled with the compressibility of gas and other properties, pneumatic artificial muscle has a high degree of nonlinear and hysterescence[2]. Therefore, in order to better study the output characteristics and control performance of pneumatic artificial muscle, many domestic and foreign researchers have established and analyzed the mathematical model of pneumatic artificial muscle.

However, due to the hysteresis and nonlinearity of pneumatic artificial muscle, as well as the complex compressed air as the power source of the system, it is quite difficult to establish a more accurate pneumatic artificial muscle model[3]. Therefore, the research on the control strategy of pneumatic artificial muscle with strong nonlinear characteristics has become a research hotspot for scholars at home and abroad.

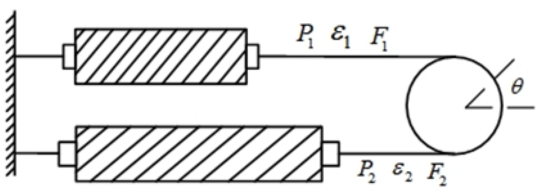
In this paper, two pneumatic artificial muscles were taken as the research object, and a kind of bionic joint based on the antagonistic movement of pneumatic artificial muscles was designed to solve the problem that the antagonistic movement of two pneumatic artificial muscles controlled the position of pulling motion complicated and difficult to control accurately. Firstly, the performance test platform of pneumatic artificial muscle was built to test the performance of a single pneumatic artificial muscle, and the mathematical model of pneumatic artificial muscle was established. Secondly, a motion control method was proposed for the configuration of the antagonistic bionic joint, and the proposed control method was simulated based on the system dynamics model, which theoretically verified the correctness of the algorithm. Finally, a biomimetic joint physical test system was established to conduct a single joint motion control test to verify the correctness of the pneumatic artificial muscle model and the effectiveness of the control strategy.

II. EXPERIMENTAL PLATFORM BUILDING

Pneumatic artificial muscle has strong flexibility and imitation, and the research of FESTO company in this field has been in the forefront of science and technology, so the pneumatic artificial muscle produced by FESTO has been widely recognized. In this paper, two FESTO pneumatic artificial muscles are taken as the research objects by simulating the above principles of antagonistic joint motion, so that they can drive joint rotation motion in the form of antagonistic structure. Figure 2 shows the initial position of the driving joint and the position at a certain working moment.



(a) Initial position



(b) Work location

Fig.2Schematic diagram of joint driven by two pneumatic artificial muscles with antagonistic structure

As shown in Figure 2, two parallel pneumatic artificial muscles of the same model are connected in the form of synchronization belt connection[4]. By changing the internal pressure of the two pneumatic artificial muscles, the degree of contraction of the pneumatic artificial muscles is changed, and then the external torque is generated to drive the joint to rotate. In the process of rotating motion, the change amount of the two pneumatic artificial muscles is equal, that is, after the length of the two pneumatic artificial muscles is determined before the working motion, the total length of the two pneumatic artificial muscles remains unchanged during the movement.

As shown in Figure 2 (a), when two pneumatic artificial muscles are used to control the initial position of the driving joint with an antagonistic structure, the same pressure is injected into the upper and lower pneumatic artificial musclesP_0, Therefore, the contraction rate of both pneumatic artificial muscles isε_0, This is the Angle of rotation of the joint $\theta = 0$. When the upper pneumatic artificial muscle is filled with pressure ΔP,at the same time, the lower pneumatic artificial muscle discharge pressure is ΔP,it can be seen that the upper pneumatic artificial muscle produces contraction motion and the lower pneumatic artificial muscle produces elongation motion[5]. At this time, an external torque will be generated to drive the joint to rotate counterclockwise.The joint rotation Angle is θ,the working position is shown in Figure 2 (b). When the external torque disappears, the pressure of the two pneumatic artificial muscles will return to the initial positionP_0,The joint Angle will return to its original position, Therefore, the rotation of the joint is mainly due to the change of the internal pressure of the two pneumatic artificial muscles, which leads to the change of the balance position. Therefore, the change of the specific position is determined by the pressure of the two pneumatic artificial muscles.

In order to build a better experimental platform in the future, we must first understand the working principle of the bionic joint control system which is antagonistic to the pneumatic artificial muscle drive[6].

