SCIENCE CHINA
Information Sciences

May 2019, Vol. 62 050213:1–050213:3
https://doi.org/10.1007/s11432-018-9709-x

• **LETTER** •
Special Focus on Human-Robot Hybrid Intelligence

Design, modelling and identification of a fiber-reinforced bending pneumatic muscle

Hongge RU[1], Jian HUANG[1*], Wenbin CHEN[2], Caihua XIONG[2],
Junzhe WANG[1] & Jun HUO[1]

[1]*School of Automation, Huazhong University of Science and Technology, Wuhan* 430074*, China;*
[2]*School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan* 430074*, China*

Received 30 August 2018/Accepted 21 November 2018/Published online 27 February 2019

Citation Ru H G, Huang J, Chen W B, et al. Design, modelling and identification and of a fiber-reinforced bending pneumatic muscle. Sci China Inf Sci, 2019, 62(5): 050213, https://doi.org/10.1007/s11432-018-9709-x

Dear editor,
Many countries are facing the social problem of an increasing aging population, which means that the demand for professional caregivers will be increasing. Meanwhile, people suffering from stroke, various injuries to joints, or some other physical diseases of the knuckles are also in desperate need of physical support [1]. While the human resources for those problems are utterly inadequate, robot-assisted devices are promising solutions to these problems. Soft pneumatic actuators have shown great potential in assisted devices, prosthetics, and rehabilitation applications. They can either extend or contract as the air pressure changes, depending on the elasticity of the rubber and the design of the fiber-wrapping, providing a traction force when compressed air is supplied.

Based on traditional linear pneumatic muscles, soft bending actuators were proposed because certain actions such as twisting, rotating, and curving cannot be performed directly by conventional rigid-bodied robots [2, 3]. Al-Fahaam et al. [3] fabricated a bending pneumatic muscle based on a 260q Qualatex latex modeling balloon, which increased in length with applied air pressure. Zhao et al. [4] developed a low-cost closed-loop-controlled soft orthotic that can provide sufficient tip force at each finger to facilitate easy grasping of light objects. Guo et al. [5] proposed a dynamic model for a continuum robot with a compliant structure but only the static characteristics were validated. A finite-element method model was designed for a bending pneumatic muscle working in free space, and a static model of a flexible pneumatic bending joint was proposed [6,7]. The bending pneumatic actuator maintains a low profile, is light weight, has compliant nature, and is robust against pressurization; however, achieving a precise control of this actuator is difficult. Although the dynamic model plays an important role in the control of bending pneumatic actuators, to the best of our knowledge, this issue continues to be rather challenging.

This study presents a design for a new fiber-reinforced bending pneumatic muscle and proposes a dynamic modeling method for the bending pneumatic actuator. The parameters of this model were identified empirically using a high-speed camera. Most related studies have employed statistical models of such an actuator. To the best of our knowledge, this study might be the first to attempt the dynamic modeling of a bending pneumatic muscle. Finally, experiments were conducted to verify the reliability of the proposed model.

Design and modelling of fiber-reinforced bending pneumatic muscle. The fiber-reinforced bending pneumatic muscle was based on linearly actuated artificial muscles. A piece of fiberglass was attached to one side of the tube, such that this fixed side cannot extend or contract when the air

---

[*] Corresponding author (email: huang_jan@mail.hust.edu.cn)

