

A Soft Robotic Gripper Based on Bioinspired Fingers *

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Abstract—In the past, partly due to modeling complexities and technical constraints, fingers of soft grippers are rarely driven by high number of actuators, which leads to lack of dexterity. Here we propose a soft robotic gripper with modular anthropomorphic fingers. Each finger is actuated by four linear drivers, capable of performing forward/backward bending, and abduction/adduction motions. The piecewise constant curvature kinematic model reveals the proposed finger has an ellipsoidal shell workspace analogous to that of a human finger. Furthermore, we build a gripper using two of our modular fingers, and test dexterity and strength of the finger. Our results show that by simple control schemes, the proposed gripper can perform precision grasps and three types of in-hand manipulations that would otherwise be impossible without the addition actuation.

I. INTRODUCTION

Traditional rigid manipulators have been popular for their strength and endurance needed mostly in industrial settings. However, with a rise of applications where delicacy and adaptability are prioritized, soft manipulators have gained much research attention recently. Raphael et al. designed a soft pneumatic five-fingered robotic hand with seven independent actuators, which can complete a variety of grasping operations, and proved that compliance is conducive to grasping to a certain extent [1]. Rahim et al. used 3D printing technology to manufacture soft prosthetic finger, and studied the influence of shape parameters on joint bending angle. The resultant finger can generate bending motion similar to human hand under tendon driving [2]. Mariangela proposed a three-fingered gripper made of different materials driven by a single actuator. The control algorithm of the gripper is simple, and it can grasp common objects [3]. Wang Wei et al. developed a gripper with shape memory alloy, which has a variety of bending forms and can change the stiffness under temperature variation [4]. Brian et al. developed a rehabilitation gloves with flexible materials, which can be used as power-assisted devices driven by

tendons [5]. However, existing flexible fingers often do not have enough degrees of freedom and can only complete the bending movement in one plane compared with rigid fingers, which limits their dexterity [6-7].

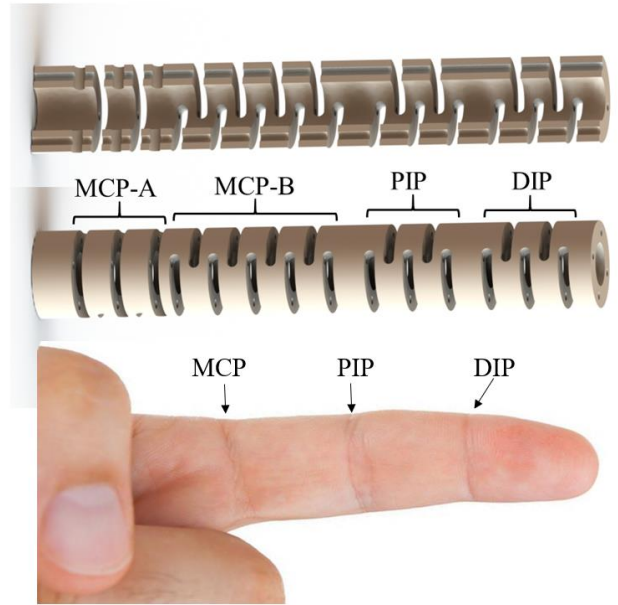


Figure 1. Comparison between human finger and the proposed finger

The metacarpophalangeal (MCP) joint contributes substantially to the mobility of human hands for it is a 2-DOF joint that allows two types of motions: bidirectional bending and abduction and adduction. The forward bending of a finger is seen in almost all grasping tasks; the backward bending, while less common, is also crucial in human hand dexterity. When grasping large objects, the MCP joint bends backwards to bring the fingertips further away from the palm, thus facilitate the grasping process by expanding the grasp space. The abduction and adduction motions are also important, as they add to the DOF of the finger and expand the grasp space as well. Furthermore, most in-hand manipulations cannot occur without abduction and adduction motions. Therefore, simulating the motions of a human hand without endowing the fingers with the ability to bend backwards, abduct and adduct is incomplete.

This paper proposes a multi degree of freedom bioinspired finger (Fig. 1) based on our previous research [9], which uses continuum structure as the joint and has adequate compliance. This bionic characteristic leaves the potential for the structure to be employed in prosthetic hand development. With four actuators, the proposed finger can perform forward and backward bending, abduction and adduction motion. Furthermore, a two-fingered soft gripper was developed,

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which can complete a variety of precision grasping operations and three in-hand manipulations.

