SPIRALING SOFT-ROBOTIC MICRO-TENTACLES BASED ON SHAPE-ENGINEERED, HIGHLY DEFORMABLE ELASTOMERIC MICROTUBES

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ABSTRACT

Microscale soft-robots hold great promise as safe handlers of delicate microobjects but their wider adoption requires greater efficiency and easier fabrication. We present elastomeric microtube pneumatic actuators functioning as microrobotic tentacles. We establish a direct peeling-based technique for building long, thin, highly deformable microtubes and their shape-engineering. Using them, we amplify the microtube's pneumatically-driven bending into multi-turn inward spiraling. The resulting micro-tentacle exhibit spiraling with the final radius ~185 μm and grabbing force ~0.78 mN, rendering itself ideal for non-damaging manipulation of fragile microobjects. This spiraling tentacle-based grabbing modality, elastomeric microtube fabrication technique, and concept of shape-engineering will enrich the field of soft-robotics.

KEYWORDS: Soft Robot, Soft MEMS, Bio-inspired, Tentacle

INTRODUCTION

Spiraling tentacle motion is ubiquitous in nature as an effective means of object handling but its artificial replication turned out to be very challenging, especially at microscale, due to its complex actuation and control schemes. Here, we report a microscale soft-robotic manipulator fully capable of reproducing the biological tentacle motion through pneumatic actuation.

Ours is distinct in three aspects: First, it is truly at *microscale* with only ~185 μm in diameter, smaller than any existing one [1]. Second, it can fully reproduce the *multi-turn* spiraling motion of biological tentacles. Such a life-like motion has been realized only by centimeter-scale artificial tentacles so far. Third, its unique features are realized through our new fabrication technique which not only allows the implementation of high aspect-ratio, thin-walled elastomeric microtubes but also enables their shape-engineering in both cross-sectional *and* axial directions for delicate motion control.

Figure 1 outlines our approach. First, we fabricate highly deformable PDMS microtubes. High deformability is ensured by the thinness of the microtube itself and its tube-wall (8–32 μm). Making such a subtle structure at a length exceeding several millimeters has been deemed unfeasible. We accomplish it with a new fabrication technique. It also allows significant asymmetrization of the microtube's cross-sectional shape which leads to bending up to a single-turn. Second, we shape-engineered the microtube to amplify the bending into multi-turn spiraling. Using a semi-analytical model, we establish a design rule which enables such a spiraling with a simple *hump*. The outcome is a soft micro-tentacle that can wind around fragile micro-objects.

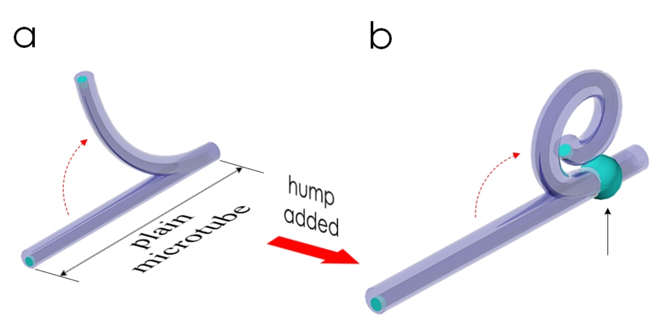

Figure 1: (a)-(b) The basic structure and working principle of our micro-tentacle. It is a PDMS microtube which bends upon pressurization. By adding a hump, we can amplify the bending into multi-turn spiraling.

