Fiber-reinforced Soft Robotic Anthropomorphic Finger

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***Abstract*—Robotic fingers have attracted considerable attentions of researchers from multidisciplinary fields. Most of the existing devices apply rigid components such as springs, joints, gears etc., to achieve the locomotor performance of the human finger. However, high-cost, complexity hold back their practical application. Meanwhile, the material properties of these rigid components are significantly different from the biological tissues to bring in considerable risk and difficulty in human-robot interaction. In this paper, a novel soft robotic anthropomorphic finger was presented, which was purely made of low cost soft hyperelastic materials (around 1.5 dollars) and was pneumatically actuated. The morphology of the robotic finger was a replica of an adult-human finger. The chambers, fiber orientation and the skin layers were designed in concert therefore to achieve human finger-like movement. The kinematic and dynamic model of the soft robotic finger were built based on experimental empirical method. While operating underwater, DPIV experiments revealed that the underwater pinch performance of a two-finger gripper prototype is significantly affect by the position relative to the gripped object.**

Keywords-anthropomorphic; soft robotics; finger

I. INTRODUCTION

Human hand is a great paragon for many artificial grippers for its dexterity. In contrast to common end-effectors, anthropomorphic fingers have dimensions that are highly approximate to humans and can perform precise and dexterous motions. Anthropomorphic fingers have become a complicated robotic system involving multiple disciplines such as mechatronics, sensor, material, etc. A number of dexterous anthropomorphic fingers have been developed [1], which requires complex multi-jointed mechanisms and control system. These robotic fingers are usually built of rigid materials such as metals or hard plastics. These fingers could achieve human-like locomotion and generate moderate force, however, high-cost, hard to fabricate and requiring highly reliable complex sensors and control systems to achieve grasping motions hold back the practical application of these prototypes. The huge disparity between rigid and biological tissue-like materials brings in considerable risk in human-robot interaction, and difficulty to grasp different items by utilizing its passive adaptability.

Material flexibility is the primary issue in traditional mechanism design. Biology has long been a source of inspiration for engineers to implement prototypes including materials, electronics and robots etc. For example, inspired by the locomotion [2], muscles [3]-[5] and skin surfaces [6] [7] of live fishes, the fish-like underwater vehicles can achieve continuous body deformations and achieve better hydrodynamic performance. With deformable soft bodies, animals in nature tend to find a simple but efficient way to interact with the environments. Many invertebrates such as octopus [8], worm [9], and starfish [10] have exceptional manipulation and locomotion abilities even without rigid skeletons. Their bodies are mainly composed of intrinsically soft materials that can deform by the muscles and absorb considerable energy of the collision during locomotion.

Inspired by nature, soft robotic robots made of soft materials has been developed recently. Design, fabrication and control methods of soft robotic robots have attracted growing attentions from scientists and engineers in multiple fields such as chemistry [11], physical [12], biology [13] and robotics [14] [15]. Soft material enables the robots to generate continuous movement. Simple movement principles reduce the demands for actuators and hence reduce the system complexity with fairly low cost. The soft robotic robots can be fabricated by several approaches including multi-material 3D printing [16], shape deposition manufacturing (SDM) [17], soft lithography [18] and integrate multiple manufacturing approaches[19]-[21] therefore to create composite structures, for example, with both fibers and soft materials. Soft robotic technology has been preliminarily used in numerous fields with potential applications in locomotion, manipulation [18] [22]-[24], rehabilitation [25] and human-machine interaction [1].

In this paper, a pneumatic fiber-reinforced soft robotic anthropomorphic finger was presented, shown in Fig. 1. This prototype can achieve bending motions similar to a real human finger. Then the design and manufacturing

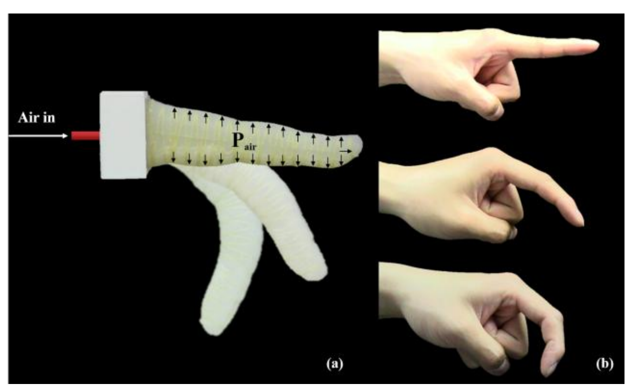

Figure 1. (a) Bending motion of the soft robotic finger under three different pressure (0 kPa, 90kPa and 180 kPa). P_{air} indicates the air pressure in the inner chamber. (b) Bending motion of a human finger.

