DOI: 10.3901/CJME.2015.1016.123, available online at www.springerlink.com; www.cjmenet.com

Dynamic Bending of Bionic Flexible Body Driven by Pneumatic Artificial Muscles(PAMs) for Spinning Gait of Quadruped Robot

LEI Jingtao[1, *], YU Huangying[1], and WANG Tianmiao[2]

1 *School of Mechatronic Engineering and Automation, Shanghai University, Shanghai 200072, China*
2 *School of Mechanical Engineering and Automation, Beihang University, Beijing 100191, China*

Received January 9, 2015; revised September 28, 2015; accepted October 16, 2015

Abstract: The body of quadruped robot is generally developed with the rigid structure. The mobility of quadruped robot depends on the mechanical properties of the body mechanism. It is difficult for quadruped robot with rigid structure to achieve better mobility walking or running in the unstructured environment. A kind of bionic flexible body mechanism for quadruped robot is proposed, which is composed of one bionic spine and four pneumatic artificial muscles(PAMs). This kind of body imitates the four-legged creatures' kinematical structure and physical properties, which has the characteristic of changeable stiffness, lightweight, flexible and better bionics. The kinematics of body bending is derived, and the coordinated movement between the flexible body and legs is analyzed. The relationship between the body bending angle and the PAM length is obtained. The dynamics of the body bending is derived by the floating coordinate method and Lagrangian method, and the driving force of PAM is determined. The experiment of body bending is conducted, and the dynamic bending characteristic of bionic flexible body is evaluated. Experimental results show that the bending angle of the bionic flexible body can reach 18°. An innovation body mechanism for quadruped robot is proposed, which has the characteristic of flexibility and achieve bending by changing gas pressure of PAMs. The coordinated movement of the body and legs can achieve spinning gait in order to improve the mobility of quadruped robot.

Keywords: quadruped robot, bionic flexible body, PAM, spinning gait, dynamics

1 Introduction

Most of quadruped robots were developed with rigid body, and they usually walk with the periodic gait. Actually, Four-legged creatures are characterized by their mobility and dynamic stability walking in unstructured environment. The trunks of many quadruped animals are not rigid, such as tigers and lizards. The trunk of these animals have flexible spine so as to bend on one side with their articulated spine when they are in turning, which can make turn faster or more stable, as shown in Fig. 1[1].

On the other hand, when the animals walk in unstructured environment they usually adopt turning gait to avoid obstacle or to change walking directions.

On the other hand, their body can bend when they are in galloping gait or running gait, such as dog, horse tiger or cheetah, their body can remains flexion or extension because they have elastic spine, as shown in Fig. 2[2]. The spine bending of different animals were evaluated by experiments[3].

Fig. 1. Body bending of four-legged animal with flexible trunk

In order to improve the mobility of quadruped robot walking in the unstructured environment, the body structure and its bionic characteristic should be considered. Walking robot should be developed with the adaptability to various unstructured terrains. The bionic flexible body mechanism can play an important role for quadruped robot. It should have the flexible property for different terrain environment, such as flexible body mechanism for turning gait, spinning gait or gait transition.

For the body structure of quadruped robot, the walking robots were generally designed with rigid body. Several researchers have paid more attention on the body structure, and the flexible body structure for the humanoid robot was

* Corresponding author. E-mail: jtlei2000@163.com
Supported by National Natural Science Foundation of China(Grant No. 51375289), Shanghai Municipal Natural Science Foundation of China (Grant No.13ZR1415500), and Innovation Fund of Shanghai Education Commission(Grant No.13YZ020)

presented.

Fig. 2. Body bending of dog with flexible trunk in galloping gait

TSUJITA, et al developed a kind of quadruped robot with bionic flexible body. They presented that the mobility and stability of locomotion strongly depends on the mechanical properties of the body mechanism[4]. The flexible spine with some joints was designed based on the human's spine structure, which is used to achieve human-like motion[5]. A kind of segmented flexible spine was put forward for a humanoid robot to maintain its dynamic walking stability[6].The dynamic locomotion stability of walking robots depends on their body mechanism. The relationship between the running speed and the dynamics of body pitching was investigated[7]. A kind of bionic body with variable stiffness was conceptual presented by using the changeable elasticity of the pneumatic actuators[8–9]. A kind of robot with changeable body stiffness using pneumatic actuators was developed to adapt to the changing environment[10]. A kind of flexibility body contained one articulated spine joint was presented[11]. REMY[12] proposed to increase the adjustable quality on the rigid body to change the centroid positions, which reflects the trunk properties of four-legged creatures during dynamic walking. A spinal structure with variable viscoelasticity and multiple joints was presented and a quadruped robot with this kind of body was developed, and the relationship between the gait pattern of the legs and viscoelasticity spine was analyzed[13]. LEESER, et al[14], developed a planar quadruped robot with articulated spine. The spine and trunk can provide three functions: increasing the effective leg length, storing/transferring energy, and providing auxiliary power to legs. The spine, as central element of the vertebrate's body, is used to enhance locomotion and to absorb shocks, which can achieve life-like locomotion or to receive a higher mobility. The spine's role varies in different vertebrates, depending on the body shape, weight and type of locomotion. The rigid connection between the front and rear body is replaced by an elastic and actuated spinal column to improve the mobility, and the use of elastic elements can protect the system against hard and abrupt movements or vibrations[15]. A salamander-like robot driven by 10 DC motors is presented, which actuate 6 hinge joints for the spine. The locomotion gaits related to vertebrate are analyzed, which are generated by a Central Pattern Generator[16]. The cheetah robot is developed by MIT with the differential actuated spine[17–18].

Some of the flexible bodies are in the stage of the conceptual design. Some of them are relatively simple and are difficult to achieve the flexible bend similar to the quadruped creatures.

About the gait of quadruped robots, which are generally classified into periodic and non-periodic[19]. The straight forward gait, such as crawl gait and trot gait are periodic, which have been widely studied. A kind of quadruped robot with parallel-leg was presented. The dynamic steady trot gait was planned and inspired by Central Pattern Generator to produce the rhythmic movement[20].

