Soft origami gripper with variable effective length

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Figure S1.A typical origami vertex (a) unfolded and (b) partially folded states

Rigid foldability is an important characteristic of origami structures that becomes significant with non-paper materials. We assume the origami structures remain rigid and all
deflection occurs at the crease lines. Then we can use the fold angle multipliers to evaluate the rigid foldability of arrays of vertices.

A typical vertex is illustrated in Figure S1. Four creases meet at each vertex; the paper between adjacent creases is a sector and the angle between adjacent creases is a sector angle, designated $\alpha$. The angle of the fold itself is the dihedral angle, denoted by $\gamma$, which is the angle between the surface normal of the two incident sectors. A crease may be a mountain fold ($\gamma < 0$), a valley fold ($\gamma > 0$), or unfolded ($\gamma = 0$). We will indicate valley folds by dashed lines and mountain folds by solid lines. We index the sector angles $\alpha_i$ and dihedral angles $\gamma_i$ so that sector $\alpha_i$ lies between folds $\gamma_i$ and $\gamma_{i+1}$, as illustrated in the figure.

The ratio between any two dihedral angles in origami vertex is a constant. We call this ratio the “fold-angle multiplier”, $\mu$:

$$
\mu = \frac{\tan \left( \frac{\gamma_2}{2} \right)}{\tan \left( \frac{\gamma_1}{2} \right)}
$$

(S1)
**Figure S2. Rigidly foldable triangle.** (a) Sector angles shown. (b) Fold angle multipliers for each consecutive pair of creases.

For an origami tessellation to be rigidly foldable, each vertex and each closed polygon in the tessellation must be rigidly foldable. For an n-degree polygon with interior angles 1 through n the fold angle multipliers ($\mu_i$) associated with the crease pairs at each vertex define a loop condition that enforces consistency around the polygon, namely:

$$\prod_{i=1}^{p} \mu_i = 1 \quad (S2)$$

Figure S3 shows the sector angles and fold-angle multipliers for a rigidly foldable triangle. Each vertex is rigidly foldable in isolation; since the product of the fold angle multipliers around the interior polygon is 1 ($1.01 \times -0.8145 \times -1.2495 = 1.003 \approx 1$), we check the six different vertexes that correspond to the current structure (apex angle $\beta$ of the inner and outer origami units as $25^\circ$ and $35^\circ$), the entire pattern is similarly rigidly fold.

**Figure S3. Actuators with different methods (video S1 and S2)** (a) pure cable-driven actuator. (b) pure shape-controlled pneumatic actuator. (c) combining both of the cable and origami structure.
**Figure S4.** Kinematics comparison between simulation and experiment for a single soft origami actuator. *(video S2 and S3)* (a) deformation of the actuator under the pressure of 40 kPa. (b) the corresponding simulation results.

**Figure S5.** The curvature of different cable lengths on the actuators under the same pressure *(also see video S3)*.

We have compared pure shape-controlled pneumatic actuator and pure cable-driven actuator with our prototype with both cable and origami structure. It can be seen from Figure.S3(a) that the bending motion of the pure cable-driven actuator is affected by the
squeezing in the ventral side, and the pure cable-driven actuator is not able to elongate, bending curves are not smooth or regular. From Figure.S3(b), the pure shape-controlled pneumatic actuator is not able to adjust the curvature to adapt to objects with different shape and size. As Figure.S3(c) shows, by combining both of the cable and origami structure, our robot can easily elongate and bend. As a result, our robot can adapt to objects with different shape and size.

From Figure S4, it can be observed that the simulation results agree well with the experiments. In supplementary video S1, the comparison between experiment and simulation of a single actuator under pressurization shows good agreement. Figure S5 and video S2 show the curvature of different cable lengths on the actuators under the same pressure.

![Apparatus for measuring the pull-off force of the soft gripper under different effective lengths.](image)

**Figure S6.** Apparatus for measuring the pull-off force of the soft gripper under different effective lengths.

To evaluate the gripping performance of the prototype, we set up an experimental platform to test the pull-off force of the gripper when grasping different objects. To this end,
we kept the object fixed and pulled the gripper vertically up at a constant speed. As shown in Figure S6, the gripped object was connected to a six-axis force transducer (Mini 40 F/T sensor, ATI, America). The bottom side of the force transducer was mounted to an optical table through the substrate.

The robotic arm (MOTOMAN MH3F, YASKAWA Inc., Japan) moved vertically upward, therefore, to pull the soft origami gripper up and away from the gripped object. During each experimental trial, we first biased the weight of the object in a force data acquisition system using a Labview program. Then the soft actuators would be inflated to a preset pressure and conform the test object. Afterward, the gripper was moved upward at a constant speed of 18 mm·s⁻¹ until the gripper was completely detached from the object, which took about 5 s. During the gripping process, the force data along Z axis was recorded simultaneously at a sampling rate of 500 Hz. Then the force data was filtered by a low-pass filter (15 Hz). The average value of 3 maximum peak forces was finally used for calculating the pull-off force of each measurement. Here in this study, the pull-off force was defined as the maximum force generated during the whole gripping process.

**Figure S7.** Grasping small size object (movie S5). (a) Grasping a sphere 10mm in diameter. (b) Grasping 3mm diameter screw