

A Helical Bistable Soft Gripper Enable by Pneumatic Actuation

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Abstract—There are many instances of helical mechanisms that are used to efficiently grasp different objects with various shapes and sizes in nature. Inspired by the helical grasping in the nature, we proposed a helical bistable soft gripper with high load capacity and energy saving. An off-the-shelf bistable steel shell (BSS) as the stiff element was inserted into a 3D printing soft helical exoskeleton to achieve coiling around and holding the objects without energy consumption. Two air pouches were designed as the actuator to control the transition between the two stable states. To facilitate gripper design, a simplified model of the gripper was conducted, and the geometric parameters of the gripper are listed in a table for reference. The transition pressures between the two stable states were experimentally characterized. Moreover, we conduct experiments to demonstrate the capability of the gripper in two working modes. The gripper exhibits coiling diameters ranging between 40 mm and 60 mm and is successfully attached to various slender objects of different geometries with a maximum holding force of 92.67 N (up to 135.1 times of its mass) in hanging mode. Finally, the gripper was integrated into a robot arm and successfully grasped different objects, and the maximum grasping weight is 221.6 g in the grasping mode.

I. INTRODUCTION

HELICAL structure using for grasping is widely observed in nature [1], such as tendrils [2-4], cephalopod tentacles [5], arboreal snakes [6], monkey tail [7], and elephant trunk [8]. Coiling around an object can enlarge the area of contact and increase the stability between the gripper and the object [9]. Compared to the finger-based design, helical gripper with a larger contact area is well-suited for applications that required high-load sustainability. Besides, helical gripper can adapt to a wide range of sizes and shapes of the objects. Those advantages make helical grasping become an effective method for slender objects with different sizes and cross-sections [10].

Inspired by these versatile appendages, researchers have

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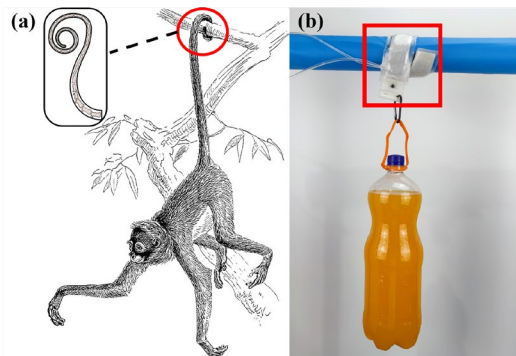


Fig. 1. (a) The spider monkey hung on the tree by its tail. (b) The helical bistable gripper is attached to the object to support its weight.

developed different helical structures of the grippers. To generate a helical motion, Hu et al. [11] modified the traditional soft pneumatic actuators with several angled chambers arranged in a row, which could be actuated using one pressure source. In addition, Wu et al. [12] use the origami structure as the helical structure to mimic the octopus arms grasping and manipulating objects. This arm has a complex motion and is remote-controlled by magnetic actuation. Nevertheless, both of these helical gripper designs exhibit limited load capacity, thereby presenting challenges in handling heavy objects. Also inspired by the arm of the octopus, a conical soft robotic arm using tendons driven to form the helical shape and add the suction cups to improve its grasp force is proposed in [13]. Besides, inspired by the boa constrictor, another helical structure realized by two strain limiting layers is reported by Galloway et al. [14]. While the helical grippers presented in [13] and [14] exhibit a high load capacity, they rely on continuous energy input to maintain the helical form, thereby limiting their potential applications. Addressing this concern, Meder et al. [15] bonded together the stretched and relaxed layers to form a helical structure and added a PCL core to mimic the lignification process of the tendril to make the gripper capable of sustaining the helical shape without energy input and improves attachment forces. It is worth noting that the helical motion in this case is irreversible and requires manual intervention for resetting. However, the demand for reversible helical motion remains crucial in some scenarios where the gripper is mounted on mobile robots to achieve the missions without human intervention [16].

