Design and Test of a New Spiral Driven Pure Torsional Soft Actuator

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Abstract. Owing to the twist degree of freedom (DOF), soft torsional motion can increase flexibility and quickly achieve positional and attitude adjustment in complex and narrow spaces. Compared with bending actuator, there is much less research on soft torsional actuators. Current soft torsional actuators often accompany with other motion couplings, so it is difficult to provide pure twist. Based on the princi-ple of spiral chambers with pneumatic driving, a new type of torsional actuator module is designed in this paper. Combined with finite element simulation, the ge-ometric parameters of the module are optimized and then fabrication is carried out by two stages. In order to control the module, a kinematic model, which is the relationship between the air pressure and the twist angle, is established by means of experimental calibration. Finally, a test platform is set up, which is used for measuring the static characteristics of the designed module. The maximum ob-tainable torsion angle and torque are obtained separately through the experiments on torsion angle test and torsion torque test.

Keywords: Soft torsional actuator · Pure twist · Kinematics · Static characteristics

1 Introduction

Due to low morphology, high energy-weight ratio and inherent compliance, soft robots have infinite DOF and can adapt to complex environments, which make them become an active area in robotic research in recent years. Soft bending actuators have been extensively studied, because they have the bending ability to mimic the motion of mollusks like earthworms, snakes, worms, elephant trunks and human hand. However, there are few studies on torsional actuators. Through the observation of soft creatures in nature, most animals have evolved with twisting DOF, such as in the shoulders, wrists, ankles and including the mentioned-above mollusks. Torsional actuators can effectively improve the flexibility of motion and have many advantages. Firstly, increase flexibility. Compared to a single bending actuator, torsional actuators can conveniently implement the same twisting operations and require smaller space. Besides, they are able to achieve complex positon and attitude quickly, which can be used in some twist joints that require compact structure and simple cable transmission, but do not need precise positional and force control. Secondly, reduce resistance. When crossing the narrow space like a hole or tunnel, soft torsional actuator can reduce the resistance by generating torsional

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deformation. Thirdly, cooperate movement. By operating with other functional components, such as bending and elongation modules, torsional actuators can realize a lot of complex motion.

As generating direct twisting motion is difficult, it is more common to design a torsional actuator based on other forms of motion. For example, rotary Peano actuators [1, 2], antagonistic shape actuators [2–4], fiber weave actuators [2, 5, 6], and pleated chamber actuators [7, 8], most of them adopt the principle of strain difference and depend on the radial or axial expansion deformation. They generate twist motion by the guide of confined layer like strings or fibers. As it is difficult to control the other direction deformation, the twisting motion is always coupled with radial or axial expansion and bending distortion. At present, research on soft torsional actuator is as follows:

Rotary Peano actuators are designed based on the principle of linear Peano actuators, utilizing the contraction occurring over the width of a long tube when it is inflated. Hideyuki et al. [1] developed a "flat tube" made of urethane, which can change its cross-sectional shape from flat to round when pressurized. When helically stacked into a cylinder, it can produce linear motion under pressurization while two positions with a circumferentially different phase between up and down are connected to each other by a wire at the same time, it can generate rotational motion in conjunction with extension. Siddharth et al. [2] made a rotary Peano actuator using the same contraction principle of the linear Peano actuators, which utilizes the contraction occurring over the width of a long tube when it is inflated. Rotary motion is generated by virtue of their helical arrangement on a cylinder but also with the change of radial, axial dimensions when pressurized.

Antagonistic shape actuators use spiral shaped structures. If the fabric at the central axis of the actuators is assumed to be inextensible, these actuators can produce rotational motion when the helix chambers are inflated. Siddharth et al. [2] introduced the principle of an antagonistic shape actuator and designed a fluidic torsional actuator by combining two oppositely oriented helix like structures into a single structure to generate pure torsional motion with minimal linear motion. Ellen T. et al. [3] utilized helical soft tubes made of fluid elastic silicon as fluid elastic actuating element. By putting them on the surface of the heart, they can produce twist and untwist motion.

