

Trajectory tracking control of the bionic joint of the musculoskeletal leg mechanism^①

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Abstract

Pneumatic artificial muscles (PAMs) have properties similar to biological muscles, which are widely used in robotics as actuators. It is difficult to achieve high-precision position control for robotics system driven by PAMs. A 3-DOF musculoskeletal bionic leg mechanism is presented, which is driven by PAMs for quadruped robots. PAM is used to simulate the compliance of biological muscle. The kinematics of the leg swing is derived, and the foot desired trajectory is planned as the sinusoidal functions. The swing experiments of the musculoskeletal leg mechanism are conducted to analyse the extension and flexion of joints. A proportional integral derivative (PID) algorithm is presented for controlling the flexion/extension of the joint. The trajectory tracking results of joints and the PAM gas pressure are obtained. Experimental results show that the developed leg mechanism exhibits good biological properties.

Key words: musculoskeletal leg mechanism, swing, bionic joint, trajectory tracking, proportional integral derivative (PID) control

0 Introduction

Four-legged creatures have advanced mobility in natural environment, which is the long-term evolution result of the biological adapting to the natural environment. Better mobility mainly depends on the structure of flexible body and legs, which is a musculoskeletal system, and the muscles and skeletal could move coordinately to adapt to different locomotion velocity and terrains^[1,2].

Various bionic leg mechanisms have been developed for quadruped robots worldwide. The biological structure consists of many bones connected with muscles and ligaments that work antagonistically and synergistically. A musculoskeletal system is required to produce animal-like motions, and researchers have carried out investigations^[3]. PAM has been widely adopted as an actuator in musculoskeletal system, and similar to a biological muscle in shape and working principles, thus can meet the relevant flexibility requirements.

PAMs have many desirable characteristics, such as flexibility similar to biological muscles, high power to weight ratio, high power to volume ratio, and inher-

ent compliance therefore have been widely used in various robotic systems^[4]. Hosoda^[5] developed a biped robot with a bio-mimetic muscular-skeleton system driven by McKibben PAM which realises stable bouncing. Takuma^[6] presented a bipedal robot and a feed-forward controller to achieve multi-modal locomotion by tuning appropriate leg compliance on individual locomotion. The rotational joints were driven by McKibben pneumatic muscles. Niiyama^[7] presented a pneumatically actuated bipedal robot called “Mowgli”, with an artificial musculoskeletal system consisting of six McKibben pneumatic muscle actuators. The robot could achieve vertical jumping with disturbance. Aschenbeck^[8] developed a canine-inspired quadruped robot in which PAMs were used to actuate the robot. Kenichi^[9] developed a quadruped robot with the minimalistic and light-weight body for achieving fast locomotion and McKibben PAMs were used as actuators to provide high frequency and wide stride motion, and also to avoid problems of overheating. A central pattern generator-based open loop controller was adopted to realise the bouncing gait of the robot. Andre^[10] presented a hopping mechanism driven by seven PAMs. The hopping direction of the robotic hind-limb could be

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controlled by using a non-linear curve fitting from experimental results. Keisuke^[11] developed a one-leg jumping robot driven by 9 PAMs that could mimic the muscular and skeletal system of a human leg. Two kinds of muscles; mono-articular type and bi-articular type were adopted. Motion experiments were conducted to verify the effectiveness of the mechanism and the control system. Niiyama^[12] presented a robot with an artificial musculoskeletal system driven by PAMs. The structure of the robot was similar to an animal for biomechanics study. The robot could achieve vertical jumping, soft landing and postural control during standing. Wang, et al.^[13,14] developed a quadruped robot driven by PAMs who adopted a basic position control method and model-based position control method to control the joint position. Their experimental investigations showed the variation of joint stiffness with time. Xie, et al.^[15] presented a lower limb mechanism driven by PAMs. Based on analyzing the output force model of PAM, a proportional integral derivative (PID) control algorithm was adopted.

