Video Article

Fabrication of Soft Pneumatic Network Actuators with Oblique Chambers

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Abstract

Soft pneumatic network actuators have become one of the most promising actuation devices in soft robotics which benefits from their large bending deformation and low input. However, their monotonous bending motion form in two-dimensional (2-D) space keeps them away from wide applications. This paper presents a detailed fabrication method of soft pneumatic network actuators with oblique chambers, to explore their motions in three-dimensional (3-D) space. The design of oblique chambers enables actuators with tunable coupled bending and twisting capabilities, which gives them the possibility to move dexterously in flexible manipulators, to become biologically inspired robots and medical devices. The fabrication process is based on the molding method, including the silicone elastomer preparation, chamber and base parts fabrication, actuator assembly, tubing connections, checks for leaks, and actuator repair. The fabrication method guarantees the rapid manufacturing of a series of actuators with only a few modifications in the molds. The test results show the high quality of the actuators and their prominent bending and twisting capabilities. Experiments of the gripper demonstrate the advantages of the development in adapting to objects with different diameters and providing sufficient friction.

Video Link

The video component of this article can be found at https://www.jove.com/video/58277/

Introduction

Soft pneumatic actuators (SPAs) are soft devices that can be actuated by the simple input of air pressure[1,2]. They can be fabricated with diverse materials, such as silicone elastomers[3], fabrics[4], shape-memory polymers[5], and dielectric elastomers[6]. Researchers have benefited from their nature of compliance, dexterous motions, and simple fabrication methods[7], such that SPAs have become one of the most promising devices for soft robotics applications[8,9]. SPAs can realize various sophisticated motions, such as creeping[10], rotation[11], and rolling[12] based on various types of deformation, including extending, expanding, bending, and twisting[13,14]. To be able to make different types of motions, SPAs are designed in different structures, such as a linear body with parallel channels[15], a monolithic chamber with fiber-reinforcements[16], and networks of repeated sub-chambers[17]. Among them, the SPAs with networks of repeated sub-chambers, the soft pneumatic network actuators, are widely employed because they can generate large deformations under a relatively low input pressure. However, in most of the previous designs, this type of actuators can only generate bending motions in 2-D space, which greatly limits their applications.

A soft pneumatic network actuator consists of a linearly arranged group of chambers connected by an internal channel. Each cubic chamber contains a pair of opposite walls which are thinner than the other pair and produces a two-sided inflation in the direction perpendicular to the thinner walls. Originally, the thinner walls of the chambers are perpendicular to the long axis of the actuator body and inflate along with the long axis. These collinear inflations in chambers and the non-extensible base lead to an integral pure bending of the actuator. To explore the actuator's motion in 3-D space, the orientation of the chambers is tuned so that the thinner-side walls are no longer perpendicular to the long axis of the actuator (**Figure 1A**), which enables the inflation direction of each chamber to offset from the axis and become not collinear. All the parallel but not-collinear inflations change the motion of the actuator into a coupled bending and twisting motion in 3-D space[18]. This coupled motion enables the actuators more flexibility and dexterity and makes the actuators a suitable candidate for more practical applications, such as flexible manipulators, biologically inspired robots, and medical devices.

This protocol shows the fabrication method of this kind of soft pneumatic network actuators with oblique chambers. It includes preparing the silicone elastomer, fabricating the chamber and base parts, assembling the actuator, connecting the tubing, checking for leaks, and, if necessary, repairing the actuator. It can also be used to fabricate normal soft pneumatic network actuators and other soft actuators which can be produced with some simple modifications to the molding method. We provide detailed steps to fabricate a soft pneumatic actuator with 30° oblique chambers. For different applications, actuators with different chamber angles can be fabricated according to the same protocol. Apart from that, the actuators can be combined to form a multi-actuator system for various demands.

Protocol

NOTE: The protocol provides the fabrication procedures of a soft pneumatic network actuator. Before the fabrication procedure, a set of molds and several actuator-tubing connectors, which are designed with computer-aided design (CAD) software must be 3-D-printed in advance. The molds are shown in **Figure 1B**.