To address the problem of low load capacity, required continuous energy input, and irreversible motion of the

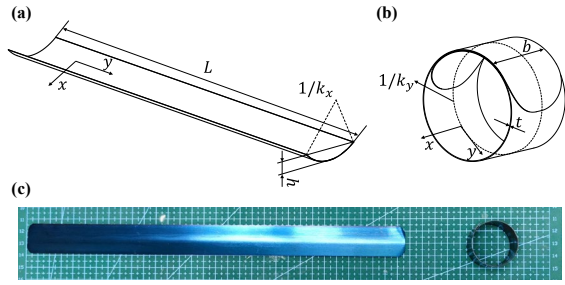


Fig. 2. The two stable states of the BSS. (a) The straight state. (b) The curled state. (c) The experimental specimen of the BSS.

helical soft gripper, researchers have incorporated the bistable mechanism into the design of the helical grippers [17-19]. The bistable structure can remain the deformed shape without any energy consumption, and the energy input is only needed in the transition between the two stable states. Therefore, the bistable mechanism is an energy-efficient actuation method for soft grippers that can passively hold an object without any energy input [20], and the two stable states of the bistable mechanism make the motion reversible. Such bistable structure is widely used in grippers [21-23], and they have different actuation methods, including pneumatic [24], magnetic [25] or electric [26] actuation.

Nevertheless, due to the particularity of the helical structure, most of the helical grippers are made with soft materials, which leads to low load capacity. Integrating the bistable mechanism into the helical soft gripper does not solve the problem that these helical bistable grippers are not strong enough to maintain relatively high payloads while holding objects without continuous energy input. As a result, existing helical soft grippers are unsuitable for application scenarios that require high payload and energy conservation. Accordingly, it is meaningful to develop a novel helical soft gripper with high-payload and energy-efficient.

One effective way to improve the load capacity of a soft gripper is combining the soft elements with stiff elements, which will provide the structural strength of the gripper to support a high payload. Inspired by the instance of helical grasping in the nature (see Fig. 1(a)), we propose a novel helical bistable soft gripper in this study (see Fig. 1(b)). This gripper is mainly composed of a soft helical exoskeleton as the soft element, a bistable steel shell as the stiff element, two air pouches as the pneumatic actuator to transform the shape of the gripper reversibly, and a high friction layer to increase the holding force. Due to the characteristics of the helical structure, the gripper not only allows to attach the slender objects to sustain its weight, but also is capable of grasping the object. Further, the gripper is energy-efficient that it requires no continuous energy input to sustain the stable state. The experiment results demonstrate that the gripper can coil around the objects with a diameter from 40 mm to 60 mm, and the maximum holding force in hanging mode is 92.67 N.

The remainder of this article is organized as follows. In Section II, the design and fabrication of the gripper are presented. Followed by a simplify model and prototype

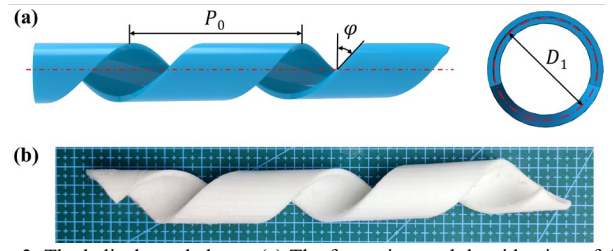


Fig. 3. The helical exoskeleton. (a) The front view and the side view of the helical exoskeleton. (b) The experimental specimen of the helical exoskeleton.

design of the gripper are shown in Section III. The pneumatic transition pressure test and a series grasping experiments are conducted in Section IV. Lately, Section V provides the discussion and conclusion.