A kind of antagonistic joint driven by two PAMs is presented, and an adaptive recurrent neural networks (ARNN) controller is designed. The joint position control is studied by the experiment and simulation with three different load cases of 0.5kg, 2kg and 10kg, which tracking error is very small less than $\pm 0.5^\circ$ for a load of 0.5kg and less than $\pm 2^\circ$ for a load of 10kg^[16]. A bionic joint driven by PAMs is presented, where a classic PI controller, an enhanced PID controller, a robust controller and sliding-mode controller are designed. The position control experiments of the bionic joint are performed. Experimental results show that the average trajectory tracking error is less than $\pm 1^\circ$ ^[17]. One-dimensional manipulator actuated by two PAMs is presented. A Takagi-Sugeno fuzzy model-based controller is designed. Experimental results show that the proposed controller can achieve excellent tracking performance under different disturbance. The tracking error of the T-S fuzzy model-based control is maintained within 2° ^[18].

Based on the biological principles of the skeletal and muscle coordinated movement, a musculoskeletal three degrees of freedom (DOF) leg mechanism driven by PAMs for a quadruped robot is proposed in this paper. The configuration of three rotating joints of the leg mechanism is different from other leg mechanisms, which can achieve side swing, forward and backward swing. The kinematics of the leg mechanism is derived to determine the relationship between the joint angular displacement and the foot position. The foot trajectory is planned as the sinusoidal function. A PID control algo-

rithm is adopted to control the swing of the leg. The experiment on the musculoskeletal leg mechanism is performed to evaluate and assess the performance of joint movement and the control algorithm.

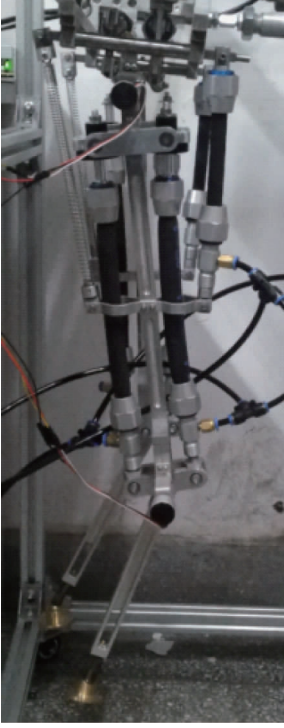
1 Musculoskeletal leg mechanism

Based on the design principles of the light weight and bionic, from the point of the mechanism, drive and motion bionic, with reference to biological leg muscle arrangement, elastic tendons, antagonistic drive bionic design concept, using the PAMs similar to biological characteristics of muscle, the musculoskeletal leg mechanism is innovatively designed, which reflects the biological flexible, multi-muscle coordinated movement, and the PAMs are reasonably arranged to achieve large enough rotating range of the bionic leg joints.

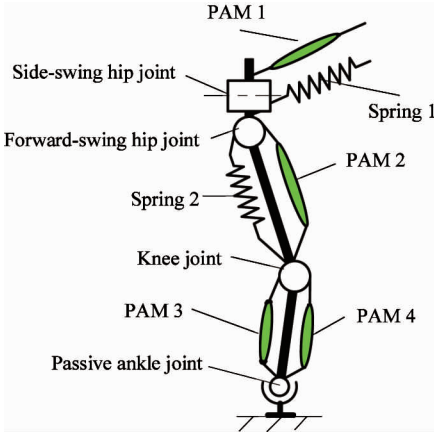
The configuration of the muscles is compatible with four-legged animals. The musculoskeletal bionic leg is based on quadruped animals, such as, dog or cheetah. For the joint rotating range of the hind limb of the cheetah, spine-hip joint has a range of 145 degrees, and the knee joint has a range of 104 degrees, the ankle joint is 95 degrees^[19].

The leg has three DOFs. FESTO-type PAMs are used to provide the non-linear properties of biological muscles. The 3-DOF musculoskeletal leg mechanism is presented in Fig.1, where PAMs play an important role in realising coordinated movements of joints. The leg mechanism has three rotational joints driven by PAMs, and these are side-swing hip joint, forward-swing hip joint and knee joint. The axis of the first joint is perpendicular to the axis of the second joint. The axes of the second and the third joints are parallel, which can increase the motion range of the foot. The 2-DOF hip joint can achieve side-swing and forward/backward swing. The ranges of motion of the joints are designed similar to those of quadruped animals.