Fiber weave actuators are defined by the constraints due to the nearly inextensible fibers on its surface. Just like the principle of McKibben actuators, these actuators generate torsional motion by the guide of the asymmetric arrangement of fibers. Panagiotis et al. [5] designed a mechanically programmable soft pneumatic actuator with silicone rubber and polymer fibers, which can achieve a wide range of motions, including axial extension, radial expansion, and twisting. In order to maximize the torsional motion, they performed finite element simulations of the actuators by simply varying the parameter of fiber angle. These soft actuators can be used in flexible and compliant endoscopes, pipe inspection devices, and assembly line robots. Hong Kai et al. [6] made an improvement on the previous developed actuators. When fabricating the soft module, they used corrugated outer layer to reduce the radial expansion and realized twisting motion through the oblique corrugated outer layer.

Pleated chamber actuators depend on the fold structure like the accordion. When the center is constrained and the chambers are inflated, the pleated chamber actuators can generate true rotary motion different from regular torsional motion. Oleg Ivlev et al. [7] developed a rotary actuator with pleated rotary elastic chambers which used a hard motor shell to generate torque from 11 Nm to 20 Nm. This actuator is mainly used for motion therapy devices for the lower extremities, providing patient friendly rehabilitation. Kargov et al. [8] also developed a likewise actuator module with the structure of pleated chamber. They combined this module and elongation module together to make an arm prototype.

These soft torsional actuators above have many problems, including coupling motion, not pure twist, difficulty in matching pressure in different chambers, etc., this paper uses the drive mode of the fluid elastic actuator (FEA) to directly generate the torsional motion by inflating spiral chambers. First of all, the structure design of the new soft torsional module is introduced. Then the geometric parameters of the soft module are optimized based on the results of finite element analysis and the fabrication is also completed. In order to establish the kinematics model of the module, a test platform consisting of a pneumatic driven system and a measurement platform is developed to calibrate the kinematics. Finally, it has been used in the test of torsion angle and torsion torque to obtain the static characteristics of the soft torsional actuator module.

2 Fabrication of Soft Torsional Module

2.1 Structure Design

As shown in Fig. 1, the soft torsional module has been designed based on the design idea of screw type twisting.

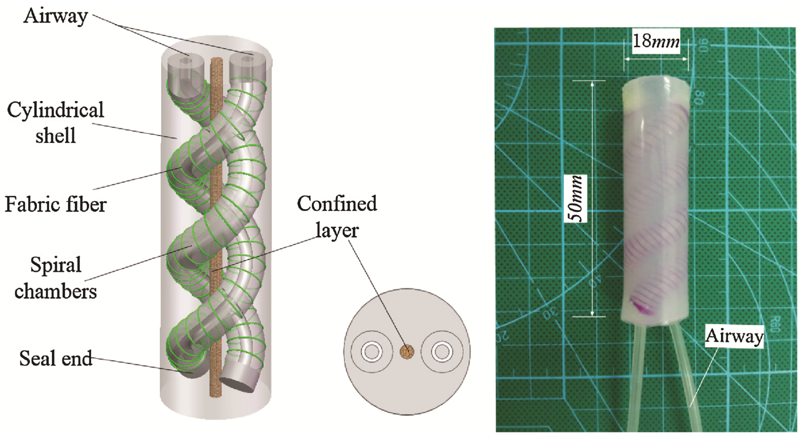


Fig. 1. Structure of soft torsional actuator module

The main body is a cylindrical structure made of silicone. As using one spiral chamber has the overturning moment, the whole module is prone to off-centering, the module adopts at least two spiral chambers, which are symmetrically distributed around the center of the actuator, to improve the twisting stability and avoid twisting offset. The inner spiral chamber is a hollow cylinder with spiral thin fiber line surrounded outside which is used to limit radial deformation and provide more efficient elongation. One end of spiral chamber is sealed with a harder silicone and the other end is connected to the airway for gas actuation. In addition, an inextensible material embedded in the center of the whole cylinder is used to limit axial elongation. When spiral chambers are inflated simultaneously, they generate elongation motion. But the constraint layer limits elongation and turns the driving force into moment, realizing torsional motion.

