Research Article

Evolution from Telescoping to Bending: An Origami-Inspired Flexible Bending Actuator

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Soft actuators have great potential in human–machine interaction and soft robotics innovation. Origami exhibiting outstanding structural and topological properties can be a paradigm for people to design various soft robots. Inspired by origami, we have previously designed a telescopic actuator with excellent performance, mainly large force output, and two-way working. Although significant advances have been made in soft bending actuators, their further study and applications are limited due to small force output in a monotonous work style. In this paper, we design a series of novel bending actuators that inherit our prior telescopic actuator’s excellent characteristics to diversify soft actuators’ motion forms. Several actuators of different sizes are fabricated using three different materials and evaluated on a designed test platform. The test results show that actuators of different sizes using different materials perform differently. Namely, the maximum tip force produced by an actuator reaches 9.6 N, and the maximum bending angle is achieved by another one up to 138°. Finally, extensive demonstrations and tests include wriggling, gripping, and bidirectional motion in the water. They show our flexible bending actuators’ distinguishing characteristics of large output force and two-way working.

1. Introduction

Rigid actuators have been widely used. However, they have many shortcomings, e.g., complex structure, poor security, and weak adaptability. To make a change, people have paid sustained attention to soft actuators as alternatives to rigid ones and developed various soft actuators in the past decade. Consisting of flexible materials, they are naturally flexible and adaptable. To date, soft actuators have been applied to drive soft robots [1, 2].

From the perspective of motion form, there are two primary soft actuators, linear actuators and bending actuators. Linear actuators can create a linear motion, and significant progress has been made in their deformation amplitude [3–5], output force [6, 7], and work modes [8]. On the other hand, bending actuators can produce bending motion, mainly driven by electric and fluid powers.

A typical electric soft actuator is made of shape memory alloy (SMA), dielectric elastomer (DE), or ionic polymer–metal composite (IPMC). SMA actuators [9–12] are limited to a slow response speed. DE actuators [13, 14] require high driving voltages and suffer from a lack of stability. IPMC [15] can produce large deformations but outputs a small force.

Compared with electric soft actuators, soft bending actuators driven by fluid enjoy excellent performances of response speed, deformation, and output force, which has been the recent research focus. Most existing soft bending actuators are driven by positive pressure fluid [16–27], achieving a deformation amplitude of about 45°–360° and an output force of about 1.2–80 N. These positive pressure-driven actuators can achieve considerable bending deformations and output forces. However, they require quite high input pressure, which can cause safety issues [28]. In contrast, a low-pressure actuator is highly valuable since it can perform much more safely [7]. Unfortunately, few soft-bending actuators are driven by negative pressure fluid. Moreover, the existing negative pressure-driven bending actuators usually do not perform satisfactorily [29].

Regardless of the material and structure used, these bending actuators have a common feature, i.e., they can only work in one way. For example, some studies have used negative pressure fluid to promote the recovery of the actuators.
Remarkably, origami exhibiting outstanding structural and topological properties can be a paradigm for people to design various soft robots [7, 8, 27, 38–40]. Inspired by origami, we have previously designed a telescopic actuator with excellent properties of large force output, bi-directional working, and good force retention [41]. Soft bending actuators expect them as well.

Can we preserve the excellent properties of our prior flexible telescopic actuators while evolving the motion pattern from telescoping to bending? It is possible and worthy. Motivated by this thought, we study a bending type of flexible actuator. Starting from our prior flexible telescopic actuator, we evolve it from an overall symmetrical structure to offset to achieve bending motion. As a result, the new actuator can output a large force and work during recovery, similar to the original telescopic actuators. Specifically, our actuators are driven by negative pressure, which is much safer. It is also our max innovation. Namely, we realize large bending deformation and force output of an actuator driven by much safer negative pressure fluid. Moreover, our flexible bending actuator can effectively work in its reset phase, requiring no additional operation.

The main contributions of this work are summarized as follows: (1) we propose a vacuum-driven flexible bending actuator inspired by origami. The actuator outputs great torque and large deformation and can work during reset. Several actuators are fabricated with different materials in different sizes. (2) We have conducted extensive tests and demonstrations on these actuators. The results show their outstanding performance and potential for wide application.