Four muscles are arranged for the leg mechanism. The flexion/extension of the side-swing hip joint or the forward-swing joint are driven by one PAM. The flexion/extension of the knee joint is driven by two PAMs in order to increase its range of rotation. PAM has the tendency of contracting and is hard to elongate. These characteristics are considered in the design of the musculoskeletal leg mechanism to avoid interference of PAMs during rotation of the joints. For the PAMs used in the knee joint, when one is charged with gas, the other end can be moved by the mechanical stretch structure.



(a) Mechanism structure



(b) PAMs arrangement

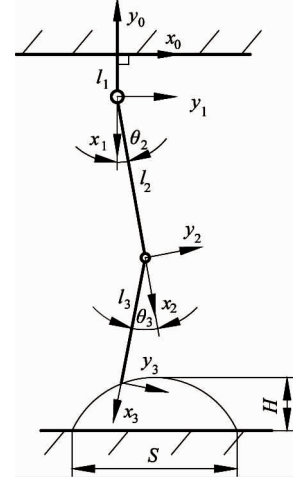
Fig. 1 Musculoskeletal leg mechanism**Fig. 2** D-H coordinate system

Table 1 D-H parameters of the leg mechanism

Link No. i	Link length a_i (mm)	Link angle α_i ($^\circ$)	Offset d_i (mm)	Joint variable θ_i ($^\circ$)
1	$l_1/2$	0	0	-90
2	l_2	0	0	θ_2
3	l_3	0	0	θ_3

The position and orientation of the foot with respect to frame $\{0\}$ can be described by a 4×4 homogeneous transformation matrix:

$${}^0_3T = \begin{bmatrix} s_{23} & c_{23} & 0 & l_2 s_2 + l_3 s_{23} \\ -c_{23} & s_{23} & 0 & -l_3 c_{23} - l_2 c_2 - \frac{l_1}{2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where $s_2 = \sin\theta_2$, $c_2 = \cos\theta_2$, $s_{23} = \sin(\theta_2 + \theta_3)$, $c_{23} = \cos(\theta_2 + \theta_3)$.

2.2 Inverse kinematics

According to the planned foot trajectory, angular displacement of each joint can be determined through inverse kinematics of the leg mechanism.

The joint angles $\theta_1, \theta_2, \theta_3$ can be determined as below using the inverse transformation method.

$$\begin{cases} \theta_1 = 0 \\ \theta_2 = \arccos\left(-\frac{(p_y + 0.5l_1)^2 + p_x^2 - l_3^2 + l_2^2}{2l_2 \sqrt{(0.5l_1 + p_y)^2 + p_x^2}}\right) \\ \quad - \arctan\left(\frac{p_x}{0.5l_1 + p_y}\right) \\ \theta_3 = \arccos\left(\frac{(p_y + 0.5l_1)^2 + p_x^2 - l_3^2 - l_2^2}{2l_2 l_3}\right) \end{cases} \quad (2)$$

2 Kinematics

2.1 Forward kinematics

Kinematics is not concerned with forces, either internal or external. Swing is the event when the foot is in the air. The kinematics of leg mechanism in the swing phase is analysed here, using the Denavit-Hartenberg (D-H) convention, as shown in Fig. 2. The link parameters are shown in Table 1.

2.3 Foot desired trajectory

For the musculoskeletal leg mechanism presented above, the rotating range of each joint has been determined by the PAM length. The side-swing hip joint can reach 23° , while the forward-swing hip joint reaches 10° and the knee joint reaches 55° . According to the rotating range of the forward-swing joint and the knee joint, the foot trajectory is planned with the sinusoidal function.