2.2 Geometric Parameter Optimization

Modeling. Figure 2 is the cross-sectional view of the module, in which the geometrical structure is affected by five variables: center distance of chambers $D = 2R$, diameter of module D_r, spiral angle α, diameter of inner spiral chambers $d = 2r$ and the whole length L. In order to obtain the response of twisting performance to every geometric parameter, Finite Element Method (FEM) software ABAQUS is used and controlling variable method is adopted to optimize the structure design.

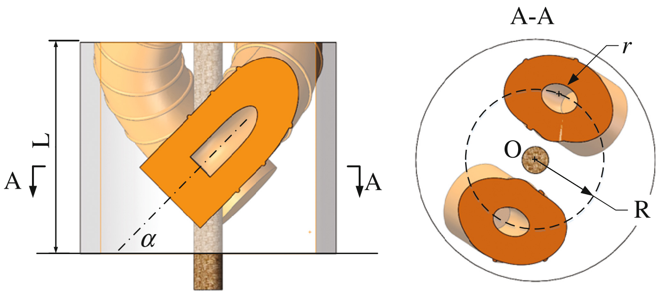
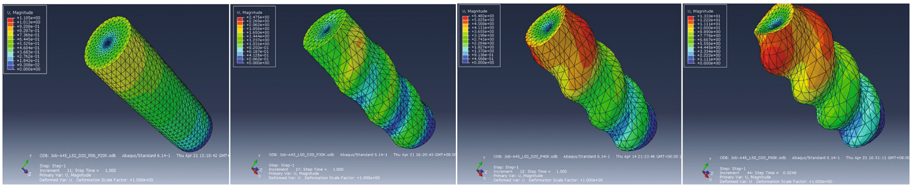


Fig. 2. The configuration and geometric parameters of torsion modules

When establishing the FEM models, the whole module is split as solid tetrahedral quadratic hybrid elements. The hyper-elastic incompressible YEOH material model is used to describe the nonlinear material behavior with the coefficients $C1 = 0.11$ and $C2 = 0.02$. The coefficients are chosen from Wacker M4601 which is used in references [9, 10]. Here, we just care about the influence of geometric parameters on soft material described by YEOH model. Even though the coefficients of material used are different from fabrication, they have similar characteristics and the simulation results is also applicable. The constraint layer was modeled as shell model with Young's modulus of $E = 31.067$ MPa and a Poisson's ratio of $\nu = 0.36$. Then, the boundary conditions are set by fixing the base and applying the pressure on the inner chambers, ranging from 0 to 60 kPa and each step 10 kPa. Finally, the deformation cloud diagram of different pressure are shown in Fig. 3.



a) P=10KPa b) P=30KPa c) P=40Kpa d) P=60KPa

Fig. 3. FEM simulation results of torsional module

Results. As the designed module is required to adapt to narrow space, its diameter should not be too large. Here, D_r is fixed as 18 mm for simulation. Firstly, the other parameters are kept unchanged and the center distance of chambers is set to 6 mm, 8 mm, 10 mm, and 12 mm respectively. It is shown in Fig. 4(a) that as the center distance of chambers increases, the torsion angle also increases. However, when the pressure is relatively lower, it is not clear whether the elastic deformation or the air pressure of the soft module plays the leading role. As the air pressure reaches a certain value (about 35 kPa) and begins to dominate, the relationship between air pressure and torsion angle becomes linear.