1. Silicone Elastomer Preparation

1. Weigh 5 g of silicone elastomer part B and 45 g of part A [9:1 (A:B) parts by weight] in the same mixing container (**Figure 2A**). Use a syringe to make sure the proportions of each part are accurate.
   NOTE: The mixing ratio varies for different silicone elastomers. The proportion of each part should be adjusted when another silicone elastomer is adopted.
2. Mix the silicone elastomer well with the planetary centrifugal mixer.
   NOTE: The silicone elastomer could be stored at a low temperature to extend its processing time.

2. Chamber Part Fabrication

1. Spray the mold release agent for silicone elastomer products evenly on the surfaces of the mold part A and part B.
2. Assemble part A and part B of the mold for the fabrication of a chamber. Hold both ends of the mold with clips to prevent the leakage of silicone elastomer.
3. Take 5 mL of silicone elastomer with a syringe and inject it slowly into the hole of the mold for fabricating the connection end (the cylindrical structure at one end of the actuator for connecting the tubing). Then, fill the whole mold with the silicone elastomer (**Figure 2B**).
   NOTE: Keep a low flow rate and move back and forth slowly, to let the silicone elastomer enter the tiny structures of the mold.
4. Pierce the bubbles that form on the surface with the tip of a needle until there are no more bubbles visible (**Figure 2C**).
5. Scrape off any excess silicone elastomer with a blade along the upper surface of the mold.
6. Place the mold in the oven at 70 °C until the silicone elastomer is cured.
7. Use a syringe to inject silicone elastomer into the bubbles and holes which appear on the surface of the actuator.
8. Scrape off any excess silicone elastomer on the surface.
9. Place the mold in the oven at 70 °C until the silicone elastomer is cured.

3. Base Part Fabrication

1. Spray the mold release agent for silicone elastomer products evenly on the surface of the mold part C.
2. Pour the silicone elastomer into part C of the mold.
3. Pierce the bubbles that form on the surface with the tip of a needle until there are no more bubbles visible.
4. Scrape off any excess silicone elastomer with a blade along the upper surface of the mold.
5. Place the mold in the oven at 70 °C until the silicone elastomer is cured.

4. Actuator Assembly

1. Evenly pour a layer of silicone elastomer, 1 mm in thickness, on one face of the base part.
2. Place the chamber part on the base part. Use a syringe to inject the silicone elastomer into the space between the chamber part and the base part (**Figure 2D**).
3. Place the actuator in the oven at 70 °C until the silicone elastomer is cured.

5. Tubing Connection

1. Tap the 3-D-printed actuator-tubing connector to accept the screw of a male stud push-in fit pneumatic fitting.
2. Use a needle to pierce the connection end of the actuator along the centerline of the cylinder. Increase the diameter of the hole with a steel rod, to about 2 mm.
3. Screw the actuator-tubing connector into the actuator (**Figure 2E**).
4. Push a section of tubing into the male stud push-in fit pneumatic fitting.

6. Leak Check and Repair

1. Connect the actuator to an air source.
2. Place the whole actuator in the water and pressurize the actuator (**Figure 2F**). Observe whether bubbles are formed due to a leak.
3. Use a syringe to inject the silicone elastomer into leak points. Place the actuator in the oven at 70 °C until the silicone elastomer is cured.
4. Repeat steps 6.1 - 6.3 if needed.

Representative Results

Single Actuator:
To verify the fabrication method and demonstrate the function of the actuator, 30°, 45°, and 60° actuators were fabricated and tested. For the experiment set-up, an air pump was employed to activate the valve. The valve was connected to the actuator to control the internal pressure. The single actuator was fixed at its connection end and placed vertically. While the actuator was being pressurized, two digital cameras were used to capture its positions from different perspectives. Analyzing the positions (**Figure 3A**) made it clear that the motion of the actuator can be described by two parameters: a bending angle and a twisting angle. These two parameters can numerically distinguish the performance of actuators with different chamber angles.

Bending and twisting tests (**Figures 3B** and **3C**) illustrated the motion of the actuators in 3-D space. The bending angle is the angle between the body line in the actuated position and the original body line in the unactuated state[18]. The twisting angle is the angle between the tip line in actuated position and the original tip line in unactuated state[18]. They were observed and calculated from 0 to 90 kPa, with a pressure step of 10 kPa. The line plot in **Figures 3B** and **3C** illustrates how both the bending and the twisting angles increased with respect to the increase of the internal pressure. The values of the bending and the twisting angles show the effect of the chamber angle on the motion of the actuators. Chambers with larger angles contributed more to the twisting than to the bending. This indicates that diverse configurations and motions can be achieved by tuning the chamber angle of a fixed-sized actuator. As shown in **Figures 3B 3C**, in the experiment, three tested actuators showed distinct capabilities in bending and twisting. For the bending capability, the 30°, 45°, and 60° actuators could bend up to 295°, 217°, and 170°, respectively. For the twisting capability, the maximum twisting angles for the 30°, 45°, and 60° actuators were 227°, 307°, and 382°, respectively.