The rest of this paper is organized as follows: first, the working principle of the origami-inspired bending actuator is analyzed in Section 2. Then, in Section 3, we design and fabricate eight such actuators using 3D printing technology and different materials. Next, we develop a test platform to evaluate the performance of the actuators in Section 4 and disclose the application potential of the actuators through a series of demonstrations in Section 5. Finally, Section 6 concludes the paper.

2. Evolution from Telescoping to Bending

Inspired by origami, we have previously designed a flexible telescopic actuator [41], and its schematic diagram is shown in Figure 1. Our telescopic actuator has excellent properties of large force output, bi-directional working, and good force retention. Soft bending actuators also are in increasing need of large force output and bi-directional working.

In nature, there are many cases of locomotion switching from stretching to bending. For example, snakes can stretch or bend when moving by changing the length of both sides of their skeletons’ motion [42–44]. Specifically, both sides of its skeleton vary simultaneously when a snake stretches. However, both sides of its skeleton change asynchronously when a snake bends.

However, when our telescopic actuator works, both sides of the skeleton change the same. Therefore, can we achieve the desired bending motion by changing both sides of the telescopic actuator’s skeleton asynchronously or differently? Furthermore, can we retain the excellent properties of the previous telescopic actuators after the evolution? The answers are “YES.” We can evolve the structure of our prior actuator to attain the new motion form of bending while preserving its desired mechanical characteristics.

As shown in Figure 1, the left and right quadrilateral mechanisms, each comprising four panels, are connected by two planar beams with a length of \( S_2 \). With the movement of the parallelogram mechanism, \( S_2 \) remains unchanged, while the length \( S_1 \) of the central axis represented by the dotted line becomes longer or shorter. As a result, the actuator extends or shortens as a whole.

The telescopic actuator’s large output force property comes from the skeleton’s four parallelogram mechanisms.
Therefore, we retain only the two upper parallelogram mechanisms in the skeleton to preserve the property. Further, we use two elastic planar beams instead of rigid ones to connect the two parallelogram mechanisms, enabling the whole actuator’s bending. The beams have lengths of $S_1$ and $S_2$, and the new structure is illustrated in Figure 2(b).

When the two upper parallelogram mechanisms move, the skeleton is driven to bend with the bending of two elastic beams of different lengths, as shown in Figure 2(b)–2(e). Next, we seal the skeleton with a flexible membrane and power it with negative pressure fluid to form an origami-inspired flexible bending actuator.

![Figure 2: Working principle of a flexible bending actuator](image)

According to the relationship between arcs and radii,

$$ R_1 = \frac{S_1}{\theta}, \quad R_2 = \frac{S_2}{\beta}, $$

$u$ can be expressed as follows:

$$ u = 2(R_1 + d - R_2)\sin\frac{\theta}{2}, $$

$$ u = 2L \sin\left(\frac{\pi}{2} - \frac{\theta}{2}\right) = 2L \cos\frac{\theta}{2}. $$

By Equations (3) and (4), we have the following:

$$ (R_1 + d - R_2)\sin\frac{\theta}{2} = L \cos\frac{\theta}{2}. $$
Substituting Equations (1) and (2) into Equation (5), we have the following:

\[
\Delta = S_1 - S_2 = \left(\frac{L}{\tan \frac{\theta}{2}} - d\right) \theta.
\]  

(6)

By Equation (6), the angle \(\theta = f(S_1, S_2, d, L)\) concerning the beam lengths \(S_1\) and \(S_2\) and the actuator dimensions \(d\) and \(L\) can be calculated. So, we can optimize the actuator’s size parameters and predict its deformation by Equation (6).

Through calculating, we find that given \(d\) and \(L\), the more the length difference \(\Delta\) between the two beams, the smaller the deformation angle of an actuator, as shown in Figure 4(a). On the other hand, within a specific range, either increasing \(L\) or decreasing \(d\) can improve the deformation potential of the actuator, as shown in Figures 4(b) and 4(c), respectively.