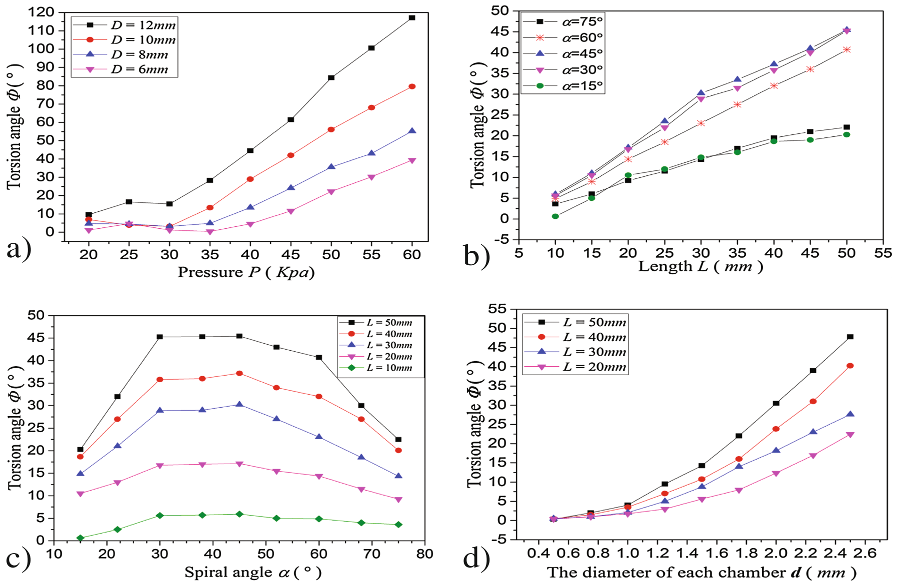


Fig. 4. Influence of different geometric parameters on the torsion angle. The parameters are (a) center distance of spiral chamber, (b) length, (c) spiral angle, (d) diamater of each chamber

In order to obtain the influence of the other geometric parameters on the torsion angle, the pressure in the linear region is chosen as the fixed parameter, i.e., $P = 50$ kPa and the other three parameters are changed respectively. Through analyzing a large amount of simulation of different modules, we can get the following results: Fig. 4(b) shows that when the whole length of the module becomes longer, the torsion angle becomes larger. Figure 4(c) shows that when the spiral angle locates between 30º and 45º, the torsion angle seems to be lager. The reason for that is as spiral angle become lager, the spiral chambers helically stacked into a cylinder are self-interference and difficult to deform, leading to smaller torsion angle. Therefore, it is suitable to choose the spiral angle by 45º. Figure 4(d) shows that as the diameter of inner spiral chambers increases, the torsion angle increases.

Considering the size of designed module should not be too large, the length of the whole module is chosen as 50 mm. As larger center distance of chambers leads to thinner outer wall and bubble deformation, it is also necessary to choose the suitable center distance. By thinking the above influence, the final selected parameters are: $\alpha = 45^\circ,\ d = 2\ \text{mm},\ D = 10\ \text{mm},\ \mathrm{L} = 50\ \text{mm},\ \mathrm{D}_r = 18\ \text{mm}$.

2.3 Fabrication

Overall, the process of the soft torsional module comprises the fabrication of the inner spiral chambers and the outer cylindrical shell.

Fabrication of the inner spiral chambers. As shown in Fig. 5, the spiral chambers are fabricated in four stages. In the first stage, assemble 3D printed molds in order, including top cover, bottom cover, cylindrical rod and shell. Then pour silicone Ecoflex-0030 into the mold and cure at room temperature as part of the second stage. The third stage of the fabrication uses fine fiber or braided thread to twine the outside surface of the chambers, in order to limit the radial expansion. In the last stage, complete the manufacture of an inner chambers by sealing the end of the cylindrical spiral chambers with the mold silica gel. It is also required that at least two identical chambers are prepared for the fabrication of outer shell.