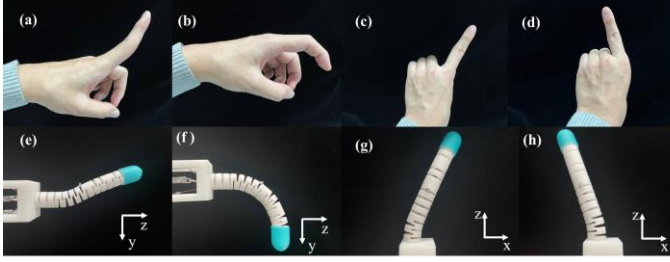


Figure 2. Four types of motion of human finger and the soft finger

II. THE BIOINSPIRED FINGER

In this paper, we follow an anthropomorphic approach in design of the finger. Human fingers (except thumb) have three joints (Fig. 1), namely, the distal interphalangeal (DIP) joint, the proximal interphalangeal (PIP) joint and the MCP joint. All three joints can produce bending motion while the MCP joint can also perform abduction and adduction. Without the additional DOF in the MCP, the motion of a finger is limited to a plane, thus excluding the hand from numerous nimble tasks. Consequently, replicating the DOF of human MCP in our design is one of our focuses. One aspect that current researches on human hands have rarely addressed is the range in the MCP's bending motion. Using the finger angle measurement scheme in Santello et al. [10], most extant designs only allow MCP joint to reach 0 and positive degrees. However, the human MCP joint is capable of reaching negative angles under motions similar to Fig. 2a. We observed that such backward bending occurs frequently when grasping large objects. To imitate the capabilities of human fingers, restoring the range of bending motion in MCP is another focus in our design.

In this paper, we use a hollow tubular structure (Fig. 1), which has an inner diameter of 12mm, an outer diameter of 16mm and a length of 105mm. Similar structures has been used in surgery for removal of osteolysis behind total hip arthroplasties [11]. There are notched structures on its surface, allowing a bending motion of the finger under tendon driving. We decompose MCP joint into MCP-Bending (MCP-B) joint and MCP-Abduction (MCP-A) joint, so there are four joints of the bioinspired finger, namely, DIP, PIP, MCP-B and MCP-A joint. The joints are arranged in two directions perpendicular to each other, so that the fingers can complete 2-DOF movements. Four through holes are evenly arranged at 90 degrees on the pipe wall for tendon's passing through. The finger is actuated by four tendons, which can control the fingers to bend in four different directions (Fig. 2e-h). We term the tendons by their responsible movement, namely TF, TB, TAB, and TAD; they respectively perform forward bending, backward bending, abduction, and adduction when tightened.

Based on the piecewise constant curvature kinematics model [12], we calculate the workspace of the soft finger (Fig. 3), which is a part of ellipsoidal shell.

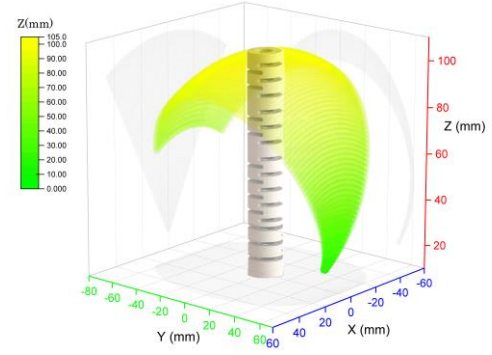


Figure 3. Work space of the bioinspired finger

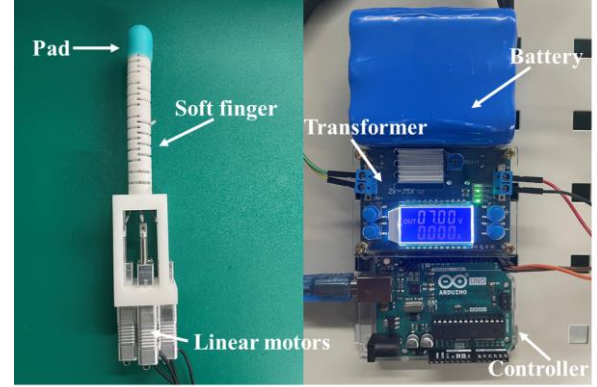


Figure 4. The soft robotic finger module

The soft fingers are made of nylon material by 3D printing technology. A silicone finger pad is installed on the distal end of the finger, which can bring even contact between finger and objects and provide enough friction for grasping. The finger adopts modular design which can be assembled in different ways. A single bioinspired finger module is shown in Fig. 4. Each tendon is actuated by a linear servo motor. A battery is used as power source of the module which can provides a constant voltage through a transformer. An Arduino uno is used as the controller of the system.

III. THE SOFT ROBOTIC GRIPPER

The modular nature of the proposed finger allows countless ways to combine the fingers and form grippers suited for various tasks. Here we propose two assembly methods involving two fingers. The first method is assembling two fingers face to face in the direction of forward bending motion (Fig. 5a), and the second is assembling two fingers where the abduction direction of one finger opposite to the adduction direction of the other finger (Fig. 5b). When the first method was used, the two fingers of the gripper can be regarded as the index finger and middle finger of a human hand. When the second method was used, the two fingers are comparable to the index finger and thumb in opposite positions of a human. An assembled gripper with the first method is shown as Fig. 6 which is actuated by 8 linear servo motors and installed on a linear guide rail.