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procedures are described in detail. The effect of air pressure on the finger's kinematic performance and the output force were then studied through kinematic and dynamic model obtained by applying an experimental method. Simple DPIV (Digital Particle Image Velocimetry) experiments were conducted to reveal its underwater griping performance.

II. Materials and Methods

A. Biological Inspiration

Hydrostatic skeletons in soft-bodied organisms are ubiquitous in nature. Many animals such as worm lacks rigid jointed skeletons but depend on hydrostatic skeletons which commonly function as actuators. Hydrostatic skeletons are fiber-reinforced structures which are typically cylindrical, fluid-filled and cavity-enclosed tissues twined by helically arranged connective fibers that limiting its deformation (elongation and contraction). By adjusting the pressure in the enclosed fluid, the deformation of the hydrostatic skeleton in all dimensions can be actively controlled, which results in diverse movements and shape changes [21], [26].

In this paper, a novel under-actuated soft robotic anthropomorphic finger inspired by the fiber-reinforced structure of the hydrostatic skeleton was presented (see Fig.1a). This finger consists of an inner elastomer bladder wrapped with inextensible but flexible reinforcements as well as combines with a strain limiting layer along the longitudinal direction. When the inner bladder is pressurized by air, it attempts to expand in all directions. Wrapping the bladder with inextensible fibers will constrain it from expanding radially and force it to expand only in the longitudinal direction. By adding a sheet of inextensible material to prevent the finger from longitudinal expanding in the side of the bottom, the finger can achieve flexible bending motions, similar to that of a human finger (see Fig.1b). The bending motion of the soft robotic finger can be preprogrammed by tuning the design parameters such as fiber angle, strain limiting placement and material propriety.

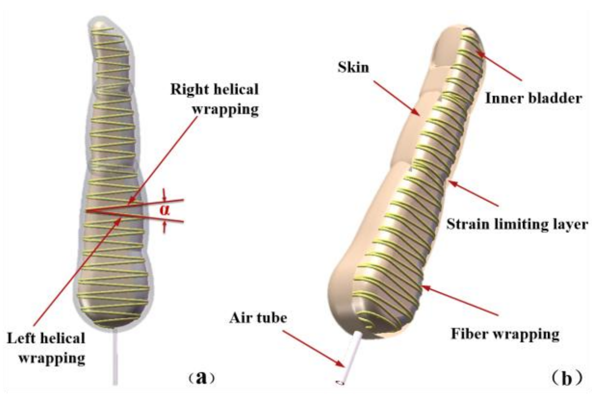

Figure 2. The design of the fiber-reinforced soft robotic finger. (a) The fiber wrapping, arranged with inextensible Kevlar thread in a left-right symmetrical double helix configuration. α refers to the angle between the left and right helical wrapping. (b) The components of the soft robotic finger.

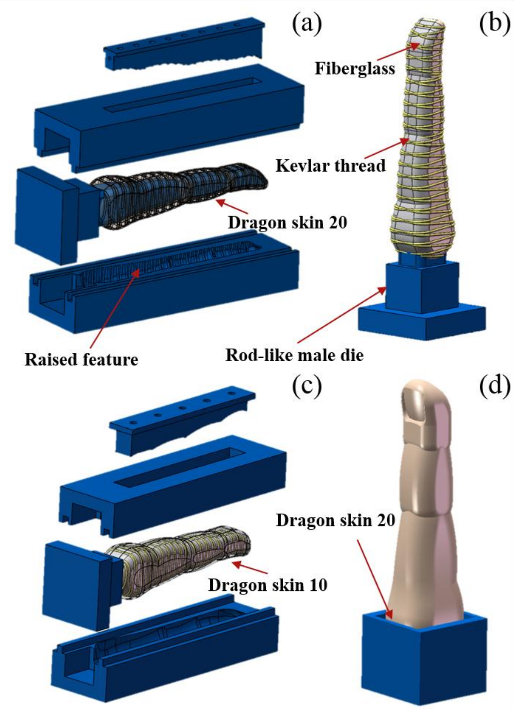

Figure 3. Schematic of the multi-step fabrication process for the fiber-reinforced soft robotic finger. (a) Molding the finger inner bladder. (b) Demolding the finger core while leaving the rod-like male die inside to hold the shape. Gluing the strain limiting layer on the bottom flat surface and wrapping with Kevlar threads. (c) Coating with an outer skin to hold the wrapping in place; (d) Removing the rod-like male die and dipping the finger in uncured silicone elastomeric material to enclose the end of the finger.