One limitation of periodic gaits is that they are ineffective on irregular terrain, such as a hole or a vertical edge on irregular terrain[19]. Non-periodic gait can change the support points of the walking robot so that the robot can walk in the unstructured environment. Non-periodic gaits usually provide good mobility and high stability. The discontinuous turning gait belongs to non-periodic gait. The turning gait of quadruped robot should be studied in order to improve its mobility. The turning gait of quadruped robot with rigid body was presented[21–22]. Compared with the flexible body, the turning speed of the quadruped robot with rigid body is relatively slower.

The bionic flexible body of quadruped robots should be developed by imitating the trunk structure of creatures to improve the mobility. PAMs have many desirable characteristics, such as properties similar to biological muscle, high power/weight ratios and inherent compliance. PAMs have been used in a wide variety of applications in robots[23–26].

A kind of bionic flexible body mechanism driven by PAMs for quadruped robot was proposed based on the principle of four-legged creatures' mobility and stability, and the role of the flexible body for the spinning movement was analyzed. The kinematics of bionic flexible body and the leg side-swing was derived. The bending dynamics of the rigid-flexible coupling body mechanism was analyzed by the moment of momentum theorem. And the gas pressure of PAM for bending the body was derived. The dynamic bending experiment of bionic flexible body was conducted. The results show that the bionic flexible body has the muscle-like property, which can be used as the musculoskeletal body for quadruped robots. The study in this paper will lay the foundation for the quadruped robot dynamically stable walking in the unstructured environment.

2 Structure Model

2.1 Configuration of quadruped robot

If quadruped robots are developed with the flexible body, they can achieve variable posture to improve their mobility and stability in the unstructured environment.

The quadruped robot with bionic flexible body is presented as shown in Fig. 3. The robot is composed of four leg mechanisms and one bionic flexible body mechanism. Each leg is designed with three rotational joints, which are side-swing hip joint, hip joint and knee joint. Each joint is driven by PAM. The bionic flexible body is composed of one bionic spine, four PAMs, fore body and rear body. The fore body and hind body are connected by the bionic spine and PAMs.

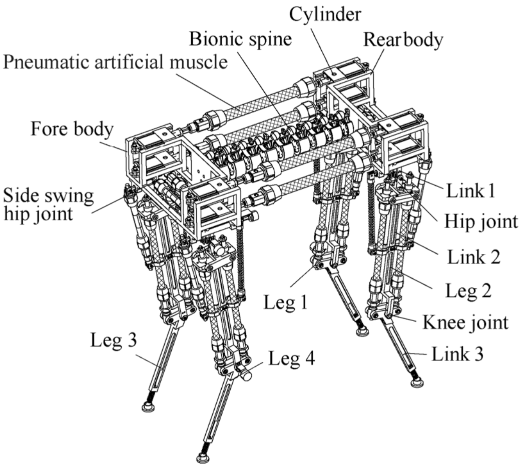


Fig. 3. Quadruped robot with bionic body

The bionic body bending is driven by PAMs. The PAM has remarkable muscle-like properties such as soft and flexible, which consists of thin rubber tube covered by high strength braided fibers. One end has a gas inlet/outlet. When the PAM is supplied with compressed air, the inner bladder expands in the radial direction and the PAM contracts or shortens to create a force in the longitudinal direction. The PAMs imitate the behavior of biological muscle and drive the fore body or rear body to achieve the relative motion.

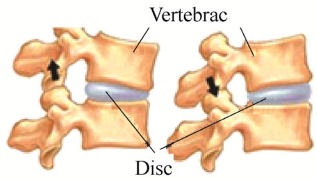
Four muscles are arranged symmetrically along the bionic spine, and the spine can achieve upwards/ downwards or leftwards/rightwards bending. When two upper/below muscles are inflated, the spine can bend upwards/downwards. When two left/right muscles are inflated, the spine can bend lateral. One cylinder is installed each end of PAM, which is used to compensate the changing of the PAM length.

2.2 Bionic spinal unit and bionic flexible body

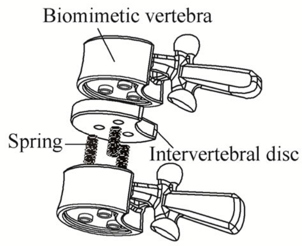
The creature spine consists of a number of spinal units, which is composed of vertebrae and intervertebral disc, as shown in Fig. 4(a).

The bionic spine mechanism for the quadruped robot is designed with 10 bionic spinal units, which is composed of biomimetic vertebra, intervertebral disc and three springs. The bionic spinal units connect each other and form 9 passive joints. The intervertebral disc is located in the middle of two biomimetic vertebrae. Three springs pass through the intervertebral disc and connect two adjacent biomimetic vertebrae, as shown in Fig. 4(b).

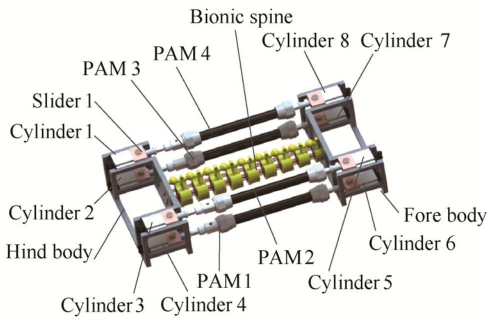
The bionic flexible body is composed of fore body, rear body, one bionic flexible spine unit, four PAMs and eight cylinder component. Each cylinder component is composed of one double-acting cylinder and one slider. Two PAMs are arranged at the left side of the body, and the other two PAMs are arranged at the right side of the body, as shown in Fig. 4(c).



(a) Actual spinal units



(b) Bionic spinal units



(c) Bionic flexible body

Fig. 4. Spinal unit and bionic flexible body

3 Kinematics

3.1 Spinning gait

The spinning gait planning of quadruped robot with flexible body aims to determine the duty factor β_i and leg phase $\phi_i (i = 1, 2, 3, 4)$. We derive the landing position of the swinging leg and the lifting position of the supporting leg from the motion speed while the legs are limited within their reachable range.