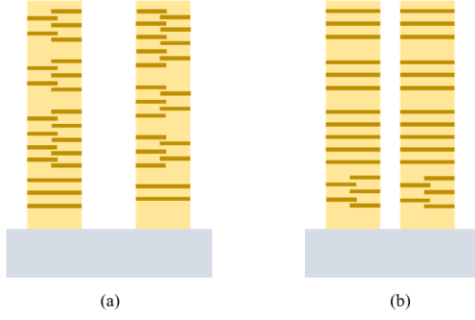


Figure 5. Two assembly methods of the fingers

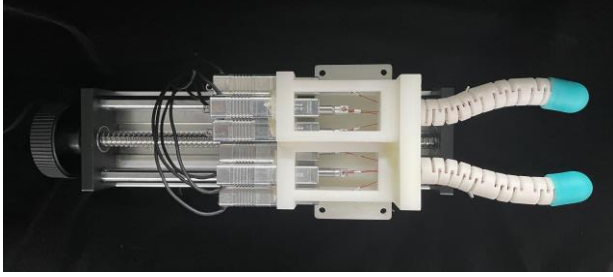


Figure 6. The soft robotic gripper

IV. EXPERIMENTS

In this section, a series of experiments were conducted to examine the function of the soft gripper. First, the grasping ability of the two-fingered gripper is tested, then the grip force of the gripper is verified. Finally, three types of in-hand manipulations were carried out with the gripper.

A. Precision Grasping with Two Fingers

Precision grasp is an important operation in daily activities which requires more dexterity of finger movement compared with power grasp. There are 3 types of precision grasp with 2 fingers in Fig. 7a-c: the first grasping is to pinch a long prism object with the index finger and thumb. In this operation, because the prism object is relatively long, the thumb and index finger need to bend backward first to form a larger grasping space to grasp the object more naturally. The second and third grasps are holding a cigarette and a card with the index and middle finger. These two operations require abduction / adduction motion to achieve side contact. Fingers with only a single bending joint can not complete these two operations because the work space is limited in a plane. The soft gripper proposed was used to perform this 3 tasks and the results were shown in Fig. 7d-f. The first grasp adopts the assembly method in Fig. 7a. The axis distance between the two fingers in this operation is 35mm. In the process of grasping, the TBs of the two fingers is first actuated to make the fingers bend backward to form a large grasping space, and then the TFs is tightened to bend the PIP and DIP forward to create contact with the object while keeping the TBs taut. The MCP joint of the two fingers has a backward bending angle, which is similar to the human hand in Fig. 7a. The second and third grasps adopt the assembly method in Fig. 5b, and the distance between the axes of the two fingers is 20 mm. During this grasping, the TAD of the left and the TAB of the right finger were tightened at the same time, so that the two fingers bend inward to hold the object. It can be seen that the soft

gripper can stably grasp cigarette and card anthropomorphically, which benefits from the high dexterity of the robotic fingers.

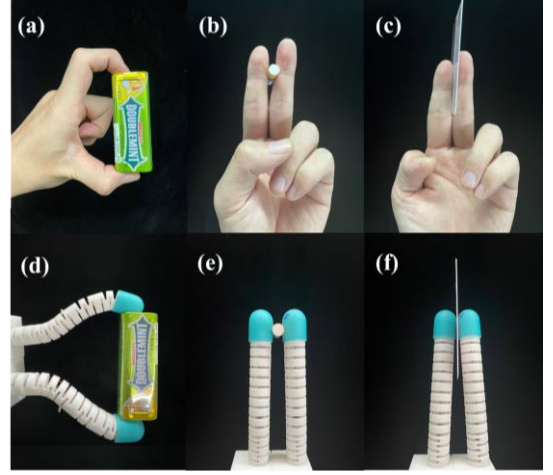


Figure 7. Design of the bionic finger

B. Grip Force

We test the grip force of the gripper by gripping discs of different sizes. Three types of discs are employed, they are right cylinders with equal height of 10mm, and diameter of 50mm, 60mm, 70mm respectively. During each trial, the disc is connected with a load cell and fixed on the platform, the grasping posture of the gripper is described in Fig. 8a. Before creating contact with the disc, the TBs of the fingers were actuated first to form a large grasping space. Then the TFs are pulled to bend the finger forward until the disc is wrapped, and the grasp is considered complete. Then the gripper is pulled vertically upward, and we record the force on the disc with respect to the displacement of the gripper. The experiment is repeated five times for each disc.