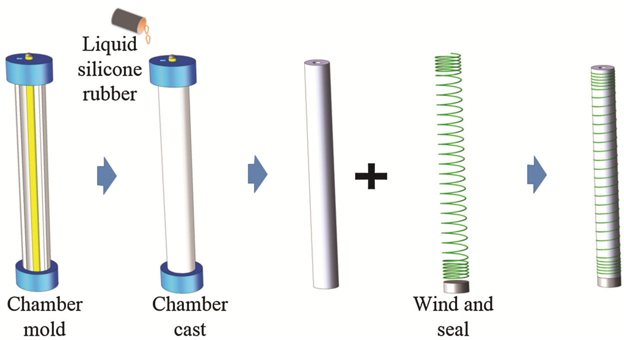


Fig. 5. Fabrication process of inner chamber

Fabrication of outer cylindrical shell. The outer cylindrical shell is also fabricated in four parts (Fig. 6). Firstly, install the finished inner chambers on the 3D printed spiral supporting frame to make a spiral configuration. Secondly, assemble other 3D printed molds in order, consisting of top cover, bottom cover, shell, and place confined layer in the center. In the third stage, pour silicone Ecoflex-0030 into the mold, then put the spiral configuration into the mold and cure at room temperature. Lastly, take out the curing module by dismantling the outer mold and withdrawing the support. Connect a medical silicone tubes to the other end of inner chambers for gas actuation. Thus, the fabrication of a soft torsional actuator module is completed.

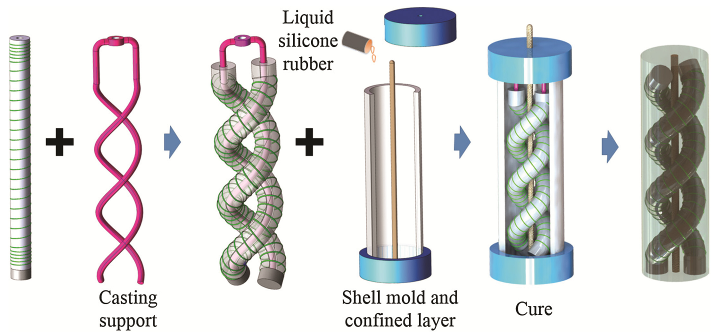


Fig. 6. Fabrication process of outer shell

3 Test Platform of Soft Torsional Module

The test platform consists of a pneumatic driven system and a measurement platform. The pneumatic driven part takes responsible for inflating the module and the experimental measuring part is used for testing the static characteristics of the module. As shown in Fig. 7, considering the collaboration of multi-modules and the scalability of

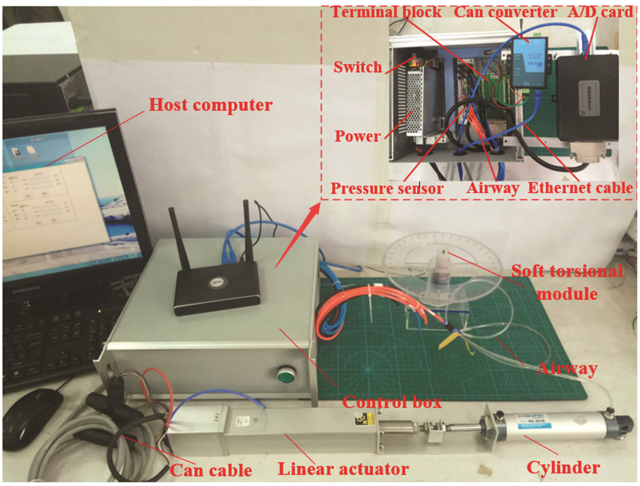


Fig. 7. The composition of test platform

subsequent experiments, the whole system mainly contains five parts: host computer, control box, linear actuator, cylinder and measurement platform.

3.1 Pneumatic Driven System

At present, research institutions and scholars at home and abroad often use air/liquid pump and electromagnetic control valve to drive and control the soft robots. However, this design concept brings the following shortcomings: (1) Regular air compression pump have large size but miniature compression pump is too expensive; (2) As they are mostly biased towards pressure regulation, it is not easy to control the speed and flow in the process. Thus, this article has designed a pneumatic driven system based on adjustable speed of stepper motor. As shown in upper right corner of Fig. 7, the control box includes switch, terminal block, can converter, A/D card, power, pressure sensor, airway and Ethernet cable.

The circuit of control system is comprised of the pneumatic drive part and the pressure feedback part. Host computer is connected to Can-converter through the Ethernet and the other side of Can-converter is connected to multiple Can-interface stepper motor driver by cascade connection. Each stepper motor drives a linear telescopic rod which drives the cylinder to fill and bleed the soft module. The acquisition part uses A/D acquisition card and pressure sensors to measure the pressure of the output of each cylinder, and then transmits the collected data back to the host computer to realize pressure feedback loop control.