3. Design and Fabrication

According to the aforementioned working principle, we design a bending actuator’s skeleton, as shown in Figure 5(a). Our actuator consists of a skeleton and soft skin. The skeleton plays the main role in the deformation, composed of two rigid parallelogram mechanisms and two elastic beams. Soft skin is an airtight film with good toughness to form a sealed cavity.

First, we use a 3D printer to print individual parts separately and a laser cutter to make elastic beams. Then, we assemble the 3D-printed parts and elastic beams to form a skeleton. Finally, we seal the skeleton with a 0.1 mm thick thermoplastic polyurethane film to obtain an actuator, as shown in Figure 5.

We fabricate eight actuators with three beams of different sizes and materials to attain different properties. The beams are made of a 0.6 mm polyethylene terephthalate (PET) sheet, a 2 mm PVC sheet, and a 0.6 mm carbon-fiber sheet. The three fabricated actuators, each with a different beam, are illustrated in Figure 5.

Considering the key effect of the difference in the upper and lower beams’ lengths on the bending angle, we fabricate two or three actuators with different beam dimensions for each material. For ease of differentiation, we name every actuator by combining its two beams’ material and lengths, \(S_1\) and \(S_2\), for example, actuators PET-48-23, CFP-48-28, and PVC-48-33. The actuators’ basic dimension parameters are listed in Table 1.

4. Performance Test and Analysis of Actuators

4.1. Experimental Setup. A test platform is developed to test the performance of different actuators, as shown in Figure 6. We fix one end of the actuator on the platform’s base and keep the other end free. A camera is mounted directly above the actuator to measure the actuator’s bending angle by recognizing the scale on a dial below. The actuator’s bending amplitude can change with the manual adjustment of the bracket’s angle. Finally, we can test the tip force generated by the actuator with a pressure sensor mounted on the bracket, and then we can calculate the actuator’s torque. During the test, a vacuum pump can generate the pressure of the actuator by controlling a vacuum proportional valve and a solenoid valve.

The dial in Figure 6 is designed to record the angle \(\beta\) defined in Figure 3, \(\beta = \theta\). According to the pseudo-rigid-body model [13, 45], an elastic beam’s bending deformation can be regarded as the rotation of two rigid beams around its center point, as shown in Figure 7.

The main devices constituting the test platform include a pulling pressure sensor LLBL-102 from Shanghai Longlvdianzi Technology Co., Ltd, a camera SunTime 300C from Xiantai Technology (Shenzhen) Co., Ltd., a vacuum manometer ZSE30AF-01-E, an air-vacuum proportional valve ITV0090-3BL, solenoid valve VEX3121-025DZ-FN, and pressure reducing valve AW20-01BG-A from SMC, a vacuum pump 550D, from Taizhou Fujiwara Tools Co., Ltd. Other parts of the test platform are mainly 3D printed.

4.2. Test Results and Analysis. We test the maximum bending angle of the actuator under different pressures and the output torque under different bending angles and pressures.

Figure 8(a) shows the maximum bending angles of the actuators PVC-48-23, PVC-48-28, PVC-48-33, PET-48-28, and CFP-48-28 under different pressures. The bending angles of all actuators gradually increase with the pressure, but the growth rate will gradually decrease until it approaches...
zero. It reveals that the actuator has a deformation limit under a certain pressure. Once the limit is reached, the actuator cannot bend further with increased pressure. The maximum bending angle of each actuator is shown in Table 2. In general, the effects of different elastic beam lengths $S_1$ and $S_2$ on the deformation of the actuator are consistent with the prediction by Equation (6).

The output torque $Q$ of the actuator is equal to the product of the tip force $F$ of the actuator and the force arm $L_{\text{arm}}$, i.e.,

$$Q = F \times L_{\text{arm}}, \quad (7)$$

where $L_{\text{arm}}$ is the distance between the elastic beam’s center point and the force sensing point, as shown in Figure 7.

Considering the actuator and test platform sizes, the force arm of the actuator is $L_{\text{arm}} = 115$ mm.

The test results of the actuators PVC-48-23, PET-48-23, and CFP-48-28 are shown in Figure 8(b)–8(d), respectively. Here, the abscissa is the pressure, and the ordinate is the actuator’s output torque. The maximum torque generated by each actuator is shown in Table 2.