B. Design and Fabrication of the Soft Robotic Finger

An anthropomorphic design scheme in soft robotic finger's morphology based on the left index finger of an adult male was chosen. The single soft robotic finger is mainly consist of five components (see Fig. 2): 1) inner bladder, which is a hollow closed chamber molded out of soft materials; 2) strain limiting layer, which is a sheet of fiberglass attached to the flat bottom surface of the inner bladder, preventing that bottom surface from lengthening when inflated; 3) fiber wrapping, arranged with inextensible Kevlar thread in a left-right symmetrical double helix configuration, which restricts radical expansion; 4) skin, which encapsulates the finger' inner components for the purpose of protection and mimics the epidermis of a real finger; 5) air tube, which is rooted into the finger to let the pressure air in.

The soft robotic finger used in this study is fabricated using a multi-step molding process. The molds for the finger were designed in SolidWorks (*Dassault Systemes*, France) and 3D printed with PLA (polylactic acid) using a desktop 3D printer (MakerBot Replicator 2, *MakerBot Inc.*, USA), which allows us to iterate rapidly [27]. The wall thickness of the rubber inner bladder is 2 mm. A rod-like mold is used to generate the inner cavity. Raised features in the male mold are transferred to the finger core out surface and form the dent for the convenience of wrapping the Kevlar fiber (see Fig. 3a). After molding the inner bladder out of Dragon skin 20 (*smooth-on Inc.*, USA), fiber wrapping was added to the surface. Woven fiberglass was then glued to the bottom flat surface to serve as a strain limiting layer. A single Kevlar thread (0.48mm diameter) was then wound around the length of the finger in a left-right symmetrical double helix configuration (shown in Fig. 3b). Fiber wrapping were further protected by placing the entire assembly into another mold to encapsulate and shape the finger in a 2mm thick silicone skin using Dragon skin 10 (*smooth-on Inc.*,USA) (as Fig. 3c shows). The finger was then removed from the mold and the rod-like male die. The open end was capped by placing it into a small mold filled with uncured silicone elastomeric material same with inner bladder (Fig.3d). Once this end cured, a plastic pneumatic tube was inserted into the inner cavity and acted as a pressure access. When pressurized fluid (air or liquid) is inflated to the interior chamber, the finger would bend as shown in Fig. 1.

C. *Experimental Setup for Characterizing the Soft Robotic Finger*

Using the fabrication process outlined in Section B, two prototypes of the soft robotic finger were manufactured. The finger were actuated by compressed air. The air tube of the finger was connected to an electro-pneumatic proportional pressure valve (ITV0030, *SMC*, Japan) which was used to control the output air pressure.

1) Experimental setup for characterizing the kinematics

To characterize the kinematics of the soft robotic finger, we inflated the finger to a certain pressure and picked out the profile curve of the single finger under different pressures (from 0 kPa to 180 kPa, with an interval of 10 kPa). A camera (LEGRIA HF M60, *Cannon*, Japan) was used to record the whole motion process for latter analysis. The profile curves of the finger at steady state was digitized by using a self-programmed Matlab program.

2) Experimental setup for characterizing the finger-tip force

In order to evaluate the finger-tip press force of the prototype, we set up an experimental platform (see Fig. 4) to test the finger-tip force when the finger bent under different pressures (from 0 kPa to 180 kPa, with an interval of 10 kPa). A data acquisition board (PCI-6284, *National Instruments*, USA) was used for data acquisition and system control. The force transducer fixed on a mounting base was used to measure the press force applied by the fingertip. The connector of the finger can be adjusted vertically along the support which is concretely mounted to the base to guarantee the fingertip can touch the force transducer while bending. Before each trial, the initial force was subtracted to eliminate bias. After the deviation elimination process, the finger will be inflated from its initial position to a certain pressure and the finger-tip will concretely touch the force transducer in the end. Until the finger came to a steady state, the force data in Z axis was recorded at a sampling rate of 500Hz until the finger came to a steady for several seconds and then filtered using a low-pass filter with a cut-off frequency of 5Hz. Each measurement trial was repeated for three times and the average value of force data was finally taken as the fingertip force under a certain air pressure.