The foot trajectories along the x -axis and z -axis are planned as sinusoidal functions. The side swing of the leg mechanism is not considered, hence the foot trajectory along the y -axis is 0. The planned trajectory of the leg mechanism is as follows:

$$\begin{cases} p_x = S(\frac{t}{T_{sw}} - \frac{1}{2\pi} \sin \frac{2\pi t}{T_{sw}}), & 0 \leq t \leq T_{sw} \\ p_y = H \sin \frac{\pi t}{T_{sw}}, & 0 \leq t \leq T_{sw} \\ p_z = 0 \end{cases} \quad (3)$$

where S is the stride length, H is the step height, T_{sw} is the swing cycle, and p_x , p_y , p_z are displacements of the foot along coordinate axes directions.

3 Dynamics

For musculoskeletal leg mechanism swing, the contact force between the foot and the environment does not need to be considered. So the leg can be considered as a series manipulator. Lagrange's formulation is used here to derive the dynamics of the nonlinear system. Firstly, the PAM isn't considered, the dynamics of the leg swing can be derived in the joint space in the following form:

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) \quad (4)$$

where $\boldsymbol{\tau}$ is a 3×1 vector of joint torques. $\boldsymbol{\tau} = (0 \quad \tau_2 \quad \tau_3)^T$. \mathbf{q} , $\dot{\mathbf{q}}$, $\ddot{\mathbf{q}}$ are 3×1 vectors of the generalized coordinates, angular velocity and angular acceleration, respectively, $\mathbf{q} = (\theta_1 \quad \theta_2 \quad \theta_3)^T$. $\mathbf{M}(\mathbf{q})$ is 3×3 inertia matrix of the leg. $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is 3×1 vector of centrifugal and Coriolis terms. $\mathbf{G}(\mathbf{q})$ is 3×1 vector of gravity terms.

Taking the knee joint as example, the relationship between the joint driving torque and the PAM output force can be derived. Meanwhile, the PAM output force is related to the inner gas pressure. The structure parameters and the force analysis of the antagonistic knee joint are shown in Fig. 3.

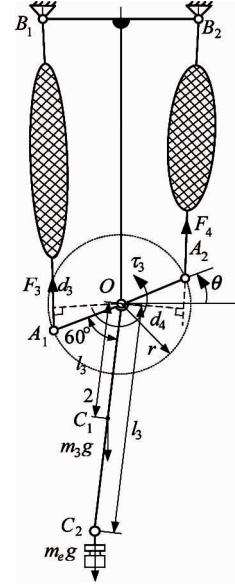


Fig. 3 Force analysis of antagonistic knee joint

The relationship between the joint driving torque and the PAM force can be expressed as

$$\tau_3 = \left(\frac{m_3 l_3}{2} + m_e l_3 \right) g \sin\left(\frac{\pi}{6} - \theta\right) + F_4 d_4 - F_3 d_3 \quad (5)$$

where τ_3 is the knee joint driving torque. m_e is the equivalent mass of the external load. $m_e g$ is the equivalent gravity of the external load. F_3 , F_4 are the PAM output forces. d_3 , d_4 are the force arms of force F_3 and F_4 , respectively.

The structural and gait parameters are shown in Table 2.

Table 2 Structural and gait parameters

No.	Variable	Value	Unit
1.	Body height	153	mm
2.	Thigh skeleton length	363	mm
3.	Shank skeleton length	257	mm
4.	Body mass	2.40	kg
5.	Thigh mass	0.43	kg
6.	Shank mass	0.28	kg
7.	Stride length S	100	mm
8.	Step height H	50	mm
9.	Swing cycle T_{sw}	10	s
10.	Equivalent mass m_e	0.3	mg

4 Leg swing experiments

The swing experiments of the musculoskeletal leg mechanism are conducted to analyse the extension/flexion of joints and the leg performance. A PID algorithm is adopted to control the flexion/extension of the

joint.

4.1 Experiment system

According to the planned foot trajectory of the leg swing, the trajectory tracking experiments of the forward-swing hip joint and the knee joint are performed. The experiment is conducted as shown in Fig. 4.