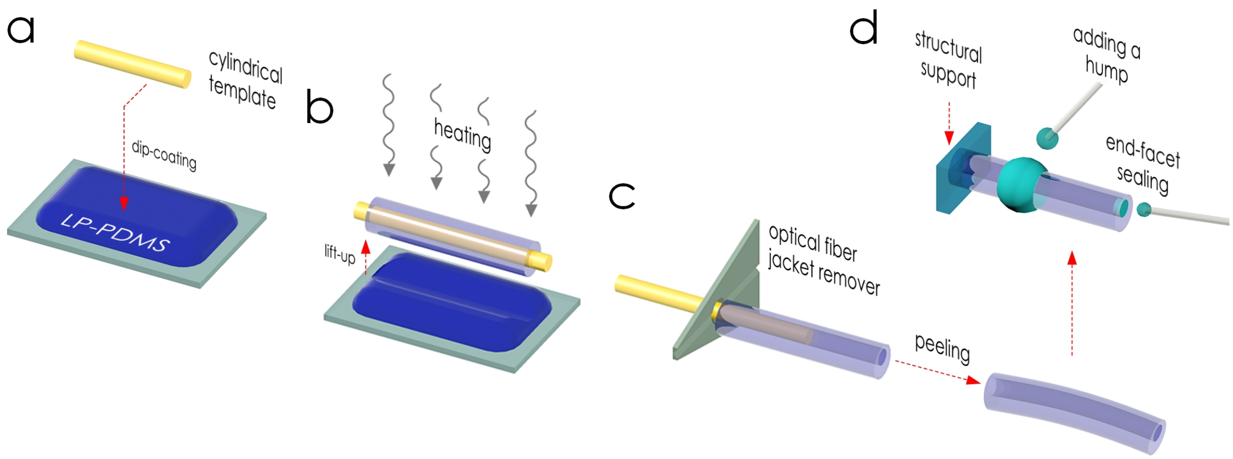

Figure 2: (a)-(b) Dip-coating PDMS around cylindrical templates for bonding-free fabrication of extremely thin-walled microtubes. (c) The resulting microtube is robust enough to be peeled from the template with a simple polymer jacket remover. This process is simpler and faster than those relying on dissolvable templates. (d) We can also mount the microtube on another PDMS block, modify its shape by adding structures on its exterior, or asymmetrize the tube's cross-sectional shape.

FABRICATION

Figures 2a-d describe our fabrication technique. It uniquely combines *in situ* thermal solidification [2] and direct peeling from solid templates, distinguishing itself from existing schemes based on sacrificial templates. Figure 2 shows that the technique not only enables fabrication of extremely thin PDMS micro-tubes but also facilitates asymmetrization of the tube wall thickness and installation of supporting structures such as the hump. The PDMS microtube is robust enough to be peeled directly from the template with a polymer jacket remover.

RESULTS AND DISCUSSION

Owing to its high aspect-ratio and thin tube-wall, the microtube bent significantly upon applying air pressure. Regardless of the pressure or cross-sectional asymmetry, however, plain microtubes with no cross-sectional shape change in the axial direction failed to achieve spiraling. Through numerical modeling, we found that adding a simple hump (Fig. 3a) can enable spiraling.