Soft robots always have the characteristics of coupling motion and nonlinear deformation. Actually, some special tasks often need several modules cooperating to finish, through analyzing the features of environment and types of tasks, it has been proved effective by using the closed-loop control of pressure and open-loop control of position system. Figure 8 shows how the system works. P_d is expected value of input pressure and P_r is the pressure feedback collected by the pressure sensors. A closed-loop system is composed of the pneumatic feedback and the PI controller.

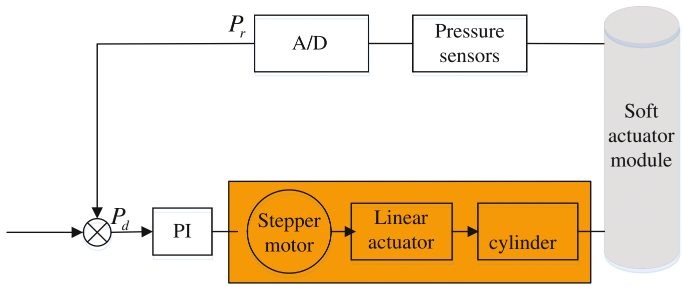


Fig. 8. Working principle of pneumatic driven system

3.2 Measurement Platform

A measurement platform is set up to measure the relationship between the pressure and torsion angle (details in Fig. 11(a)). It consists of the base, whole circle instrument and rotation pointer. The bottom of the torsional module is fixed to the center of the whole circle instrument and a rotation pointer is mounted on top to indicate the torsion angle. When used for test, it needs to cooperate with pneumatic driven system for driving. The airways of the driven system connect to the airway of the soft module, thus, the pressure can be adjusted by the host computer.

4 Experiments

Since the test platform is completed, it can be used for kinematic calibration and characteristics measurement including the torsion angle test and torsion torque test.

4.1 Kinematic Calibration

For the purpose of controlling the soft torsional module, kinematics modeling is needed. Due to the nonlinearity of soft material, it is difficult to establish the kinematics model. However, from the FEM analysis results shown in Fig. 4, when the pressure increases, the torsion angle also increases. Though it shows nonlinear at the initial part, it seems to be linear relationship when the pressure reaches certain value. Thus, the kinematic calibration method can be used to solve the kinematics.

Kinematic fitting. Now, we use the test platform above to calibrate the kinematics. Firstly of all, the angle measuring increment is set to 5°, and the measuring range is 0–10°. Then, the torsional module is inflated to each specific angle and the air pressure is recorded. Finally, the data on air pressure - torsion angle (see in Fig. 9, blue curve) are obtained by averaging the values of five measurements.

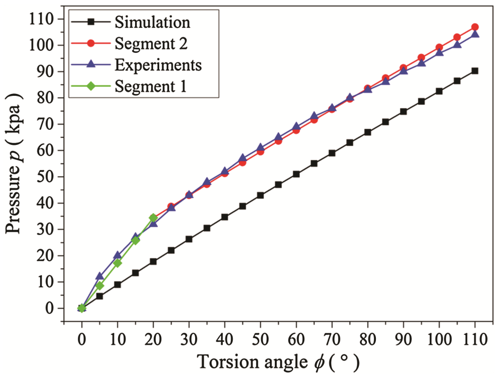


Fig. 9. The kinematic relationship (Color figure online)