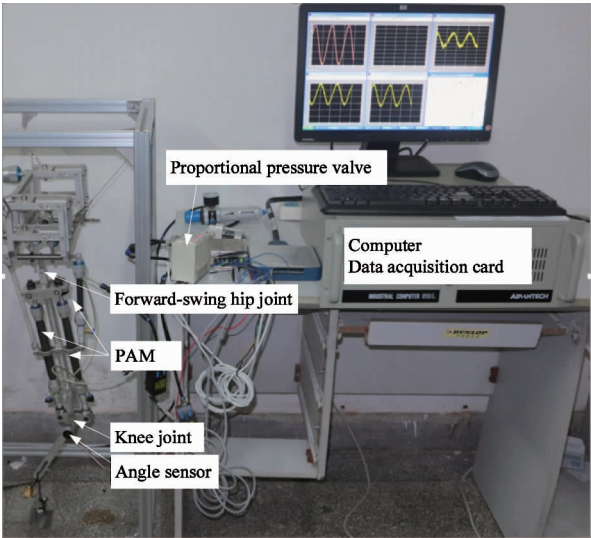


Fig. 4 Experimental platform of the leg swing

The trajectory tracking of the leg mechanism in swing is considered as the basis of performance criteria to demonstrate the accuracy and effectiveness of the proposed control algorithm. Experiments of the musculoskeletal leg mechanism are conducted to analyse the extension and flexion characteristics of the leg mechanism, and to assess the range of motion of each joint and the control algorithm.

The experimental system (see Fig. 5) is composed of the leg mechanism, industrial PC, data acquisition card , pressure regulating valve, proportional pressure

valves, pressure sensor and potentiometer. The hardware used in the experiment is shown in Table 3.

The NI PCI-6281 data acquisition card is used to obtain the joint position signal and the PAMs gas pressure by real-time collecting. These data are imported into computer. After the control program calculating, the control voltage signals are outputted and imported into the proportional pressure valve, and thus output gas pressure of the proportional valves are regulated and imported into the PAMs. The inner gas pressure of PAMs are controlled within 0.1Mpa and 0.6Mpa.

4.2 Experimental results

Precise position/angle control of PAM is not suitable. Instead the force/torque can be controlled relatively with ease by controlling the gas pressure which results in high-precision dynamic real-time compensation for the traditional PID controller. A proportional pressure valve is used to control the inner pressure of the muscles. The pressurized gas is exported by the air compressor and is supplied to the PAMs through the pressure regulating valve and proportional valve. The pressure regulating valve is used to change the system pressure, and the proportional valves are used to transform analogue input signal into a corresponding gas pressure. The proportional valve can be dynamically controlled by the controller, and the gas pressure is controlled at a certain value. A non-contact rotary position sensor is fixed on each joint, and a pressure sensor is used for measuring the gas pressure. Each PAM is supplied with one proportional valve. The maximum shrinkage of the PAMs is 20% of the initial length. The maximum pressure used was 0.6MPa, and the sampling frequency was 100Hz.

Table 3 Hardware used in the experiment

No.	Name	Model	Company
1.	Pressure regulating valve	LFR-1/8	FESTO
2.	Pneumatic FRL	LFR-1/8-D-MINI-MPA	FESTO
3.	Micro mist separator	AFD20-01-A	SMC
4.	Industrial Personal Computer	IPC-610MB-L	Advantech
5.	Data acquisition card	PCI-6218	NI
6.	Proportional pressure valve	ITV0050-3ML	SMC
7.	PAM 1	MAS-10-82N-AA-MC-O	FESTO
8.	PAM 2	MAS-10-80N-AA-MC-O	FESTO
9.	PAM3 and PAM4	MAS-10-180N-AA-MC-O	FESTO
10.	Angular displacement sensor	WDH22L-2410-W360-04	SENTOP
11.	Terminal box	SCB-68A	NI