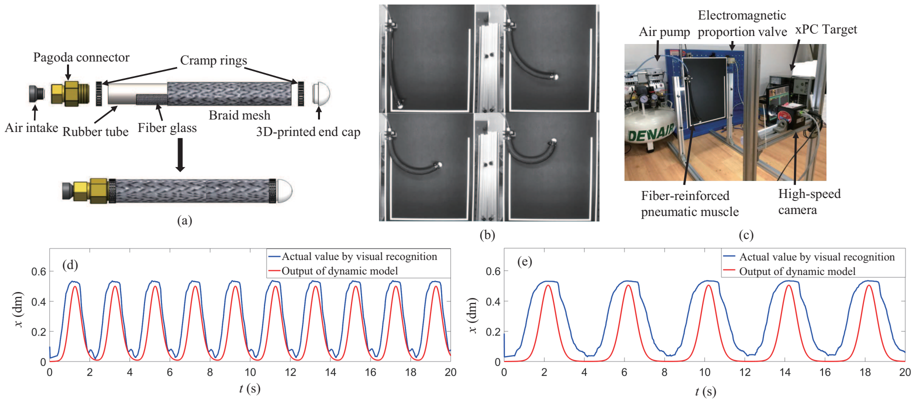

Figure 1 (Color online) (a) Fabrication of the fiber-reinforced pneumatic muscle; (b) photographs of the actuator at different air pressures; (c) experiment apparatus; (d) experimental result when the input is 0.5 Hz; (e) experimental result when the input is 0.25 Hz.

is supplied (see Figure 1(a)). Because the other side can still be deformed as the air is supplied, the actuator will bend toward the fixed side with the increase of air pressure. One end of this actuator was plugged with a white, 3D-printed end cap, which works as a choke plug and an identifying mark for visual recognition for the position of the end cap (see Figure 1(b)). The compressed air will be fed in from the other end through a pipe, which is fixed on a black acrylic board, known as the reference point, in visual recognition.

Herein, visual recognition was applied for real-time position sensing and the identification of the proposed dynamic model. Noticing that the shape of the actuator is extremely similar to an arc, the bending angle of this actuator is related to the distance between the two ends, which can be written as follows [8]:

$$D = d\cdot\left(\frac{L_0+L}{L_0-L}\right)\cdot\sin\frac{L_0-L}{2d},\quad L=f^{-1}(D), \tag{1}$$

$$D = 2\sin\left(\frac{\theta}{2}\right)\cdot\left[\frac{f^{-1}(D)}{\theta}+\frac{d}{2}\right], \tag{2}$$

where D is the distance between the reference point and the white distal end; L is the length of the deformable side; and L_0 is the length of the fixed side, which is a measurable constant as the fixed side will not contract; d is a constant indicating the radius of the actuator, which varies little when inflated; and θ is the bending angle of this actuator.

Thus, the bending angle can be substituted by the distance D or length L, which also means that D and L can completely indicate the state of this actuator.

An agonistic-antagonistic pneumatic muscle was described using a second-order differential equation [9]. Considering that the deformable side of this fiber-reinforced pneumatic muscle is free to stretch like the agonistic-antagonistic pneumatic muscle, the dynamic character of this actuator could be similar to the three-element dynamic character of the agonistic-antagonistic pneumatic muscle. In this case, we considered the change in length of the deformable side as the output

$$x = L_0 - L. \tag{3}$$

The air pressure in the actuator p is considered as the input. The second-order differential equation is represented as the initial equation of the dynamic model

$$M\cdot\ddot{x}+N\cdot\dot{x}+Q\cdot x=P, \tag{4}$$

where M, N, Q, and P are the air pressure-dependent functions, which are yet to be identified.

Parameter identification. The toolbox of CFTOOL in Matlab was applied for the parameter identification problem. First, a series of step signals varying from 0 to 3.0 bar was input and the corresponding outputs were recorded for identifying Q and P. The first- and second-order derivative values are zero in this situation. The bending pneumatic muscle platform is shown in Figure 1(c).

According to the fitting results in the Appendix A, a potential field model of different types can be described based on the sigmoid function. Applying the sigmoid function, we obtain

$$P=\mathrm{e}^{b_1\cdot p},\quad Q=a_1\cdot\mathrm{e}^{b_1\cdot p}+c_1, \tag{5}$$

where a_1, b_1 and c_1 are all constants and shown in Table A3 of the Appendix A as well as the parameters in M and N.

Meanwhile, the fitting curve exactly matches the principles of the fiber-reinforced bending pneumatic actuator. The motion of the bending pneumatic muscle can be divided into three phases, namely a low-pressure phase, a rapid-bending phase, and a close-to-saturation phase. When the air pressure is relatively low (0–0.8 bar) and the rubber tube expands to the braid mesh, the actuator undergoes a small deformation (low-pressure phase). The tube is strictly limited by the braid mesh, and the rubber contracts rapidly (rapid-bending phase). Finally, when the air pressure is higher than 2.5 bar, the motion of the actuator is minimal (close-to-saturation phase). The whole process acts exactly like the sigmoid growth curve; therefore, the static model can be fitted by a sigmoid function.