Duty factor β_i is the ratio of *i*th leg in stance phase time T_{sp} to the walking cycle *T*, is given by

$$\beta_i = \frac{T_{sp}}{T}. \tag{1}$$

Leg phase ϕ_i be the ratio of time interval from the leg begins to move to the *i*th leg begins to move to the walking cycle. t_0 is the time when the robot starts moving time, and t_i is the time when the *i*th leg begins to move time.

The leg phase can be expressed by

$$\phi_i = (t_i - t_0)/T \quad (0 \leqslant \phi_i < 1). \tag{2}$$

Suppose one spinning gait cycle is divided into six sections shown in Fig. 5.

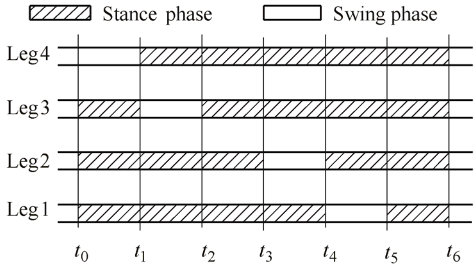


Fig. 5. Stance phase and swing phase during one spinning gait

The phases of the legs are

$$\begin{aligned} \phi_4 &= (t_0 - t_0)/t_6 = 0, \\ \phi_3 &= (t_1 - t_0)/t_6 = 1/6, \\ \phi_2 &= (t_3 - t_0)/t_6 = 1/2, \\ \phi_1 &= (t_4 - t_0)/t_6 = 2/3. \end{aligned} \tag{3}$$

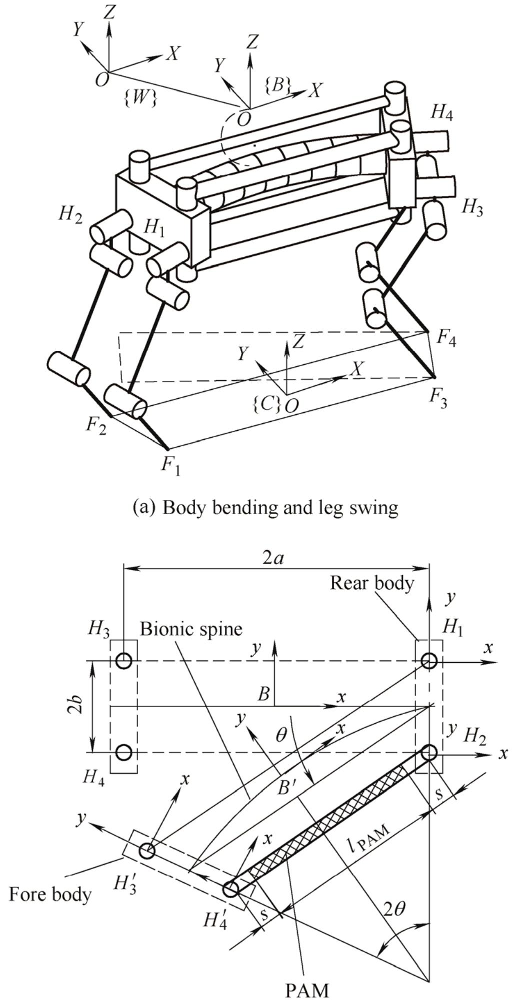
For quadruped robot, the gait formula can be expressed as $\boldsymbol{g} = [\beta_1, \beta_2, \beta_3, \beta_4; \phi_1, \phi_2, \phi_3, \phi_4]$, which describes lift and fall action sequence of each leg, and also describes the interval time between adjacent legs. The spinning gait planning can be expressed as

$$\boldsymbol{g} = \left(\frac{5}{6}, \frac{5}{6}, \frac{5}{6}, \frac{5}{6}; \frac{2}{3}, \frac{1}{2}, \frac{1}{6}, 0\right). \tag{4}$$

3.2 Kinematics of the bionic flexible body

The coordinate systems of robot for kinematics are shown in Fig. 6. The kinematics of the robot can be represented in the world coordinate frame $\{W\}$. The body initial coordinate of quadruped robots is $\{B\}$, whose coordinate origin is in the center of body. The coordinate systems of hip joints for side-swing are $\{H_i\}$, and the foot coordinate systems are $\{F_i\} (i = 1,2,3,4)$.

The body bending angle is θ, then the angle between the fore body and the rear body is 2θ. The positions and orientations of hip joints with respect to body can be expressed by the homogeneous transformation matrix:



(a) Body bending and leg swing

(b) Bionic body bending

Fig. 6. Bionic body bending of quadruped robot

$$\begin{aligned}
{}^{B}_{H_1}\boldsymbol{T} &= \begin{pmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \\
{}^{B}_{H_2}\boldsymbol{T} &= \begin{pmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & -b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \\
{}^{B}_{H_3}\boldsymbol{T} &= \begin{pmatrix} 1 & 0 & 0 & -a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \\
{}^{B}_{H_4}\boldsymbol{T} &= \begin{pmatrix} 1 & 0 & 0 & -a \\ 0 & 1 & 0 & -b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \\
{}^{B}_{H'_3}\boldsymbol{T} &= \begin{pmatrix} \cos 2\theta & -\sin 2\theta & 0 & a - b\sin 2\theta - \dfrac{a\sin 2\theta}{\theta} \\ \sin 2\theta & \cos 2\theta & 0 & b\cos 2\theta - \dfrac{a}{\theta} + \dfrac{a\cos 2\theta}{\theta} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \\
{}^{B}_{H'_4}\boldsymbol{T} &= \begin{pmatrix} \cos 2\theta & -\sin 2\theta & 0 & a + b\sin 2\theta - \dfrac{a\sin 2\theta}{\theta} \\ \sin 2\theta & \cos 2\theta & 0 & -b\cos 2\theta - \dfrac{a}{\theta} + \dfrac{a\cos 2\theta}{\theta} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.
\end{aligned} \tag{5}$$

According to Fig. 6, the relationship between the real-time length of PAM and the body bending angle can be derived:

$$l_{\mathrm{PAM}} = 2\left(\frac{a}{\theta} - b\right)\sin\theta - 2s, \tag{6}$$

where a—Half of the body length,
b—Half of the body width or the mounting size of PAM,
s—Length of the pipe head for mounting the PAM.