From Figure 8(b)–8(d), at a certain angle, the torque of the actuator increases approximately linearly with the pressure increase. However, when the pressure rises to a certain level, the growth rate of torque slows down slightly, mainly affected by the deformation of the elastic beam and the sealing membrane. On the other hand, at a certain pressure, the
larger the bending angle, the smaller the output torque of the actuator.

Also, the larger the bending angle of the actuator, the greater the pressure that the actuator can bear. Note that abnormal deformation occurs whenever the pressure carried by the actuator exceeds a certain magnitude. On the other hand, for a larger bending angle, more significant pressure is required for the actuator to generate torque effectively.

4.3. Performance Comparison among Actuators. To explore the influence of the elastic beam’s material on the actuator’s performance, we compare the actuators PVC-48-28, PET-48-28, and CFP-48-28. As shown in Figure 8(a), under the same pressure, the PET-48-28 actuator has the largest bending angle, followed by the PVC-48-28 actuator, and the CFP-48-28 actuator has the smallest bending angle. Namely, the stiffer the elastic beam, the smaller the bending angle of the actuator under the same pressure.

As illustrated in Figure 8(e), under the same bending angle, the CFP-48-28 actuator can carry the highest pressure, followed by the PVC-48-28 actuator, and the PET-48-28 actuator can bear the lowest pressure. Table 2 shows that the maximum tip force of the three actuators is 7.7, 5.8, and 2.6 N. It implies that the greater the rigidity of the elastic beam, the greater the pressure that the actuator can bear under the same bending angle, and the greater the maximum output torque of the actuator.

We continue to compare the actuators, PVC-48-23, PVC-48-28, and PVC-48-33, to explore the effect of the elastic beam’s size on the actuator’s performance. As shown in Figure 8(a), under the same pressure, the actuators PVC-48-23, PVC-48-28, and PVC-48-33 produce bending angles from small to large. In a word, within a specific range, the more significant the difference between beam lengths $S_1$ and $S_2$, the smaller the bending angle of the actuator under the same pressure.

As illustrated in Figure 8(f), the actuators PVC-48-33, PVC-48-28, and PVC-48-23 output torques from large to small under the same bending angle and pressure. It indicates that within a specific range, the more significant the difference between beam lengths $S_1$ and $S_2$, the smaller the output torque of the actuator at the same pressure and bending angle.

The response times of different actuators are shown in Table 2. The PET-beamed actuators’ response times are the shortest, followed by PVC and CFP-beamed actuators. Overall, the stiffness of an actuator’s beam determines its response time. Namely, the less the beam’s stiffness, the shorter the actuator’s response time.

5. Application Demonstrations

Our bending actuator can work in bi-directions, a feature rarely explored in previous related work. In addition, our actuators also have excellent characteristics such as large bending amplitude and large output torque. To demonstrate them, we conducted several experiments, i.e., wriggling, gripping, and bidirectional motion in the water.

The wriggling motion on a flat cloth reveals our actuator’s large deformation range, as shown in Figure 9. When the pressure provided to the actuator increases, the actuator’s bending angle increases, thus decreasing the distance between the feet’ ends. When the pressure reduces, the actuator’s bending angle decreases, thus leading to the distance increase between the feet’ ends. The actuator can keep creeping forward in this continuous cycle, as shown in Figure 9. Within a single cycle, the actuator’s motion amplitude reaches 25% of its length at the elongation state. The wriggling motion velocities of the actuator under vacuum pressures of $-10$, $-20$, and $-30$ kPa are 3, 11.5, and 16.2 mm/s, respectively. Since the actuator’s motion amplitude is close in different cycles, increasing the negative pressure within a specific range can increase the actuator’s motion frequency, thereby accelerating the creep. See Movie S1 for wriggling motion.

In addition, we assemble the two actuators into one gripper to demonstrate the gripping motion. In Figure 10, we use
FIGURE 8: Test results of actuators: (a) bending angle of different actuators; (b) test data of PVC-48-23 actuator; (c) test data of PET-48-23 actuator; (d) test data of CFP-48-28 actuator; (e) comparison of actuators with different beam materials; (f) comparison of actuators in different beam lengths.
TABLE 2: Maximum output torque and other characteristics of different actuators.