II. DESIGN AND FABRICATION

A. Design of the Gripper

1) *The hybrid structure of the gripper:* We use a bistable steel shell (BSS) as the stiff element integrated into the soft helical exoskeleton to form the main part of the gripper. The function of the BSS is the same as the bone of the animal, playing a role of improving the stiff and load capacity of the gripper. The BSS has two stable states due to the residual stresses in metallic shell structures from the fabrication process [27]. In contrast to the soft materials, the BSS provides a relatively large coiling force due to the residual stresses. The soft helical exoskeleton has the same effect as the muscle that provides the compliance to conform to the shape and size of the objects. The proposed gripper can attach to the slender object to support its weight like the spider monkey.

2) *The bistable mechanism of the gripper:* The bistable mechanism is inspired by the Venus Flytrap that changes the shape between the open and closed state to catch insects [28]. This rapid triggering characteristic is highly desirable for grasping, and the BSS has two stable states: the straight state (see Fig. 2(a)) and the curled state (see Fig. 2(b)). Fig. 2(c) presents two stable states of the experimental specimen of the BSS obtained from a commercially available slap bracelet. The main geometry of the BSS is characterized by the following parameter: the overall length L , the width b , the thickness t , the radius of the straight state $1/k_x$, and the radius of the curled state $1/k_y$. These critical parameters determine the coiling diameters of the gripper and the transition pressure between the two states.

3) *The helical structure of the gripper:* Due to the curled state of the BSS cannot generate the helical shape, a soft helical exoskeleton is developed to couple with the BSS to generate the helical motion. When the BSS is inserted into the helical exoskeleton, the curled states of BSS will change to a helical shape while the straight states keep the same shape. The main design parameters of the helical exoskeleton are the pitch of the helical, the helical angle, and the diameter of the helical, denote as P_0 , φ and D_1 respectively (see Fig. 3(a)). In addition, the helical exoskeleton is ease

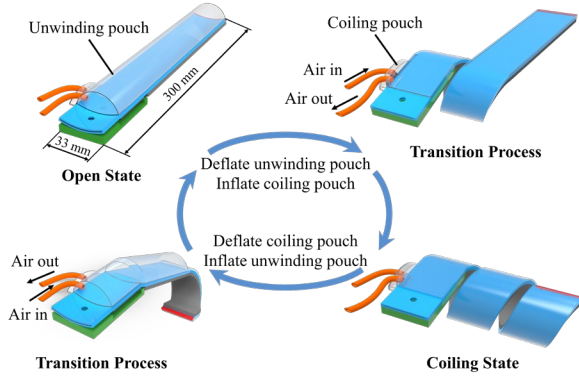


Fig. 4. The switching process of the helical bistable soft gripper between the two states.

fabricated with off-the-shelf materials by 3D printing technology. Therefore, the helical shape can be customized by these parameters based on the context of use. Fig. 3(b) presents the specimen of the helical exoskeleton made by the 3D printer.

B. Working Principle of the Gripper

The proposed helical bistable soft gripper has two stable states: open state and coiling state. The gripper has two air pouches, one of which is the unwinding pouch, and the other is the coiling pouch. The unwinding pouch is fixed on the top of the gripper, and the coiling pouch is sandwiched by the gripper and the supporter. We can control the transition between the two states by actuating the two air pouches in a sequence. The pouch will swell and provide the force to change the state of the gripper when the air is input into the pouch. The bending motion of the BSS will propagate to the whole gripper when the force reaches a critical value and acts on the part of the BSS. Therefore, the volume of the coiling pouch can be designed to be small, while the unwinding pouch requires a large volume to uncoil the gripper.

Fig. 4 presents the switching process of the gripper between the two states. In the open state, the gripper transforms to the coiling state by inflating the coiling pouch and deflating the unwinding pouch. In contrast, inflating the unwinding pouch and deflating the coiling pouch will transform the gripper to the open state from the coiling state. The gripper will sustain the current state when both air pouches are deflating and maintaining the stable states do not require continuous energy input. It should be noted that, due to the volume of the unwinding pouch is larger than the coiling pouch, the gripper transforms to the open state when inflate the two air pouches at the same time.