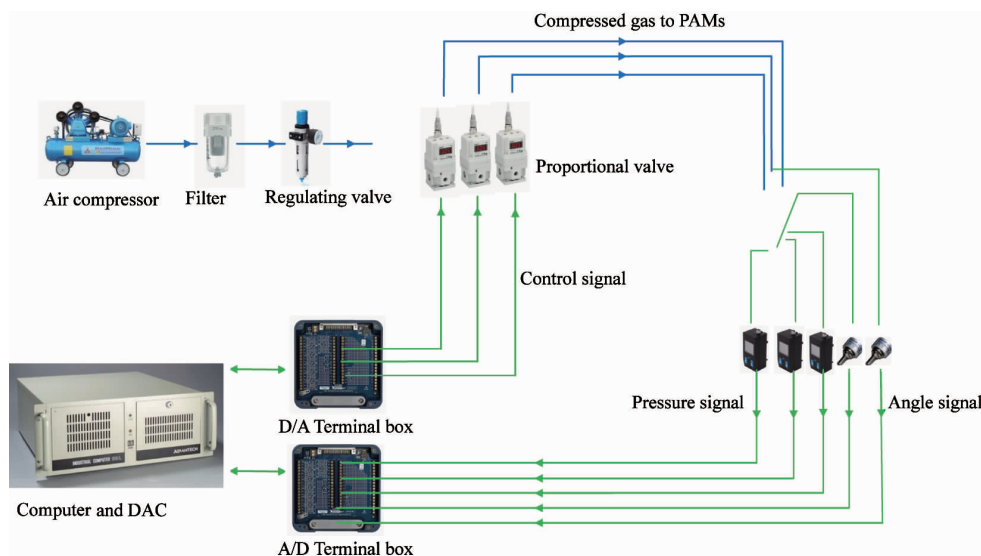


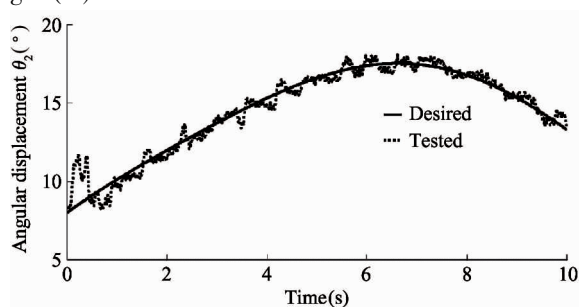
Fig. 5 Experiment system of the leg swing

The proposed control method was experimentally tested on the musculoskeletal leg mechanism. The proportional gain k_p , integral gain k_i and differential gain k_d are obtained through a trial and error procedure, and these are given as follows:

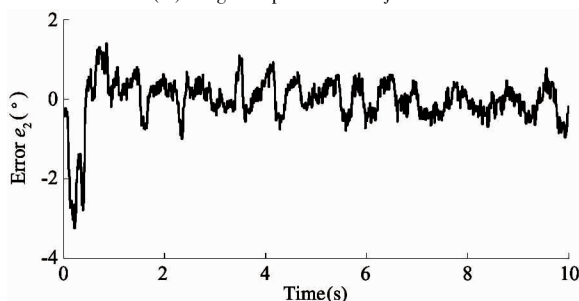
For joint 2, $k_p = 0.5$, $k_i = 8$, $k_d = 0.08$,

For joint 3, $k_p = 3$, $k_i = 0.5$, $k_d = 0.15$.

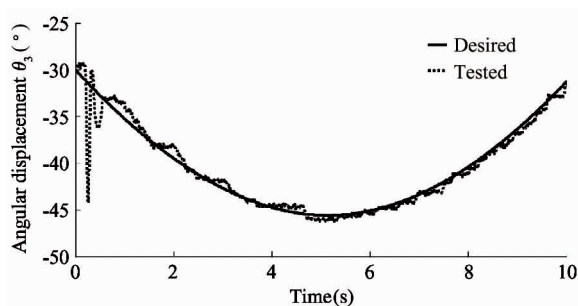
The leg swing is related with the forward-swing hip joint and the knee joint. So the trajectory tracking results of this two joints and the PAM gas pressure can be obtained, as shown in Fig. 6. The joint trajectory tracking results are shown in Fig. 6(a) ~ Fig. 6(d). The gas pressure of PAMs during leg swing is shown in Fig. 6(e).