The results in Fig. 8b reflects that the peak force of all discs appeared at around 20mm on the x-axis. We observe this is roughly the point where the fingers contact points glide to become diagonal to each other. At this point, the distance between the fingertips and the edge of the disc in the pulling axis is exactly the disc radius. However, the gripper held on to the disc and continued to pull for 30mm to 50mm, much larger than the radius of selected discs. Because before the grasp, the MCP joints are bent backwards, the PIP and DIP joints need to bend forward further. Under such grasp configuration, the flexible nature of the fingers allows the gripper to be stretched, thus holding on to the disc longer. Such occurrence can not occur in rigid grippers.

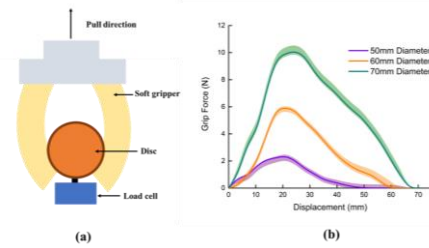


Figure 8. The setup of grip force test and the experiment result

C. In-hand Manipulation

In-hand manipulation has been a challenging operation for dexterous manipulators, and has embodied the superior human hand dexterity. In this subsection, 3 types of in-hand manipulations are tested: moving along the x-axis, moving along the y-axis and rotating around the z-axis. The experimental object is a disk with a diameter of 50 mm and height of 10 mm.

In each group, the disk was grasped stably before being moved. The grasp method is the same as described section IV.B. When moving the disk in the opposite direction of the x-axis, the TF of the left finger is loosen and that of the right finger is tighten, so the disk received a resultant force in the negative x direction and moves accordingly (Fig. 9a). When moving the disk along the y-axis, the TAD of the outer finger and the TAB of the inner finger were tightened so two fingers bend to the left at the same time, moving the disk in the negative y direction (Fig. 9b). It should be noted that due to the bending of the centerline of the fingers, the disk rotates around the x-axis simultaneously. To rotate the disk around the z-axis, the TAD of two fingers are tightened simultaneously, causing both fingers to rotated clockwise, driving the disk to rotate accordingly. The results show that the soft gripper can move the disk a distance of 15mm along the x-axis, 22mm along the y-axis and rotate it 76 degrees around z-axis.

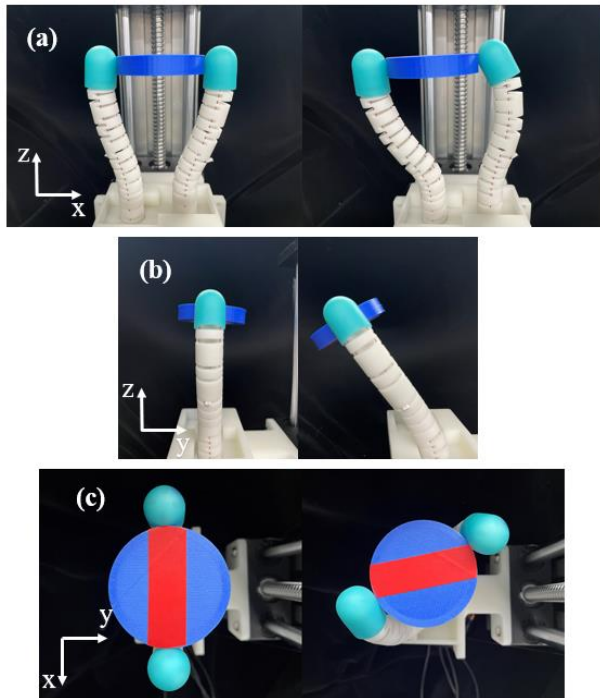


Figure 9. In-hand manipulation test

V. CONCLUSION AND FUTURE WORK

This paper explores applying high DOF actuation onto bio-inspired fingers with continuum structures, and

investigates dexterous manipulations under such application. Actuated continuum structures often trade modeling simplicity and predictability for compliance, and this adds difficulty for designing continuum fingers with high DOFs. We show the benefits of such DOF addition: the workspace of the finger is expanded substantially, and the finger is capable of sophisticated tasks. The finger retained characteristics of soft interactions while gaining dexterity from additional actuators. Given its anthropomorphic nature, the proposed finger structure can certainly be applied to prosthetic hand development. Although current technology does not allow incorporating the proposed finger into prosthetic hands without giving up certain DOFs, such possibility is not invalidated as smaller and innovative actuators might become available in the future.

Future works include: installing sensors for fingers to increase the sensing ability and provide feedback for finger control; trying different finger assembly methods such as adding fingers to 3 or 4 to broaden the usage scenarios of the gripper; studying the finger stiffness adjustment strategy under tendon driving to enable the fingers to switch between high compliance and strong load capacity; exploring the application of the fingers in prosthetic hand.

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