3.3 Kinematics of leg in stance phase

While the body bends, the leg in stance phase begins to swing with body.

The kinematics of leg in stance phase is derived as follows:

$$ {}^0_1\boldsymbol{T} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, $$

$$ {}^1_2\boldsymbol{T} = \begin{pmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_3 \\ 0 & 0 & -1 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, $$

$$ {}^2_3\boldsymbol{T} = \begin{pmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & l_2 \\ -\sin\theta_3 & -\cos\theta_3 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, $$

$$ {}^3_4\boldsymbol{T} = \begin{pmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & l_1 \\ 0 & 0 & -1 & 0 \\ \sin\theta_4 & \cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. $$

3.4 Coordinated movement of body and legs

The robot walks with the spinning gait, the body bending and legs swing should keep coordinated movement. The coordinated movement of body and legs should meet the dynamic stability conditions. The angle of the body bending and leg swing angle should be controlled within a reasonable range in order to implement the coordinated movement. It is necessary to analyze the movement range of the hip joint in leg and body.

3.4.1 Movement range of hip joint in leg

When the robot walks with the spinning gait, the leg in stance phase begins to swing with body, as show in Fig. 7. The position and orientation of hip joint in leg with respect to foot can be expressed by the homogeneous transformation matrix:

$$ {}^{F_i}_{H_i'}\boldsymbol{T} = {}^0_1\boldsymbol{T}(\theta_1)\,{}^1_2\boldsymbol{T}(\theta_2)\,{}^2_3\boldsymbol{T}(\theta_3)\,{}^3_4\boldsymbol{T}(\theta_4), \tag{7}$$

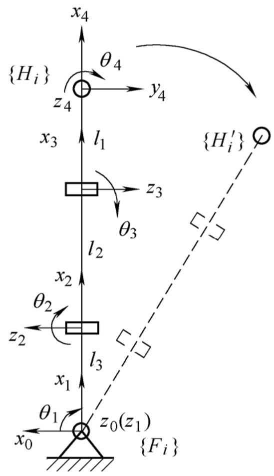


Fig. 7. D-H coordinate systems of leg in stance phase

When the leg in the initial state, the pose of foot with respect to the hip joint is as follows:

$$ {}^{H_i}_{F_i}\boldsymbol{T} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & -h \\ 0 & 0 & 0 & 1 \end{pmatrix}, $$
$$ {}^{H_i}_{H_i'}\boldsymbol{T} = {}^{H_i}_{F_i}\boldsymbol{T}\,{}^{F_i}_{H_i'}\boldsymbol{T} = \begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{8}$$

where

$$ \begin{cases} p_y = -l_1\cos\theta_1\cos(\theta_3-\theta_2) - l_3\cos\theta_1 - l_2\cos\theta_1\cos\theta_2, \\ p_z = l_2\sin\theta_2 - l_1\sin(\theta_3-\theta_2). \end{cases} \tag{9}$$

Eq. (9) is after leg swing, the position vector of hip joint in leg with respect to the initial point in the plane of yoz.

3.4.2 Movement range of hip joint in body

The coordinated movement between the body bending and legs swing is shown in Fig. 8. The broken lines indicate that the robot is in the initial state, the solid lines indicate that the robot is in the state after the body bending.

When the body bends as well as the leg in stance phase begins to swing with body, the hip joint has a displacement, as shown in Fig. 8.

Take leg 4 as an example, the movement range of hip joint in body is derived as follows.

According to the homogeneous transformation matrix ${}^{B}_{H_4}\boldsymbol{T}$ and ${}^{B}_{H_4'}\boldsymbol{T}$, then

$$ {}^{H_4}_{H_4'}\boldsymbol{T} = {}^{B}_{H_4}\boldsymbol{T}^{-1} \bullet {}^{B}_{H_4'}\boldsymbol{T} = \begin{pmatrix} \cos 2\theta & -\sin 2\theta & 0 & p_x \\ \sin 2\theta & \cos 2\theta & 0 & p_y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{10} $$

where

$$ \begin{cases} p_x = 2a + b\sin 2\theta - \dfrac{a\sin 2\theta}{\theta}, \\ p_y = b - c\cos 2\theta - \dfrac{a}{\theta} + \dfrac{a\sin 2\theta}{\theta}. \end{cases} \tag{11} $$

Eq. (11) is after leg swing, the position vector of hip joint in body with respect to the initial point in the plane of *xoy*.

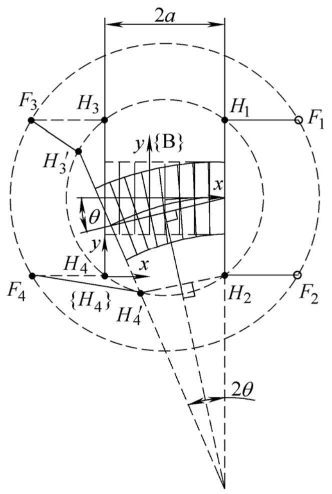


Fig. 8. Coordinated movement between body and legs

3.4.3 Calculation results

According to the PAM length of leg mechanism, the rotating range of each joint is $\theta_1 \in [90°,120°], \theta_2 \in [-5°,75°]$, $\theta_3 \in [8°,22°], \theta_4 \in [0,30°]$.

The link length of leg is $l_1 = 35$ mm, $l_2 = 363$ mm, $l_3 = 257$ mm.