We use the ratio of the twisting angle and the bending angle to analyze the status of each tested actuator under different internal pressures (**Figure 4**). This value can also reflect the overall performance corresponding to the chamber angle of the actuators. As to a single actuator, the value of the ratio shows a general decline with the increase of internal pressure. Twisting behavior is dominant when the actuator is started at the low pressure. In the middle range of the actuation, the bending behavior gradually prevails, and the increasing rate of the twisting behavior begins to decline. The bending behavior becomes dominant and the value of the ratio comes to a minimum when the actuator approaches its maximum capacity of pressure. From a macro-perspective, the actuator with a larger chamber angle has a larger value of the ratio under the same pressurization level. The actuators with larger chamber angles are preferable for more self-twisting motions while the actuators with smaller chamber angles are suitable for bending motions with auxiliary twisting motions. This ratio helps the determination of the chamber angle when actuators are designed for specific uses.

Application of the Actuator with Oblique Chambers:
The significance of the actuators with oblique chambers is to expand the motion space of the pneumatic network actuators into a 3-D space. More abundant forms of motions make them possess a broader application range.

As the core element of a soft gripper, actuators with oblique chambers show their superiority on grasping, holding, and manipulating objects of different shapes, especially long, thin, and rod-like shapes. Grippers based on normal pneumatic network actuators always have difficulties in grasping long, thin, and rod-like objects due to the limitation of the bending radius. However, actuators with oblique chambers can overcome this limitation by generating an adjustable helical configuration according to the object and providing sufficient friction between objects and itself. **Figures 5A** - **5C** demonstrate a single 30° actuator grasping a ping-pong ball, a USB disk, and a pen. **Figures 5D** - **5F** show a gripper assembled by two 30° actuators grasping a plastic tube, lifting a hammer, and manipulating a measuring cylinder, cooperating with a UR10 robot.

The protocol provides a fabrication method of a single actuator with oblique chambers. Following the protocol, actuators with different chamber angles can be created by simply modifying the mold. When actuators are connected in series or in parallel, complicated motions can be achieved. The programmable designing of actuators and their arrangement opens up great possibilities for more extensive applications.

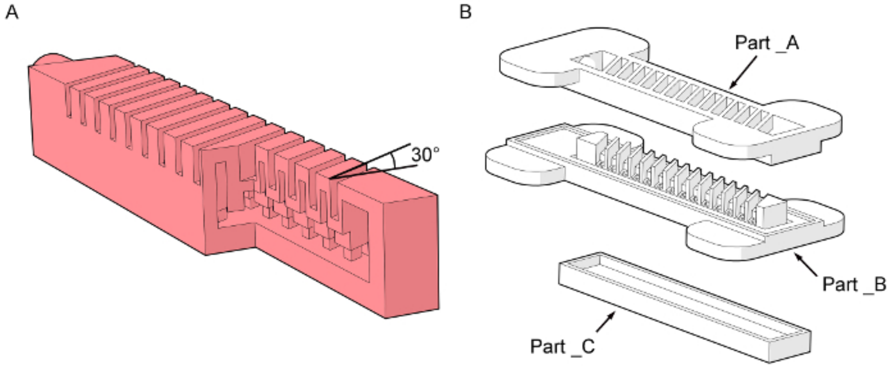

Figure 1: **The soft pneumatic network actuator and the molds.** These panels show CAD models of (**A**) the actuator with 30° oblique chambers and (**B**) the corresponding molds. Please click here to view a larger version of this figure.