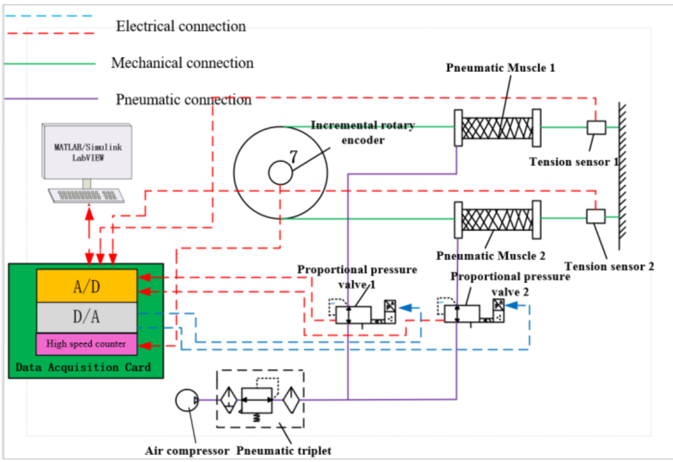


Fig.3 Control system schematic diagram of anti - pneumatic artificial muscle drive simulation joint

According to the working principle and experimental process of the above control system, the experimental platform of the following object is built, as shown in Figure 4.

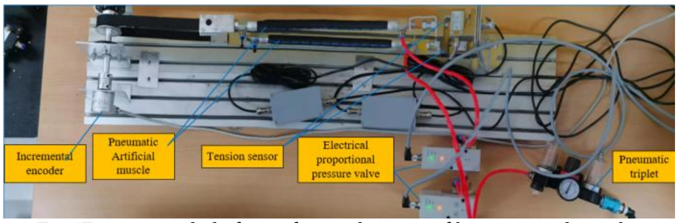


Fig.4Experimental platform of control system of bionic joint driven by antagonistic pneumatic artificial muscle

III. MATHEMATICAL MODEL OF CONTROL SYSTEM OF BIONIC JOINT DRIVEN BY ANTAGONISTIC PNEUMATIC ARTIFICIAL MUSCLE

When establishing the mathematical model of the control system of the bionic joint driven by antagonistic pneumatic artificial muscle, the complexity of the gas state is taken into account. In order to facilitate calculation and simulation analysis, the following assumptions need to be made [7] :

- Air, the working medium adopted, is regarded as an ideal gas.
- Ignore the leakage of pneumatic components due to poor sealing and other reasons.
- Ignoring the changes of temperature and pressure in the pneumatic artificial muscle and proportional pressure valve chamber, it is considered that they are evenly distributed in each internal position, and the parameters of each internal point do not change with time, which is the quasi-equilibrium.
- Proportional pressure valve The outlet pressure of the valve is equal to the pressure in the pneumatic artificial muscle.
- The influence of gas inertia force caused by the change of gas flow velocity and the influence of gravity field are ignored in the dynamic process.
- Changes in external pressure and temperature have no influence on the pneumatic system.
- The flow of gas into and out of the pneumatic artificial muscle and through the proportional pressure valve port is a stable one-dimensional flow.

A. Namic characteristic equation of pneumatic artificial muscle

According to the structure of the cylinder, the cylinder is divided into single acting and double acting cylinders. The working principle of the single acting cylinder is that the compressed air enters from one end to push out the piston rod, and its return is completed by the spring; The working principle of the double-acting cylinder is that when one side of the piston is charged, the other side is discharged. The two sides of the piston alternately supply gas and push the piston rod out and back according to the pressure difference on both sides [8]. And the acting area of the cylinder remains constant as it moves. However, according to the working nature of pneumatic artificial muscle, there is only one working condition of pneumatic artificial muscle in the process of movement, that is, it can only be inflated or vented in a working process, and its working area will constantly change in the process of movement. Therefore, there are differences between pneumatic artificial muscles and developed cylinders.

When studying the dynamic characteristics of pneumatic artificial muscle, Professor Yang Gang from Huazhong University of Science and Technology put forward a new research idea [9], that is, the pneumatic artificial muscle is regarded as a cylinder with a single cavity and changing section. The mature cylinder dynamic theory is applied to pneumatic artificial muscle.