In the horizontal plane, the movement range of hip joint H_4 in leg can be calculated by Eq. (9), as the shadow region shown in Fig. 9. The trajectory of hip joint H_4 in body can be calculated by Eq. (11), as the green curve shown in Fig. 9.

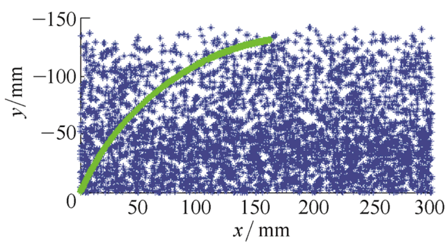


Fig. 9. Movement range of hip joint in body and leg

The intersection of the shadow region and the green curve indicates that the bending angle of body is less than 40°.

4 Dynamics

The dynamic modeling is to determine the relationship between the body bending torque or PAM driving force and the body bending angle.

4.1 Driving force of PAM

The musculoskeletal bionic flexible body is rigid-flexible coupling. The bionic spine is composed of several vertebrae units, and each vertebrae unit is composed of two vertebrae and three springs, as shown in Fig. 10. The floating coordinate method is adopted to analyze the dynamic model of each vertebrae unit[27].

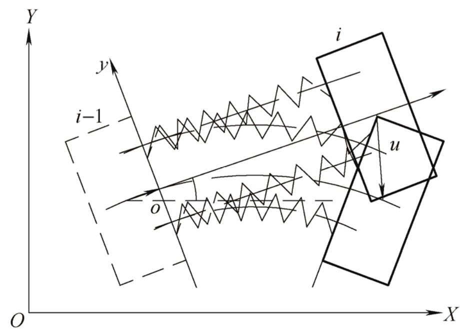


Fig. 10. Vertebrae unit

The kinematic energy and potential energy of *i*th vertebrae unit can be expressed by

$$ \begin{cases} E_{ki} = \dfrac{1}{2} m_i \dot{u}_i^2 + \dfrac{1}{2} J_{ci} \omega_i^2, \\ E_{pi} = k_i \Delta x_i^2, \end{cases} \tag{12} $$

where $\omega_i = \dot{\theta} / n$,

k_i —Spring stiffness,

J_{ci} —Moment of inertia of *i*th vertebrae unit.

The dynamic of rigid-flexible coupling spine with n vertebrae units can be expressed by

$$ \boldsymbol{\tau} = \frac{\mathrm{d}}{\mathrm{d}t} \frac{\partial \sum_{i=1}^{n} E_{ki}}{\partial \dot{q}} - \frac{\partial \sum_{i=1}^{n} E_{ki}}{\partial q} + \frac{\partial \sum_{i=1}^{n} E_{p}}{\partial q}, \tag{13} $$

where $\boldsymbol{\tau}$ —Driving moment for bending the body,

n—Number of vertebrae unit, n=10,

$\boldsymbol{q}$—Joint variable, $q = \theta$.

The needed driving force of PAM for bending the body can be derived by the moment of momentum theorem. The forces acting on the body are shown in Fig. 11.

For the fore body, there is following equation according to the moment of momentum theorem:

$$J_1\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2}=\sum \boldsymbol{M}_E(\boldsymbol{F}_i), \quad (14)$$

where J_1 —Moment of inertia of the fore body about the central axis,
F_i —External force acting on the body.

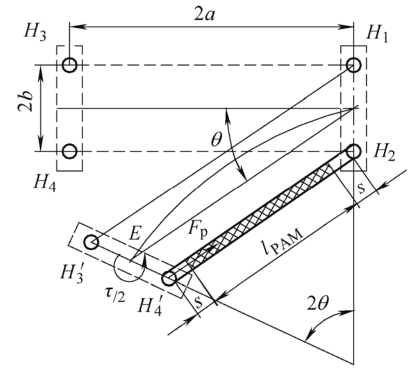


Fig. 11. Force analysis of body

The total moment of all external forces is

$$\sum \boldsymbol{M}_E(\boldsymbol{F}_i)=2\boldsymbol{F}_p b\cos\theta-\frac{\boldsymbol{\tau}}{2}. \quad (15)$$

The needed driving force of PAM for bending the bionic body should be

$$\boldsymbol{F}_p=\left(J_1\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2}+\frac{\boldsymbol{\tau}}{2}\right)\Big/(2b\cos\theta). \quad (16)$$

4.2 Gas pressure of PAM

The pneumatic muscle has elasticity and its elasticity can be changed by operating inner pressure. PAM exhibits non-linear characteristic, which is related to the elasticity and the friction among the rubber, the braid and the end constraints.

The force model of PAM should be analyzed. As the PAM is made from viscoelastic material, it is a challenging problem for determining the accurate model because of the nonlinearity of PAM. Some force models have been suggested, which can be used to analyze the characteristics of the PAM, and determine the relationship between the muscle contraction and force of PAM.

PAM can only exert a unidirectional pulling force. The relationship among inner pressure, force and contraction can be derived, and for different PAM, there are different express form and coefficient. The force produced by PAM can be expressed as a function of total pressure p and contraction ratio ε [14].

$$\boldsymbol{F}(\varepsilon,\boldsymbol{p})=\boldsymbol{p}\left(\frac{\pi d_0^2}{4}\right)\left(\beta_1(1-\varepsilon)^2-\beta_2\right),$$
$$\beta_1=\frac{3}{\tan^2\alpha_0},\ \beta_2=\frac{1}{\sin^2\alpha_0}, \quad (17)$$

where $\boldsymbol{p}$ —Inner pressure of the PAM,
β_1, β_2 —Constants related to the PAM parameters,
α_0 —Initial braid angle, which is defined as the angle between the PAM axis and each thread of the braided sheath before expansion,
ε —Contraction ratio, $\varepsilon=l_0-l/l_0$, l_0 is the initial length, d_0 is the initial diameter of the PAM.