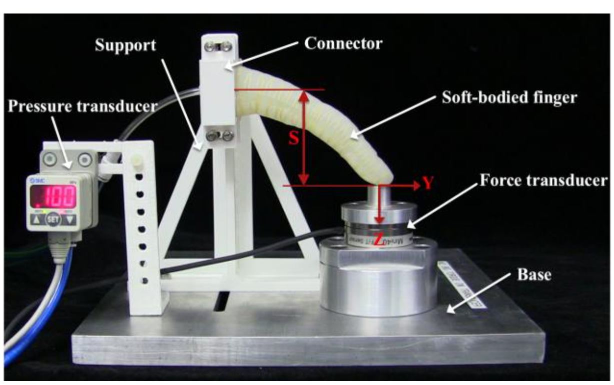

Figure 4. Illustration of the force measurement platform. *S* refers to the distance in Z axis between the axi of the finger and Y plane of the force transducer.

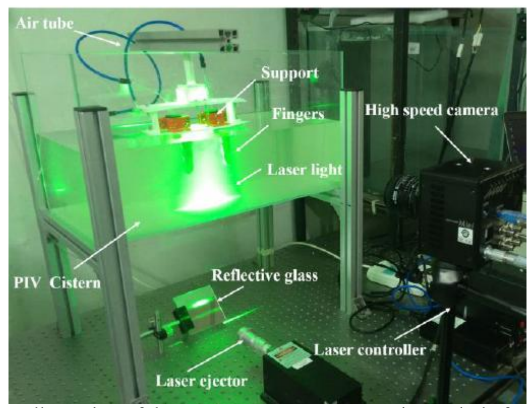

Figure 5. Illustration of the DPIV measurement experimental platform. Two soft fingers were fixed on a support in parallel and submerged under water in a cistern. The near-neutrally buoyant glass beads with a diameter of 20 m were seeded in the water and a laser sheet with a thickness of 1.5mm was used to illuminate these particles. Particle movements in the vertical and horizontal planes were recorded by the high speed camera

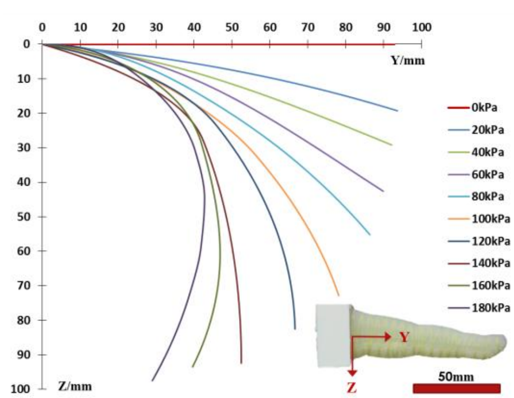

Figure 6. Profile curves of the finger under different air pressures.

3) Experimental setup for characterizing the underwater performance

DPIV (Digital Particle Image Velocimetry) experiments were also performed to investigate the grasping performance of the two-finger gripper prototype underwater (see Fig.5).

The near-neutrally buoyant glass beads with a diameter of 20 μm were seeded in the water and a laser sheet with a thickness of 1.5mm that carefully adjusted to sweep the mid-sagittal plane was used to illuminate the particles between two fingers. Particle movements in this plane were recorded by a high-speed camera (FASTCAM Mini UX100, *Photron Inc.*, Japan) with an acquisition frequency of 500Hz. The velocity fields were then calculated by applying cross-correlation algorithm [28], and the flow patterns caused by the grasping movement were then obtained.

III. Results and Discussion

With respect to angular deflection, the finger demonstrated an obvious sensitivity to pressure value, which suggests the fingertip amplitude ranges from 0 to 100 mm in Z direction as the pressure varies from 0 kPa to 180 kPa, as Fig.6 shows. We could fit an empirical formula between the profile curves and control pressure P applying a polynomial fitting method：

$$Y=\sum_{i=0}^{2}\lambda_i Z^i\ ,\lambda_i=\alpha_i P^3+\beta_i P^2+\gamma_i P+\eta_i \qquad (1)$$

where Y、Z are Y-value and Z-value in the coordinate system of profile curves. $\alpha_i,\beta_i,\gamma_i,\eta_i$ are coefficients obtained from fitting process. We found that the finger-tip amplitude ranges from 0mm to 63.8mm in the Y direction and 0 to 97.5mm in the Z direction. The results show that the soft robotic finger has a relatively large operating space (the length of the soft robotic finger is 92.8mm).