To determine the functions that describe M and N, a sinusoidal signal of air pressure was input for the dynamic response with a period of 2 s. The peak value of the input is 2.4 bar, whereas the bottom value is 0 bar. The output curve was similar to sinusoidal functions; thus, the bottom and peak were the points wherein $\dot{x}$ was 0. These extreme points can be used to calculate the value of M, which is shown in Table A3 (Appendix A). Then, the fitting surface for N was obtained by calculating all the output values. Similar to P and Q, the function for N can be written as follows:

$$N = a_2 \cdot \mathrm{e}^{b_2 \cdot p} + c_2. \tag{6}$$

All the parameters are shown in Table A3 of Appendix A. Finally, an empirical dynamic model of this fiber-reinforced pneumatic muscle was identified. The identification details are listed in Appendix A.

The parameter a_2 is much smaller than the other parameters due to several reasons. N corresponds to the damping coefficient in the three-element model of a pneumatic muscle. The fluid friction in the inlet of the pneumatic muscle did not affect the overall damping. However, the friction between the outer sheath and rubber tube slightly varies little with changes in the air pressure [9]. In this case, N was almost constant and a_2 was very small.

$$\begin{aligned} M \cdot \ddot{x} + (a_2 \cdot \mathrm{e}^{b_2 \cdot p} + c_2) \cdot \dot{x} + (a_1 \cdot \mathrm{e}^{b_1 \cdot p} + c_1) \cdot x \\ = \mathrm{e}^{b_1 \cdot p}. \end{aligned} \tag{7}$$

Experimental results. To verify the reliability of this dynamic model, a simulation was conducted according to (7). Considering the same input as the sinusoidal signal input for identification, the corresponding output was calculated. Figure 1(d) shows the comparison between the recognition and simulation results, indicating that the dynamic model can describe the dynamic characteristics of a bending pneumatic muscle to a good extent. In addition, another simulation with a 0.25-Hz input signal was conducted; the result is shown in Figure 1(e). Simulation results suggested that the dynamic model of a bending pneumatic muscle was reliable.

Conclusion. Herein, a new fiber-reinforced pneumatic muscle was proposed. The dynamic model of this pneumatic muscle was described using a second-order differential equation. The parameters in the empirical model were identified experimentally based on visual recognition, and the simulation results showed that the model was reliable.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 61473130, 91648203, 51335004).

Supporting information Appendix A. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Peng L, Hou Z G, Peng L, et al. Robot assisted rehabilitation of the arm after stroke: prototype design and clinical evaluation. Sci China Inf Sci, 2017, 60: 073201

2 Huang J, Qian J, Liu L, et al. Echo state network based predictive control with particle swarm optimization for pneumatic muscle actuator. J Franklin Inst, 2016, 353: 2761–2782

3 Al-Fahaam H, Davis S, Nefti-Meziani S. Power assistive and rehabilitation wearable robot based on pneumatic soft actuators. In: Proceedings of the 21st International Conference on Methods and Models in Automation and Robotics (MMAR), 2016. 472–477

4 Zhao H C, Jalving J, Huang R K, et al. A helping hand: soft orthosis with integrated optical strain sensors and EMG control. IEEE Robot Autom Mag, 2016, 23: 55–64

5 Guo Y, Kang R J, Chen L S. Dynamic modeling for a continuum robot with compliant structure. In: Proceedings of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2015

6 Polygerinos P, Wang Z, Overvelde J T B, et al. Modeling of soft fiber-reinforced bending actuators. IEEE Trans Robot, 2015, 31: 778–789

7 Zhang L B, Bao G J, Yang Q H, et al. Static model of flexible pneumatic bending joint. In: Proceedings of International Conference on Control, Automation, Robotics and Vision, 2007

8 Ru H, Huang J, Xiong C, et al. Design and control of a soft bending pneumatic actuator based on visual feedback. In: Proceedings of the World Congress on Intelligent Control and Automation (WCICA), Changsha, 2018

9 Reynolds D B, Repperger D W, Phillips C A, et al. Modeling the dynamic characteristics of pneumatic muscle. Ann BioMed Eng, 2003, 31: 310–317