Then the inner pressure of the PAM can be calculated:

$$\boldsymbol{p}=\boldsymbol{F}_p\Big/\left\{\left(\frac{\pi d_0^2}{4}\right)\left[\beta_1(1-\varepsilon)^2-\beta_2\right]\right\}. \quad (18)$$

5 Experiment

When the PAM of the body mechanism is supplied with pressurized air, the relative rotating movement between the fore body and the rear body is produced.

The bionic body can achieve bending along different direction. On the one hand, it can bend along upwards or downwards, which is helpful to the running or jumping gait. On the other hand, the body can bend along leftwards or rightwards, which is helpful to the spinning gait. As the spinning gait is analyzed in this paper, so the experiment of body lateral bending is only conducted.

5.1 Experiment system

The dynamic bending experiment of bionic flexible body was conducted to study the working characteristic of PAM, and to determine the relationship among the body bending angle, PAM real length and gas pressure. The bending experiment principle of bionic flexible body for quadruped robot is shown in Fig. 12. The experimental system is composed of one bionic artificial spine, PAMs from FESTO Company, fore body, hind body, pneumatic control system, NI data acquisition card, proportional valves, pressure regulating valve, displacement sensor and pressure sensor.

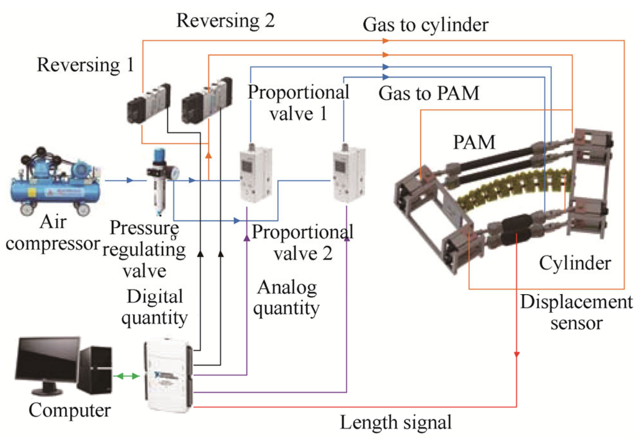


Fig. 12. Experimental system

One end of PAM is supplied with compressed air, and the other end is mounted a displacement sensor, which is used to measure the real length of PAM. Each PAM needs one proportional valve to control inlet gas or outlet gas. Proportional valve is a kind of digital switching solenoid valve with rapid response performance, which is an ideal interface element between the electronic and pneumatic components. The most significant feature is the ability to accept directly a digital signal to the fluid system pressure and flow pulse width modulation, which can provide an effective means to control PMA.

The experiment principle of bionic flexible body bending is as follows: The pressurized air is exported by the air compressor and is inputted into the PAMs through pressure regulating valve and proportional valve. The proportional valve is dynamically controlled through NI data acquisition card and Labview software. The gas pressure is controlled at certain value, and the PAMs length can change with changing of gas pressure. The hardware used in the experiment is shown in Table 1.

Table 1. Main hardware used in the experiment

No.	Name	Model name	Company
1	Proportional valve	VPPM-6L-L-1-G18-0L6H-V1P-C1	FESTO
2	Pressure sensor	SDE1-D10-G2-W18-L-PU-M8	FESTO
3	Reversing valve	LFR-1/8	FESTO
4	Displacement sensor	QL40	BOSO
5	Data acquisition card	USB-6212 Bus-Powered M Series Multifunction DAQ Device	NI
6	Pneumatic artificial muscles	MAS-20-200N-AA-MC-O	FESTO

5.2 Experimental results

5.2.1 Experiment system

The bending experiment is conducted to evaluate the control algorithm and the bending characteristic of the musculoskeletal body. The PAM length should be controlled within a reasonable range in order to obtain the suitable bending angle of the bionic body.

The PID control algorithm is adopted to control the PAM length. The control system is shown in Fig. 13.

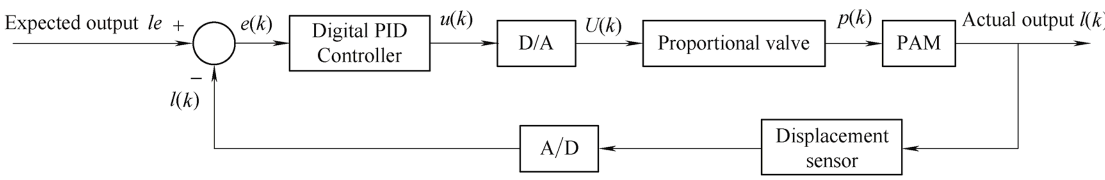


Fig. 13. Block diagram of body control

The compressed air is supplied through a ϕ6mm tube from the compressor to the valves and PAMs. The pressure sensors are used to measure the air pressure. The data acquisition card records the signal of pressure sensors and input into the PC. The software Labview is adopted to monitor and collect the data imported by the data acquisition card.

The hardware used in the experiment system is shown in Fig. 14. The biomimetic vertebrae are manufactured by 3D printer.

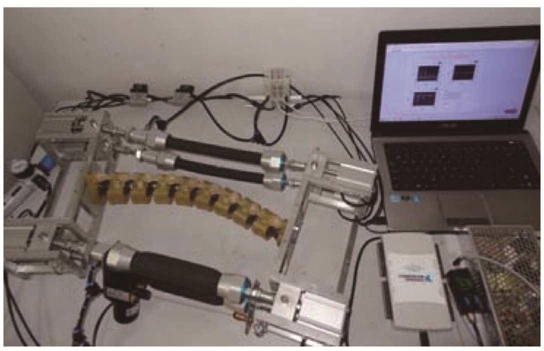


Fig. 14. Experiment system of bionic flexible body

5.2.2 Tracking experiment of PAM length

The body parameters are as follows: $a = 160$ mm, $b = 80$ mm, $s = 60$ mm. The PAM initial length l_0 is 200mm and the initial diameter d_0 is 20mm. The initial braid angle of PAM is 30°.