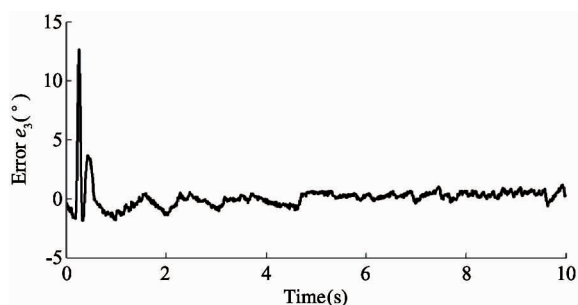
(a) Angle displacement of joint 2



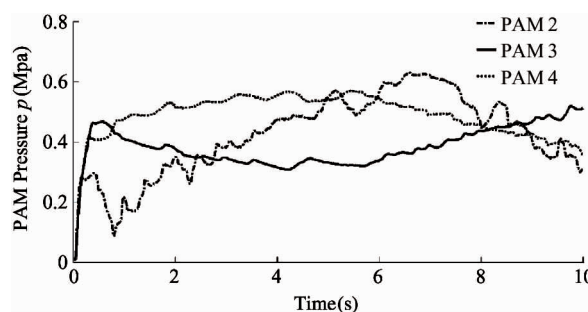
(b) Tracking error of joint 2



(c) Angle displacement of joint 3



(d) Tracking error of joint 3



(e) PAM inner pressure

Fig. 6 Experimental results

From Fig.7, the rotating range of the forward-swing joint is 10° , and the knee joint is 15° . As PAMs has highly nonlinear and time-varying behavior, it is difficult to achieve excellent tracking performance. For the musculoskeletal leg mechanism, the trajectory tracking error of joint should be controlled within 2° . It is noted that better effectiveness of the joint trajectory tracking is achieved. The tracking errors are within $\pm 1^\circ$. At the beginning position of the leg swing, there is a relatively larger error. This is due to the instantaneous action of the proportional valve and thus leading to the pressure mutation of the PAMs. The experimental results show that the PID controller can be implemented in controlling the swing movement of the musculoskeletal leg mechanism, and the bionic leg could achieve stable swing according to the planned foot trajectory.

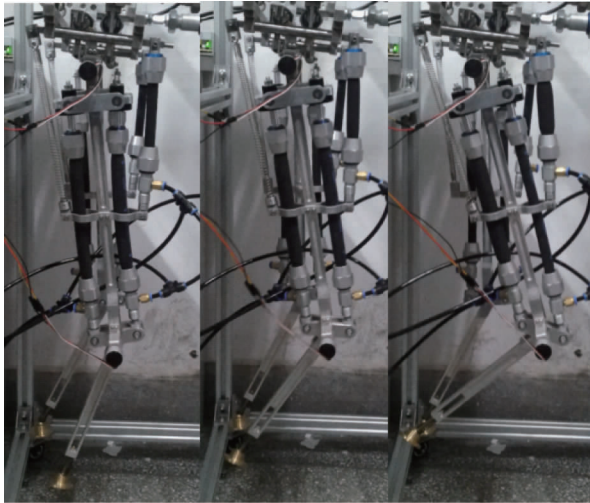


Fig. 7 Swing of the musculoskeletal leg mechanism

5 Conclusions

A musculoskeletal leg mechanism driven by PAMs is presented, which can be applied to a quadruped robot to improve the flexibility and mobility of the robot. The kinematics of the leg mechanism are derived to determine the angular displacement of joints due to the planned trajectory of foot. The swing experiments of the musculoskeletal leg mechanism is conducted to evaluate its movement performance. A PID control algorithm is used for joint trajectory tracking of the leg mechanism. The experimental results show that the required range of joint rotation and the planned movement of the leg mechanism can be achieved. Future work will focus on the jumping planning and control of the musculoskeletal leg mechanism.

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