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Max angle (°)</th>
<th>Max force (N)</th>
<th>Max torque (N mm)</th>
<th>Response time (s)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC-48-23</td>
<td>84</td>
<td>4.4</td>
<td>506</td>
<td>0.70</td>
<td>137.9</td>
</tr>
<tr>
<td>PVC-48-28</td>
<td>110</td>
<td>5.8</td>
<td>664</td>
<td>0.67</td>
<td>137.7</td>
</tr>
<tr>
<td>PVC-48-33</td>
<td>138</td>
<td>5.2</td>
<td>598</td>
<td>0.54</td>
<td>139.1</td>
</tr>
<tr>
<td>PET-48-23</td>
<td>99</td>
<td>4</td>
<td>460</td>
<td>0.45</td>
<td>121.5</td>
</tr>
<tr>
<td>PET-48-28</td>
<td>128</td>
<td>2.6</td>
<td>298</td>
<td>0.45</td>
<td>121.7</td>
</tr>
<tr>
<td>PET-48-33</td>
<td>124</td>
<td>2.6</td>
<td>300</td>
<td>0.23</td>
<td>120.0</td>
</tr>
<tr>
<td>CFP-48-23</td>
<td>57</td>
<td>9.6</td>
<td>1,103</td>
<td>1.16</td>
<td>126.8</td>
</tr>
<tr>
<td>CFP-48-28</td>
<td>65</td>
<td>7.7</td>
<td>891</td>
<td>1.18</td>
<td>127.9</td>
</tr>
</tbody>
</table>

Figure 9: Demonstration of wriggling motion: (a) elongation state; (b) contraction state.

Figure 10: Demonstration of gripping objects: (a) a 434 g dragon fruit; (b) a 202.5 g orange; (c) a 139.3 g banana; (d) a 22.9 g date; (e) a 16.3 g grape; (f) a 52.2 g egg; (g) a 93.4 g empty box of 200 × 142 × 60 mm; (h) an empty mineral water bottle with diameter 160 mm.
this gripper to hold a dragon fruit, an orange, a banana, a date, a grape, an egg, an empty box, an empty plastic bottle, etc. See Movie S2 for gripping movements.

Note that negative pressure liquid like water can also drive our actuators. For example, we use a large syringe filled with water to drive the CFP-48-28 actuator. As shown in Figure 11, the actuator could turn the object around 43° and return it to its original position during the reverse motion. Actuators using other beam materials can also perform work during the reset phase, and their performance depends on the beam’s elasticity. Namely, the greater the beam’s elasticity, the stronger the actuator’s performance in its reset phase. See Movie S3 for movement in the water.

6. Conclusions

This paper attempts to evolve our prior flexible actuator inspired by origami from telescopic to bending while preserving its excellent properties. Starting from it, we design a flexible bending actuator and analyze its deformation potential. Then, we use three different elastic beam materials to make several actuators of various sizes and conduct extensive experiments on them. The performance test results show that our actuator can produce large bending amplitude and torque and work in recovery. In addition, the actuator’s performance can be affected dramatically by its elastic beams’ material and lengths. Overall, the more rigid an actuator’s elastic beam, the more enormous its torque; on the contrary, the more flexible an actuator’s elastic beam, the more extensive its bending range. For example, the maximum tip force of the actuator with a CFP beam reaches 9.6 N, and the maximum bending amplitude of the actuator with a PVC beam reaches 138°. As demonstrated, our actuators have great potential in applications including wriggling, gripping, bidirectional, and underwater motions. Our ongoing work is to use our flexible bending actuator to drive soft robots.

Data Availability

All data generated or used to support the findings of this study are included within the article. The demonstration videos of flexible bending actuators are available at: https://github.com/RiSYSLab/Robotics/tree/flexible-bending-actuator-videos.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Movie S1: The actuator performs wriggling locomotion.
Movie S2: Two actuators imitate gripping locomotion. Movie S3: The actuator moves in the water. (Supplementary Materials)

References