The expected length of PAM changes with time is set as

$$l_{\text{PAM}} = 200 - 1.6t^2 \quad \left(160 \text{ mm} < l_{\text{PAM}} < 200 \text{ mm}\right). \quad (19)$$

The experiment results of PAM length tracking are shown in Fig. 15. The parameters of PID are $k_{\text{P}} = 3$, $k_{\text{I}} = 1$, $k_{\text{D}} = 1$.

The experiment results show that the PID control algorithm is feasible.

5.2.3 Body bending angle

The PID control algorithm is adopted to control the PAM into different length. During the experiment, the minimum length of PAM can be compressed to 140 mm. The PAM length change from 200 mm to 140 mm, and the body bending angles under different PAM length are measured. The results of experiment and calculation by Eq. (6) are shown in Fig. 16.

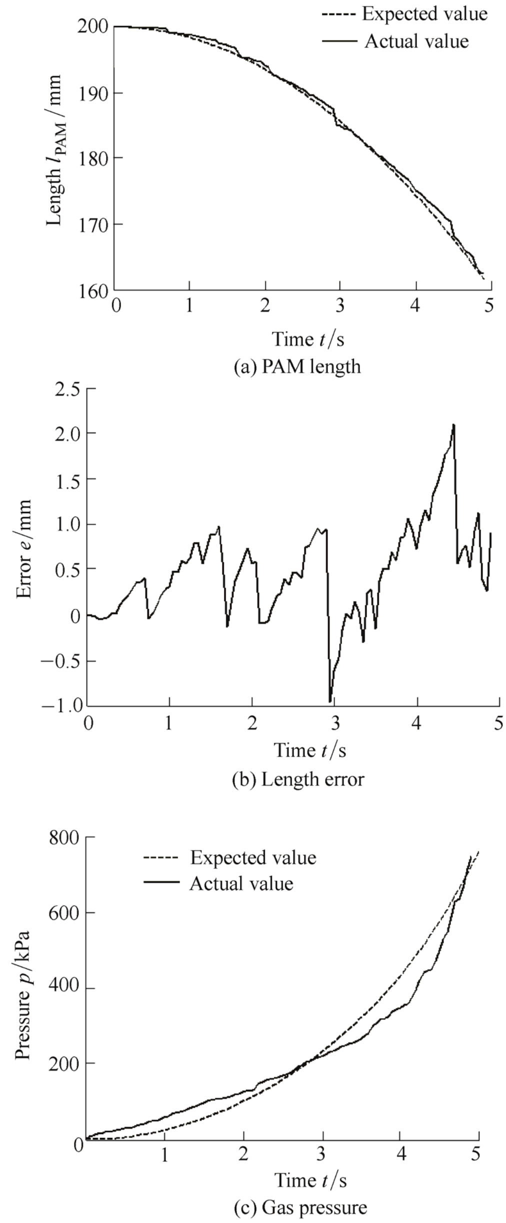


Fig. 15. Experimental results

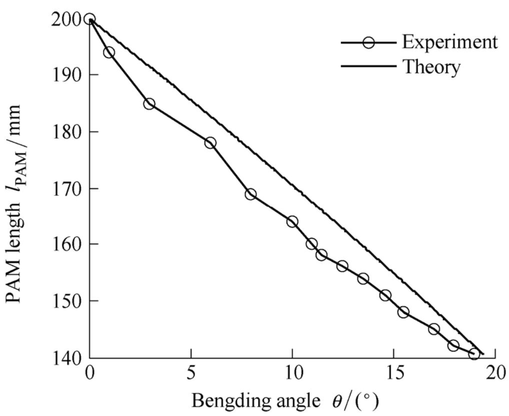


Fig. 16. PAM length versus body bending angle

The body bending angle is related with the body length, body width, PAM length and PAM mounting size. The maximum bending angle of the bionic flexible body can reach 18°.

6 Conclusions

(1) A kind of bionic flexible body driven by PAMs for quadruped robot is proposed, which is composed of one bionic flexible spine, fore body and rear body. The body has the property of flexibility by changing PAM pressure.

(2) The quadruped robot can achieve the spinning gait by the coordinating movement between the bionic body and the leg mechanism together.

(3) The bending angle of the bionic body is related with the body length, body width, PAM length and PAM mounting size.

(4) The experimental is conducted to evaluate the bending characteristic of the bionic flexible body. The PID control algorithm is adopted and the bending feasibility is investigated. The body bending angle is measured by changing the PAM pressure. The maximum bending angle of the bionic flexible body can reach 18°.

References

[1] PARK S H, KIM D S, LEE Y J. Discontinuous spinning gait of a quadruped walking robot with waist-joint[C]//*International Conference on Intelligent Robots and Systems*, Edmonton, Alta, 2005: 2744–2749.

[2] BERTRAM J E A, GUTMANN A. Motions of the running horse and cheetah revisited: fundamental mechanics of the transverse and rotary gallop[J]. *Journal of the Royal Society*, 2009, 6(35): 549–559.

[3] JULIANNA M G. Static and dynamic mechanical properties of intact intervertebral joints[J]. *Journal of Experimental Biology*, 1993, 174 (1): 247–280.

[4] TSUJITA K, MIKI K. A study on trunk stiffness and gait stability in quadrupedal locomotion using musculoskeletal robot[C]//*15th International Conference on Advanced Robotics*, Tallinn, Estonia, 2011: 316–321.

[5] MIZUUCHII I, TAJIMA R, YOSHIKAI T, et al. The design and control of the flexible spine of a fully tendon-driven humanoid "kenta"[C]//*IEEE/RSJ International Conference on Intelligent Robots and Systems*, Lausanne, Switzerland, 2002: 2527–2532.

[6] OR J. A hybrid CPG–ZMP control system for stable walking of a simulated flexible spine humanoid robot[J]. *Neural Networks*, 2010, 23(3): 452–460.

[7] DENG Qi, WANG Shigang, LIANG Qinghua, et al. The effect of body pitching on leg-spring behavior in quadruped running[J]. *Journal of Bionic Engineering*, 2010, 7(3): 219–227.