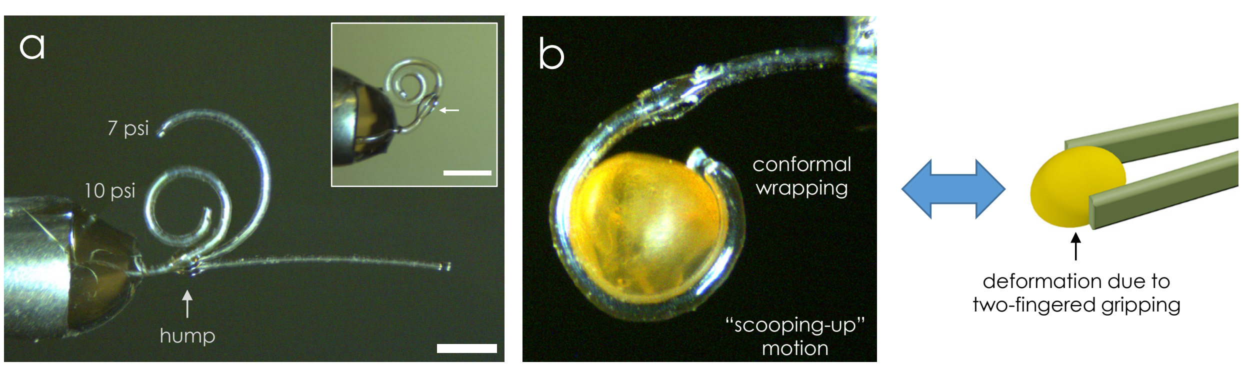

Figure 3: (a) Microscope images of the spiraling motion of the PDMS micro-tentacle as the pneumatic pressure increases. The inset shows the impact of hump position optimization which resulted in the best multi-turn spiraling. (Scale bar: 1 mm) (b) compares the traditional two-fingered gripping and our new tentacular conformal wrapping and scooping motion which is much gentler to the target object.[3]

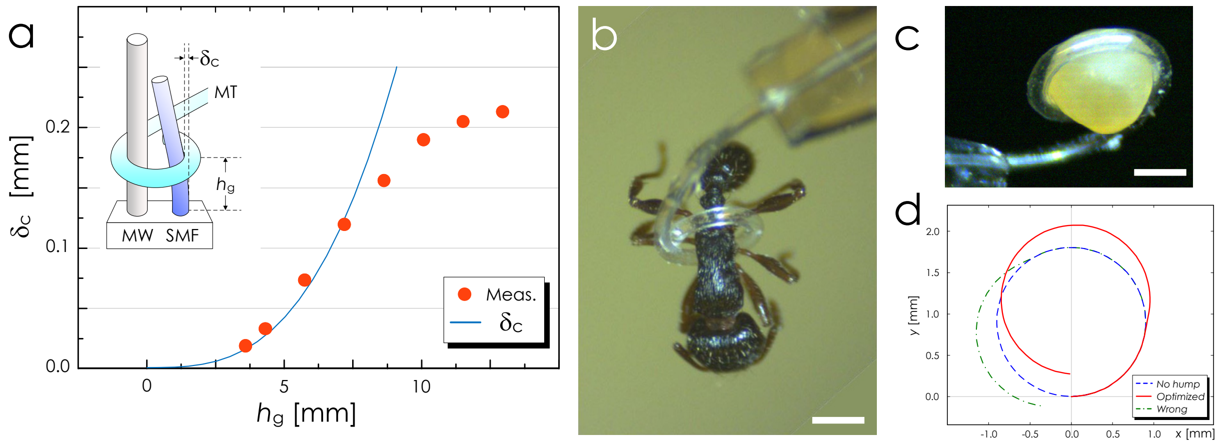

Figure 4: (a) Measured deflection of a cantilever grabbed by the PDMS micro-tentacle. The inset shows the experimental setup (MW: metal wire, SMF: glass optical fiber, MT: micro-tentacle). Based on the standard beam deflection theory, the point-loaded force was estimated to be 0.78 mN. (b) and (c) Optical micrographs showing the micro-tentacle's ability to grab and hold an ant and a Mallotus villosus egg by winding around it conformally. (Scale bars: 500 μm) (d) Theoretical modeling results for the impact of the hump position.

The spiral formed by the PDMS micro-tentacle is ideal for grabbing and holding microscale objects. To estimate its grabbing force, we configured it to deflect a cantilever (Fig. 4a) and determined that the microtentacle can exert 0.78 mN of squeezing force at 9.8 psi. Thanks to the softness of PDMS and the spiraling motion, the micro-tentacle can function as a soft-robotic grabber of fragile micro-objects. We observed that it can conformally wind itself around irregularly shaped fish eggs, giving it minimal mechanical stress (Figs. 3b and 4c), and grab and hold an ant without harming it (Fig. 4b). The most critical part of the PDMS micro-tentacle's spiraling motion turned out to be the size and position of the hump which, as shown in Fig. 4d, can either promote or demote the formation of the inward spirals.

CONCLUSION

All the results indicate that our new bio-inspired micro-tentacle will play important roles in future soft-robotics and microTAS.

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