The experimental results on finger-tip press force was shown in Fig.7. We found an approximately linear relationship between finger-tip force F and control pressure P:

$$F=\mu P \qquad (2)$$

where μ is a coefficient (0.0281-0.0238) fitted from the force experiments. The soft robotic finger was found to generate a maximum force at the distal end of above 4 N, which is acceptable for grasping and manipulating a number of small items in daily life.

The experiment on underwater pinch operation revealed the effect of the finger movement on surrounding water. Two typical flow patterns were picked out for analysis (Fig. 8). When soft robotic fingers were inflated, the fingertips snapped quickly and directed the water in a complex way. Quite interesting, as shown in Fig.8a, the flow above the red dotted line was pushed upwards, while the flow below the dashed line was squeezed downwards and then wrapped around the fingertips. Two vortexes with opposite directions were observed to enclose the tips before the moment that the finger tips contact (Fig.8b). The DPIV results manifest an interesting point that the pinching performance may be greatly influenced by the pinching position when pinching objects underwater. We hypothesized that, when the object was floating at the position below the red dashed line, it could be pushed away by the jet flow formed by the finger motions before moment of pinch grasping. However, if the fingers were controlled to pinch the object above the red dashed line, the object may be "suck up" by the flow jet and be cached by the gripper eventually. This issue will be studied in detail in the future.

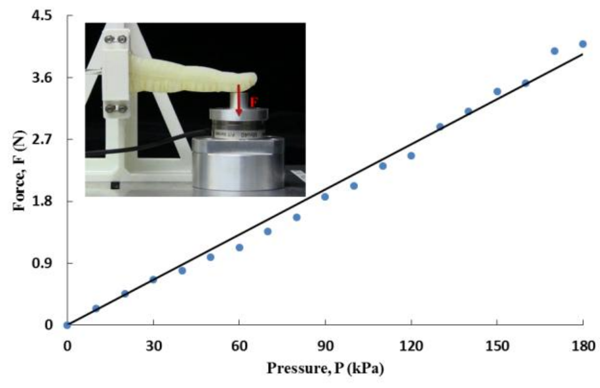

Figure 7. The finger-tip force vs. air pressure.

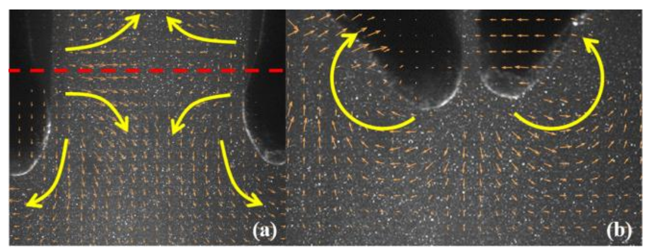

Figure 8. Instaneous flow field near the finger tip underwater during pinching operation. (a) The wake flow when two fingertips were closing. The red dotted line indicates the boundary of the flows with different directions.(b) The wake flow before the moment of collision of the finger tips.

IV. Conclusions

In this paper, a pneumatic actuated fiber-reinforced soft robotic anthropomorphic finger was presented. This prototype, which replicates the human finger in both morphology and size, can achieve bending motion which is similar to that of a human finger. The entire finger was mainly made of purely soft, inherently and flexible materials and structures, rather than using rigid plastic or metal parts. The soft robotic finger is easy to build, impact-resistant, inherently safe, low-cost and easy to control. The finger presented here can be built in one day using materials with a cost less than \$1.5. The soft materials applied in this project has an estimated Young's moduli of 250 kPa, which is close to the moduli of biological tissues and can absorb impact during operation.

The finger's displacement of deformation and force on the fingertip under different air pressures were quantified. The single prototype in this paper can achieve maximum bending displacement of 100mm and output force up to 4N. The pinching performance in underwater environment was also investigated by analyzing the flow patterns through the DPIV method. The underwater tests showed that a good pinch performance may be related to the part used for operation. The soft robotic finger presented here has potential applications for human-robot interaction. In the future, more studies will be conducted on evaluating the performance of the soft robotic finger. Anthropomorphic soft gripper that imitates a real human hand including both palm and fingers is also on the way.

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