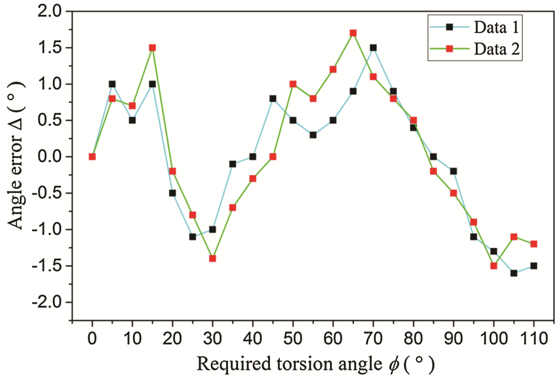


Fig. 10. The angle error between simulation and experiment

The result of kinematic fitting as shown by the green and red line in Fig. 8 is consistent with the measured curve (blue). In the lower part with a torsion angle <20º, as the air pressure is relatively lower, it is not clear whether the elastic deformation or the air pressure of the soft module plays the leading role. So we use a segmentation linear function to describe each corresponding relationship separately when the angle is within the range 0–20º and more than 20º. The final segmentation fitting results are plotted with green and red lines in Fig. 9.

Kinematic Verification. As the segment kinematics model is established, the motion control of the soft torsional module can be carried out. To verify the accuracy of the kinematics, the test experiment has been adopted. Firstly, a set of specified angles are chosen and the segment kinematics is used to calculate the values of the required air pressures. Secondly, calculated air pressures are used to inflate the torsional module to reach actual torsion angles. Through subtracting the actual torsion angles from the specified angles chosen, the angle error is shown in Fig. 10 above, which presents the torsion angle error is about ±1.7º, verifying the accuracy of the kinematics model.

In order to further test the twisting function, static characteristics tests are conducted on soft module. To a torsional actuator, torsion angle and torsion torque are two important indicators of its performance. Based on the pneumatic driven system, the following two experiments, namely, torsion angle test and torsion torque test, are designed to obtain the maximum twist angle and torque performance.

4.2 Torsion Angle Test

According to the measurement platform shown in the Fig. 11(a), when soft torsional module is placed in the middle of the platform, the pneumatic driven system is controlled by the host computer to inflate the module to some specified angles. By increasing the pressure step by step, the maximum angle that the soft torsional module can achieve is measured. As shown in Fig. 11(d), the module can generate pure torsional motion with minimal linear motion and the torsion angle can reach 120º.

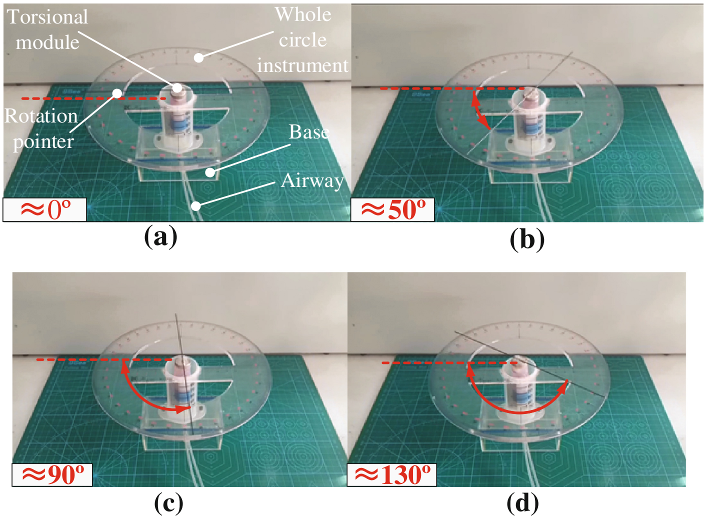


Fig. 11. Experiments of torsion angle test

4.3 Torsion Torque Test

A force sensor is added on the measurement platform for torque test, as shown in Fig. 12(a). The rotation pointer and force sensor equal to the force arm and force. The initial angle is preset at zero displacement and the relationship between air pressure and torque can be measured by increasing the pressure gradually. Through averaging the values of several measurements, the final result is shown in Fig. 12(b). The maximum obtainable torque corresponding to zero displacement is 0.026 Nm.