FIG. 5 is the charging and discharging principle diagram of double acting cylinder. As can be seen from Figure 5, the compressed gas enters through the rodless chamber on the left and exits through the rodless chamber on the right. According to the theory of establishing the cylinder dynamic characteristic model, the dynamic characteristic equation of the rodless cavity intake on the left side of the cylinder can be obtained as follows:

$$\frac{dP_1}{dt}=\frac{k}{V_1}\left(Q_{m1}TR-P_1A_1\frac{dx}{dt}\right) \qquad (1)$$

The dynamic characteristic equation of the rod-chamber exhaust on the right side of the cylinder is:

$$\frac{dP_2}{dt}=\frac{k}{V_2}\left(Q_{m2}TR-P_2A_2\frac{dx}{dt}\right) \qquad (2)$$

Where: P_1 and P_2 are the pressure in the left and right cavities of the cylinder; Q_{m1} and Q_{m2} are the mass flow from the left side of the cylinder and the right side of the cylinder; A_1 and A_2 are the acting area of the left and right cavities of the cylinder; V_1 and V_2 are the cavity volume of the cylinder; x is piston displacement; T is the average absolute temperature of the gas; R is the gas constant, for air, $R=287J/(kg\cdot K)$; k is the isentropic index, for air, $k=1.4$.

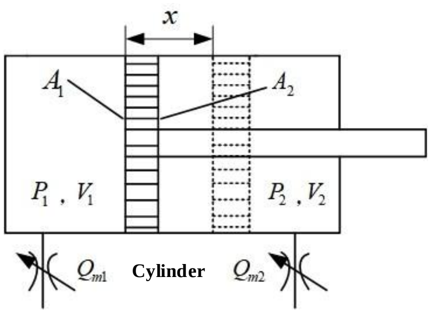
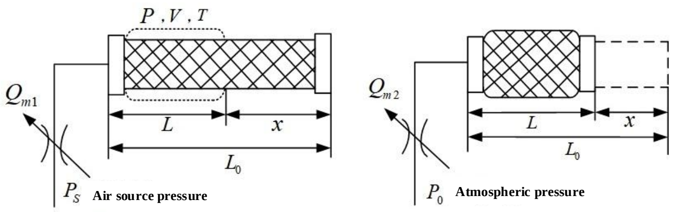


Fig.5 Schematic diagram of double acting cylinder charging and discharging

According to the established cylinder dynamic characteristic equation,the dynamic characteristics of pneumatic artificial muscle during charging and exhaust were analyzed respectively[10].Figure 6 shows the schematic diagram of pneumatic artificial muscle charging and exhaust. The initial length is L_0,the charging and venting process of pneumatic artificial muscle is regarded as the thermodynamic process of variable mass system.



(a)Schematic illustration of pneumatic artificial muscle inflatable contraction

(b)Simplified schematic diagram of pneumatic artificial muscle exhaust elongation

Fig.6: Simplified schematic diagram of pneumatic artificial muscle inflation and exhaust

The pneumatic artificial muscle is inflated and contracted in a positive direction. When the pneumatic artificial muscle is inflated and contracted, the upstream of the throttle port is the air source pressure P_S ,downstream is the pressure in the cavity of pneumatic artificial muscle P .At this time, the pneumatic artificial muscle performs inflatable contraction movement to the left, and the contraction size is x .In this case, the axial size of the pneumatic artificial muscle is L .According to the dynamic characteristic equation of rodless air inlet on the left side of cylinder (1), the dynamic characteristic equation of pneumatic artificial muscle during aeration and contraction can be written as:

$$\frac{dP}{dt}=\frac{k}{V}\left(Q_{m1}TR-P\overline{A_1}\frac{dx}{dt}\right) \qquad (3)$$

In formula, V is the volume of the pneumatic artificial muscle at the end of contraction; $\overline{A_1}$ is the equivalent acting area of the cylinder when the pneumatic artificial muscle contracts.

Among them:

$$\overline{A_1}=\frac{V-V_0}{x} \qquad (4)$$

In Formula, V_0 is the initial volume of pneumatic artificial muscle.