[8] MIKI K, TSUJITA K. A study of the effect of structural damping on gait stability in quadrupedal locomotion using a musculoskeletal robot[C]//*IEEE/RSJ International Conference on Intelligent Robots and Syste*ms, Vilamoura, Algarve, Portugal, 2012: 1976–1981.

[9] TSUJITA K, MIKI K. Stability analysis on quadrupedal gaits according to body's flexibility using musculoskeletal robot[C]//*IEEE International Conference on Robotics and Biomimetics*, Phuket, Thailand, 2011: 1609–1614.

[10] TSUJITA K, KOBAYASHI T, MASUDA T. Feasibility study on stability of gait patterns with changable body stiffness using pneumatic actuators in quadruped robot[J]. *Advanced Robotics*, 2009, 23(5): 503–520.

[11] DENG Q, WANG S G, XU W, et al. Quasi passive bounding of a quadruped model with articulated spine[J]. *Mechanism and*

Machine Theory, 2012, 52(6): 232–242
[12] REMY C D, BUFFINTON K, SIEGWART R. Stability analysis of passive dynamic walking of quadrupeds[J]. *The International Journal of Robotics Research*, 2009, 29(9):1–13.
[13] TAKUMA T, IKEDA M, MASUDA T. Facilitating multi-modal locomotion in a quadruped robot utilizing passive oscillation of the spine structure[C]//*IEEE/RSJ International Conference on Intelligent Robots and Systems*, Taipei, Taiwan, 2010: 4940–4945.
[14] LEESER K F. *Locomotion experiments on a planar quadruped robot with articulated spine*[D]. Boston: Massachusetts Institute of Technology, 1996.
[15] KUEHN D, GRIMMINGER F, BEINERSDORF F, et al. Additional DOFs and sensors for bio-inspired locomotion: towards active spine, ankle joints, and feet for a quadruped robot[C]//*IEEE International Conference on Robotics and Biomimetics*. 2011: 2780-2786.
[16] IJSPEERT A J, CRESPI A, RYCZKO D, et al. From swimming to walking with a salamander robot driven by a spinal cord model[J]. *Science,* 2007, 315(5817): 1416–1420.
[17] SEOK S, WANG A, MICHAEL CHUAH M Y, et al. Design principles for energy-efficient legged locomotion and implementation on the MIT cheetah robot[J]. *IEEE/ASME Transactions on Mechatronics*, 2015, 20(3): 1117–1129.
[18] DONG J H, SEOK S, LEE J, et al. High speed trot-running: implementation of a hierarchical controller using proprioceptive impedance control on the MIT cheetah[J]. *International Journal of Robotics Research*, 2014, 33(11): 1417–1445.
[19] PABLO G D S, ELENA G, JOAQUIN E. *Generation of Periodic Gaits*[M]. Publisher Springer London: Quadrupedal Locomotion, 2006: 57–87, 89–120.
[20] ZHANG J Q, GAO F, HAN X L, et al. Trot gait design and CPG method for a quadruped robot[J] . *Journal of Bionic Engineering*, 2014, 11(1): 18–25.
[21] MAHMOUD A, OKADA T, BOTELHO W T. Estimation and verification of the trajectory forms generated by a legged sliding robot[C]//*IEEE International Conference on Robotics and Biomimetics*, Guilin, China, 2009: 227–232.
[22] OKADA T, HIROKAWA Y, SAKAI T, et al. Synchronous Landing control of a rotating 4-legged robot, PEOPLER, for stable direction change[C]//*CLAWAR, Climbing and Walking Robots, Part II .the 8th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines*, Springer Berlin Heidelberg, London, UK, 2005: 85–96
[23] NIIYAMA R, KUNIYOSHI Y. A pneumatic biped with an artificial musculoskeletal system[C]//*The 4th International Symposium on Adaptive Motion of Animals and Machines*, Cleveland, USA, 2008: 80–81.
[24] TONDU B, LOPEZ P. Modeling and control of mckibben artificial muscle robot actuators[J]. *Control Systems Magazine*, 2000, 20(2): 15–38.
[25] DOUMIT M, FAHIM A, MUNRO M. Analytical modeling and experimental validation of the braided pneumatic muscle[J]. *IEEE Transactions on Robotics*, 2009, 25(6): 1282–1291.
[26] NIIYAMA R, NISHIKAWA S, KUNIYOSHI Y. Athlete robot with applied human muscle activation patterns for bipedal running[C]// *IEEE-RAS International Conference on Humanoid robots*, Nashville, TN, USA, 2010: 498–503.
[27] LEI J T,YU H Y. Dynamics analysis of bionic flexible body driven by pneumatic artificial muscle for quadruped robot[J]. *Journal of Shanghai Jiao Tong University*, 2014,48(12): 1688–1693: 1699. (in Chinese)

Biographical notes

LEI Jingtao, born in 1970, is currently an associate professor at *School of Mechatronic Engineering and Automation, Shanghai University, China*. She received her PhD degree from *Beihang University, China*, in 2007. She was a postdoctoral fellow at *Robotics Institute of Beihang University* from 2007 to 2009. Her main research interests include bionic robot and modular technology of service robot.
Tel: +86-21-56334407; E-mail: jtlei2000@163.com

YU Huangying, born in 1989, is currently a master candidate at *School of Mechatronic Engineering and Automation, Shanghai University, China*. His research interests include bionic robot.
E-mail: yuhuangying2007@163.com

WANG Tianmiao, born in 1960, is currently a professor at *School of Mechanical Engineering and Automation, Beihang University, China*. He received his PhD degree from *Northwestern Polytechnical University, China*, in 1990. He was a postdoctoral fellow at *National Intelligent Technology and Systems Laboratory, Tsinghua University, China*, and *Italian National Bionic Mechanics Laboratory* from 1990 to 1995. His research interests include biomimetic robots, medical robots and robot modular technology.
Tel: +86-10-82338805; E-mail: wtm_itm@263.net