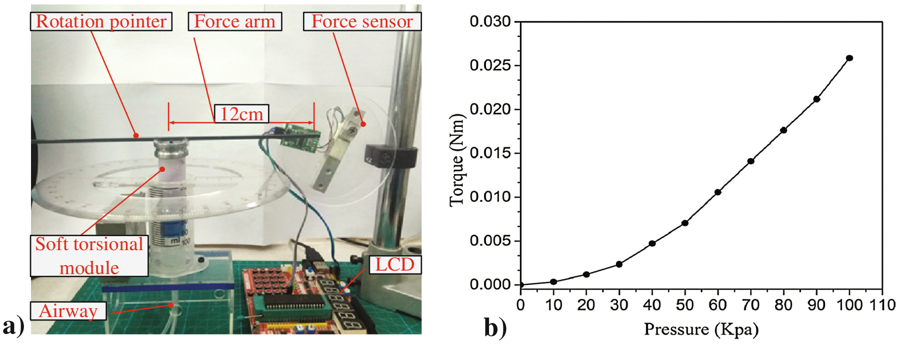


Fig. 12. Experiments of torsion torque test. (a) experimental device; (b) Torque characteristics for the module

5 Conclusions

(1) Compared to soft bending actuators, there is little research on soft torsional actuators and the torsion motion is often coupled with other kinds of motion. Based on the principle of spiral chambers with a pneumatic drive, a new torsional module has been designed and fabricated, whose geometric parameters have been optimized by the FEM. It is proved that the designed torsional actuator module is easy to control and can provide large angle of pure twist.

(2) Even though kinematics modeling of soft actuators is a hard work because of the nonlinearity of the materials, the FEM analysis results show that the relationship between pressure and torsion angle approximates linear. Therefore, the kinematic model has been established by means of experimental measurement and calibration and angle control precision of $\pm 1.7^{\circ}$ has been achieved.

(3) In order to obtain the static characteristics of the module, a test platform including pneumatic driven part and measurement part has been set up. The maximum obtainable torsion angle is got by 120° through torsion angle test and the maximum obtainable torque corresponding to zero displacement is got by 0.026 Nm through torsion torque test.

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References

1. Tsukagoshi, H., Kitagawa, A., Kamata, Y.: Wearable fluid power composed of transformed flat tube actuators. In: 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems, Hamburg, pp. 1178–1183. IEEE (2002)
2. Sanan, S., Lynn, P.S., Griffith, S.T.: Pneumatic torsional actuators for inflatable robots. J. Mech. Robot. **6**(3), 031003 (2014)
3. Roche, E.T., Horvath, M.A., Wamala, I., Alazmani, A., Song, S.E., Whyte, W., Kuebler, J.: Soft robotic sleeve supports heart function. Sci. Transl. Med. **9**(373), eaaf3925 (2017)
4. Yee, N., Coghill, G.: Modelling of a novel rotary pneumatic muscle. In: Proceedings of 2002 Australiasian Conference on Robotics and Automation, vol. 27, p. 29, November 2002
5. Connolly, F., Polygerinos, P., Walsh, C.J., Bertoldi, K.: Mechanical programming of soft actuators by varying fiber angle. Soft Robot. **2**(1), 26–32 (2015)
6. Yap, H.K., Ang, B.W.K., Lim, J.H., et al.: A fabric-regulated soft robotic glove with user intent detection using EMG and RFID for hand assistive application. In: 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, pp. 3537–3542. IEEE (2016)
7. Ivlev, O.: Soft fluidic actuators of rotary type for safe physical human-machine interaction. In: 2009 IEEE International Conference on Rehabilitation Robotics, Kyoto, pp. 1–5. IEEE (2009)
8. Kargov, A., Breitwieser, H., Klosek, H., Pylatiuk, C., Schulz, S., Bretthauer, G.: Design of a modular arm robot system based on flexible fluidic drive elements. In: 10th International Conference on Rehabilitation Robotics, Noordwijk, pp. 269–273. IEEE (2007)

9. Polygerinos, P., et al.: Towards a soft pneumatic glove for hand rehabilitation. In: 2013 International Conference on Intelligent Robots and Systems (IROS), Tokyo, pp. 1512–1517. IEEE (2013)
10. Soft Robotics Toolkit. http://softroboticstoolkit.com/book/pneunets-modeling. Accessed 3 June 2017