As previously assumed, the pneumatic artificial muscle works while still maintaining an ideal cylinder. Therefore, the volume V of the pneumatic artificial muscle at the end of aeration contraction is:

$$V=\frac{\pi D^2L}{4}=\frac{\pi D_0^2\left(L_0-x\right)}{4\sin^2\theta_0}\left[1-\left(1-\frac{x}{L_0}\right)^2\cos^2\theta_0\right] \qquad (5)$$

When the exhaust of the pneumatic artificial muscle is extended, the upstream of the throttle port is the pressure P in the cavity of the pneumatic artificial muscle, downstream is atmospheric pressure P_0 . According to the dynamic characteristic equation of exhaust with rod-chamber on the right side of cylinder of Formula (2), the dynamic characteristic equation of exhaust elongation of pneumatic artificial muscle can be obtained:

$$\frac{dP}{dt}=\frac{k}{V}\left(Q_{m2}TR-P\overline{A_2}\frac{dx}{dt}\right) \qquad (6)$$

Where, $\overline{A_2}$ is the equivalent acting area of the cylinder when the pneumatic artificial muscle is extended.

$$\overline{A_2}=\frac{V-V_x}{x} \qquad (7)$$

Where, V_x is the volume in the exhaust elongation process of the pneumatic artificial muscle.

In summary, equations (3) and (6) are dynamic characteristics equations of pneumatic artificial muscle. Unlike a cylinder, its area remains constant throughout its movement. According to equations (4) and (7), the operating area of pneumatic artificial muscle will change continuously during movement, and the change of the area is related to the shrinkage size.

IV. DRIVING JOINT DYNAMICS EQUATION

According to the schematic diagram of using two pneumatic artificial muscles to control the driving joint with antagonistic structure shown in Figure 4-2, if friction and disturbance and other factors are ignored, the dynamic equation of the driving joint can be obtained by coupling (1) :

$$J\frac{d^2\theta}{d^2t}+B\frac{d\theta}{dt}=\left(F_1-F_2\right)r= \left[F\left(P_0+\Delta P,\varepsilon_0+\frac{r\theta}{L_0}\right)-F\left(P_0-\Delta P,\varepsilon_0-\frac{r\theta}{L_0}\right)\right]r \qquad (8)$$

Where, J is the moment of inertia of the joint; B is joint viscous damping coefficient; θ is the joint rotation Angle.

V. SIMULATION ANALYSIS OF ELBOW JOINT REHABILITATION SYSTEM DRIVEN BY ANTAGONISTIC PNEUMATIC ARTIFICIAL MUSCLE

According to the theoretical knowledge introduced above and the dynamic mathematical model of the control system for elbow rehabilitation driven by antagonistic pneumatic artificial muscle, the dynamic model of the control system for elbow rehabilitation driven by antagonistic pneumatic artificial muscle was simulated and analyzed by using MATLAB Simulink. A package subsystem was established for the dynamic characteristics equation of air intake and exhaust of pneumatic artificial muscle, the mass flow equation of inflow and outflow proportional pressure valve and the dynamic equation of driving joint respectively. Then the signal line was connected through the coupling relationship between them to obtain the Simulink simulation model as shown in Figure 7. Table 1 describes the parameters of the Simulink simulation model. Moreover, the experimental platform of control system for elbow joint rehabilitation driven by antagonistic pneumatic artificial muscles was built, as shown in Figure 4. By comparing the simulation and experimental data, the feasibility and accuracy of the dynamic mathematical model of the control system for elbow rehabilitation driven by the antagonistic pneumatic artificial muscle were partially verified, which laid the foundation for the control theory analysis of the simulation model later.