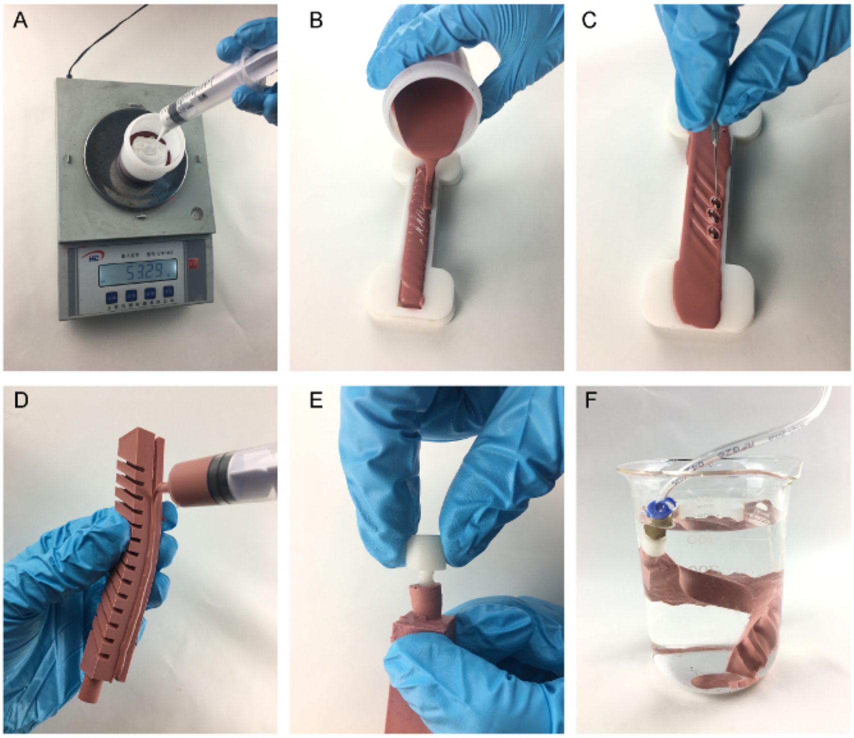

Figure 2: Overview of the fabrication process. These panels show the different steps of the fabrication process: (**A**) weighing the silicone elastomer, (**B**) pouring the silicone elastomer, (**C**) piercing the bubbles, (**D**) assembling the actuator, (**E**) screwing in the actuator-tubing connector, and (**F**) checking for leaks. Please click here to view a larger version of this figure.

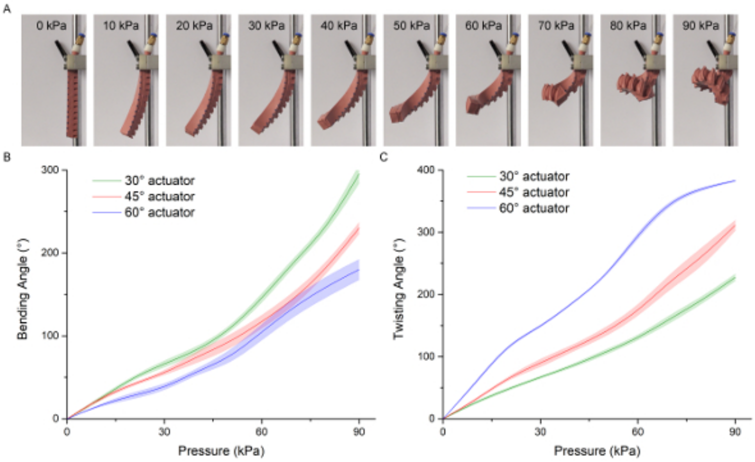

Figure 3: Performances of tested actuators. (**A**) This panel shows the position pictures of the 30° actuator from 0 to 90 kPa. (**B**) This panel shows the bending angle *versus* the internal pressure from 0 to 90 kPa. It is reprinted from Wang *et al.*[18], with permission from Elsevier. (**C**) This panel shows the twisting angle *versus* the internal pressure from 0 to 90 kPa. It is reprinted from Wang *et al.*[18], with permission from Elsevier. Please click here to view a larger version of this figure.

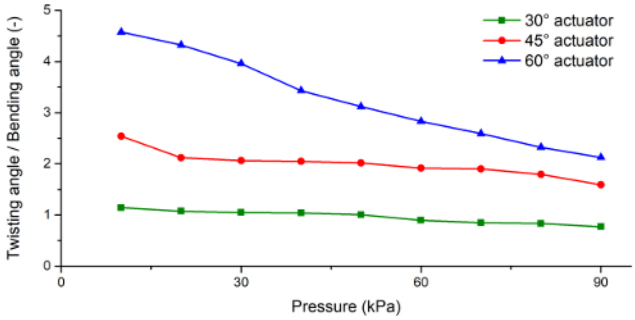

Figure 4: Performance evaluation. This panel shows the ratio of the twisting angle and the bending angle for the 30°, 45°, and 60° actuators, with pressure from 10 to 90 kPa. Please click here to view a larger version of this figure.

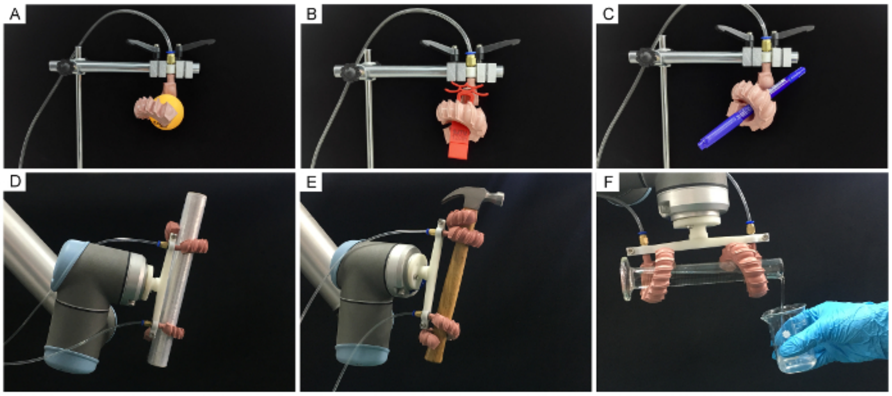

Figure 5: Experiments of a single actuator and a soft gripper consisting of two actuators. The single actuator grasps (**A**) a ping-pong ball, (**B**) a USB disk, and (**C**) a pen. The gripper (**D**) grasps a plastic tube, (**E**) lifts a hammer, and (**F**) manipulates a measuring cylinder. Please click here to view a larger version of this figure.

Discussion

The paper presents a method protocol to guide the fabrication of soft pneumatic network actuators with oblique chambers. Following the protocol, one actuator can be fabricated independently within 3 h. The key steps in the protocol can be summarized as follows. (i) The silicone elastomer is prepared in proportion and mixed well. (ii) The silicone elastomer is poured into the mold for the fabrication of the chamber part and the base part. (iii) The bubbles on the exposed surface are pierced and any excess silicone elastomer on the exposed surface is scraped off. (iv) The silicone elastomer is cured in the oven. (v) The two parts are bonded together by the silicone elastomer. The fabrication process is completed with another curing step in the oven. (vi) The actuator is connected to an air source to check for any leaks. The actuator should be repaired with the silicone elastomer if it leaks.

To ensure the quality and actuation performance of the fabricated actuators, several critical steps in the protocol are discussed as follows, including the selection of the material, the elimination of bubbles, and the connecting method for air-tightness.

The silicone elastomer should have a large tensile elongation to ensure the deformation capability of the actuators. In addition, the silicone elastomer should have good fluidity in its liquid state so that it can be poured smoothly into the millimeter-scale features of the mold. The silicone elastomer selected in section 1 of the protocol can generate up to 700% tensile deformation and low viscosity in a liquid state. This silicone elastomer can be replaced with other proper materials that satisfy the above requirements.

The air mixed in the internal structure of the uncured actuator in the pouring process should be eliminated before the mold is placed into the oven, to avoid defects in the cured actuator. The mixed air will rise up to the exposed surface of the uncured actuator and form bubbles. Therefore, the piercing process is conducted in sections 2 and 3 of the protocol. This process can be skipped if the pouring process is conducted in a vacuum chamber.

The air connection between the actuator and the air pump should be well designed to guarantee the air-tightness. Typically, the tubing can be inserted directly into the actuator and glued firmly to the actuator. However, this connection method requires tedious operations and often leads to leaks under a large internal pressure. The method in section 5 of the protocol presents a mechanical connecting which is easier to install and more reliable.

The limitations of the protocol root in the molding process, which, in essence, is a 2.5-D fabrication method[19]. The chamber is made by connecting several parts with planar morphology. Thus, complicated inner structures and small-scale characteristics are difficult to achieve. Although soft 3-D printing approaches have appeared in recent years, the printing materials of these are too friable to make the actuators endurable in contrast to the molding-based method.

Disclosures

The authors have nothing to disclose.

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