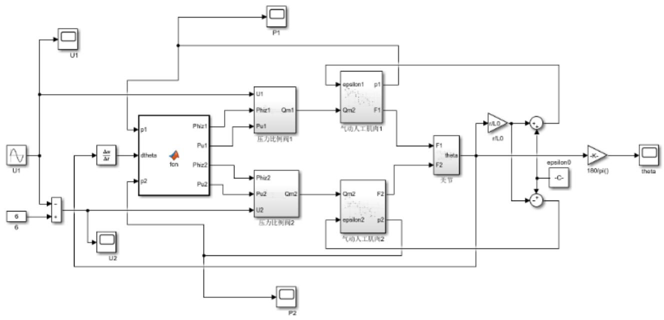


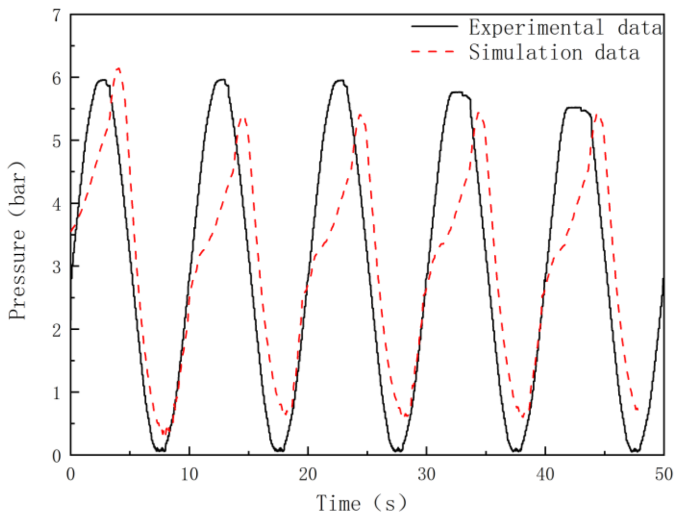
Fig.7 Simulink simulation model of the elbow joint system driven by an antagonistic pneumatic artificial muscle

Tab.1 Parameters of Simulink simulation model

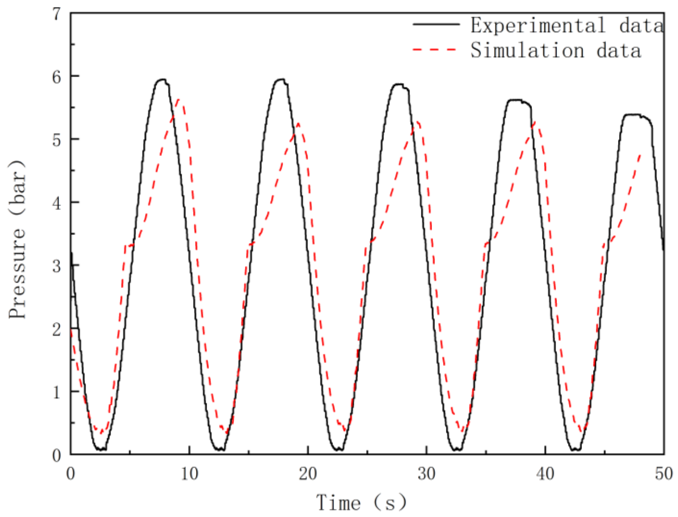
Parameter	Numerical value	Parameter	Numerical value
Initial length of pneumatic artificial muscle L_0	0.3 m	**Flow coefficient of proportional pressure valve C_q**	1
Initial diameter of pneumatic artificial muscle D_0	0.02 m	**Effective opening area of proportional pressure valve A_q**	20 mm^2
Initial braid Angle θ_0	25°	**Air source pressure P_s**	0.6 MPa
Initial shrinkage rate ε_0	0.1	**Atmospheric pressure P_0**	0.1 MPa
Elastic modulus of pneumatic artificial muscle E	1.3 MPa	**Isentropic index k**	1.4
Pneumatic artificial muscle diaphragm wall thickness tr	0.002 m	**Gas constant R**	287.1 J/(kg·K)
Coefficient of friction μ	0.002	**Mean absolute temperature of gas**	300 ℃
Joint damping coefficient B	120 N·m·s/deg	**Joint radius r**	20 mm
Joint moment of inertia J	20 Kg·m2		

Set the control input signal to $U=3\sin(0.2\pi t)+3$. The initial joint Angle is zero and is in a static state. At this time, the pressure in the cavity of the two pneumatic artificial muscles is equal. Data collected include pressure of pneumatic artificial muscle in two chambers and joint Angle. The comparison between simulation and experimental results is shown in Figure 8.

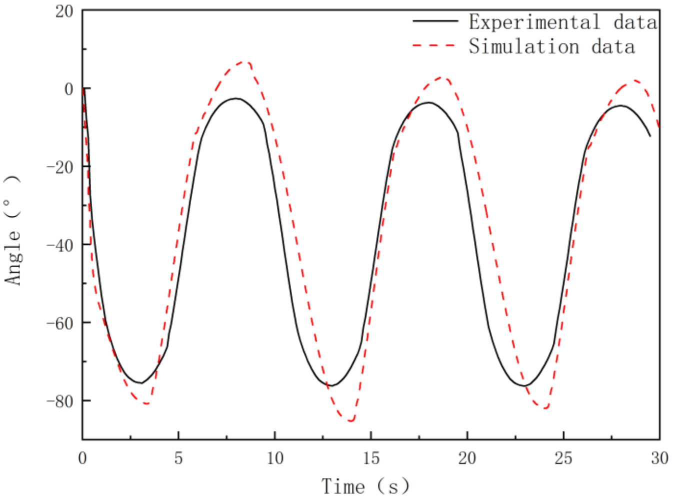
According to the comparison between the experimental results of the pressure in the cavity of two pneumatic artificial muscles and the simulation curve shown in Figure 8 (a) and (b), the experimental range of the internal pressure of pneumatic artificial muscle 1 is 0~ 0.6MPa, and the simulation range is 0.06~ 0.54MPa, with the maximum error of 6%. The experimental range of internal pressure of pneumatic artificial muscle 2 is 0~ 0.6MPa, the simulation range is 0.03~ 0.55MPa, and its maximum error is 5%. The pressure tracking effect of the two pneumatic artificial muscles is good. Only slight fluctuation occurs in the inflation stage, and the tracking error is slightly larger, but the general motion trend is the same. The main reason for this phenomenon is that in the modeling process, the mass flow equation of the inflow and outflow proportional pressure valve adopts piecewise function, which also has nonlinear, resulting in errors between the experimental waveform and the simulation waveform.



(a) Pressure of pneumatic artificial muscle 1



(b) Pressure of pneumatic artificial muscle 2



(c) Joint Angle

Fig.8 Comparison of dynamic characteristic experiment and simulation

According to the comparison between the experimental results of the joint Angle and the simulation curve shown in Figure 8 (c), the experimental range of the joint Angle is 0° ~ -76.2°, and the simulation range is 8.3° ~ -80.6°, with a maximum error of 8.3%. The tracking effect of joint Angle is better in the ascending process, but the tracking error is slightly larger in the descending process, but the general motion trend is consistent. The main reasons for this phenomenon are:

(1) The friction force in the actual experiment is opposite to the direction of motion, which is consistent with the sign function in modeling. However, in the actual operation process, the symbolic function will cause mutation, resulting in the operation difficulty, so the saturation function is used in the simulation instead, so there is a certain error;

(2) Pneumatic artificial muscle has a large hysteretic characteristic, which becomes more obvious with the increase of pressure, and the modeling error will also increase;

(3) The friction coefficient changes during the experiment, while the fixed friction coefficient is considered in the modeling and simulation, which will also result in certain errors.

CONCLUSION

In this chapter, based on the principle of antagonistic joint movement, two pneumatic artificial muscles are used to control and drive joint rotation. Then, using the same analytical method as the electro-pneumatic control system, the dynamic equations of air intake and exhaust, the mass flow equation of inflow and outflow proportional pressure valve and the dynamic equation of driving joint were taken as the nonlinear dynamic mathematical model of the control system of elbow joint rehabilitation driven by antagonistic pneumatic artificial muscle. Finally, the nonlinear dynamic mathematical model of the system is simulated by Simulink and verified by experiments. By comparing the simulation and experimental results, the results show that: The Angle of the control system of the elbow rehabilitation driven by the antagonistic pneumatic artificial muscle and the motion trend of the simulation curve of the internal pressure of the two pneumatic artificial muscles are basically consistent with the experimental curve, thus verifying the feasibility and accuracy of the nonlinear dynamic mathematical model established. The characteristics and motion state of the control system driven by the antagonistic pneumatic artificial muscle for elbow joint rehabilitation are accurately reflected. The mathematical simulation model established in this paper is closer to the actual experimental data, which lays a foundation for the selection of control strategy and experimental research in the future.

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