C. Materials and Fabrication

The helical bistable soft gripper is composed of a drilled BSS, two air pouches, a helical exoskeleton, a connector, a supporter, an end cover, and high friction layer (see Fig. 5(d)). Most of the component are fabricated by 3D printing technology. The connector, supporter, and end cover are 3D

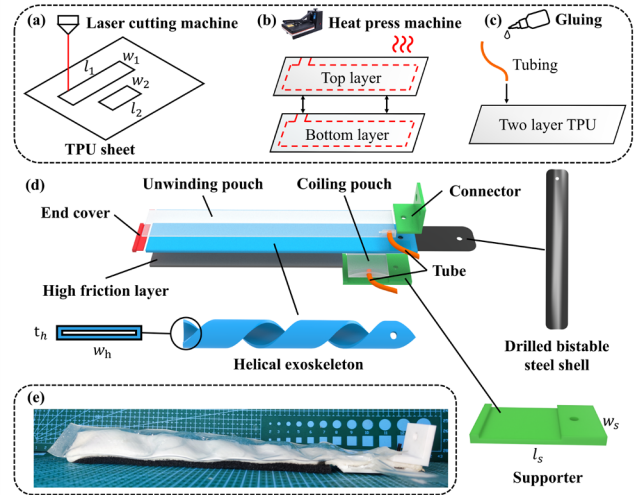


Fig. 5. Fabrication process of the helical bistable soft gripper. (a-c) Construction steps to manufacture the air pouches. (d) The component of the gripper. (e) Final assembly of the helical bistable soft gripper.

printed (CR-3040 Pro) with PLA material. The soft helical exoskeleton should have sufficient resilience and be soft to generate the helical motion coupled with the BSS without destroying the bistable property of the gripper. For this reason, the commercially available TPU filaments (TPE-83A, eSun) are chosen as the material of the soft helical exoskeleton. We use thermoplastic polyurethane (TPU) with a thickness of 0.4 mm as the material of the air pouches, which can withstand a relatively large air pressure. The construction steps of the air pouches are shown in Fig. 5(a)–(c). The TPU sheets are cut into the desired geometry by the laser cutting machine for the unwinding pouch and the coiling pouch (see Fig. 5(a)). Then the TPU sheets are bonded together by the heat press machine (see Fig. 5(b)), and the tube for the air supply is glued at the edge of the sheets (see Fig. 5(c)).

The designed connector serves the purpose of installation onto various devices, while the supporter is designed to prevent the transformation of the gripper from the open state to the coiling state due to its weight. The BSS is drilled with a hole to connect the supporter, helical exoskeleton, and connector. The coefficient of friction between the gripper and the object is very important for holding a mass or grasp an object. The sponge exhibits a notable friction coefficient when it is compressed and enabling contact with objects without scratching the surface. Hence, the sponge tape is used as the high friction layer of the gripper. Fig. 5(e) illustrates the final assembly of the helical bistable soft gripper. The BSS is inserted into the soft helical exoskeleton and is fixed with a screw to connect other component and prevent it from sliding. Then the end cover, two air pouches, and the high friction layer are assembled by glue to finish the fabrication of the gripper.

III. MODEL AND PROTOTYPE DESIGN

A. Simplified Model of the Gripper

The simplified model as an elastic spring model can be

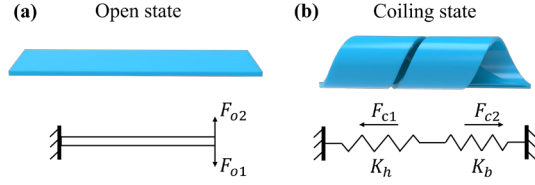


Fig. 6. Simplified model in the two states when only the BSS is inserted into the helical exoskeleton. (a) Open state. (b) Coiling state.

TABLE I
VALUE FOR GEOMETRIC PARAMETER OF THE GRIPPER

parameter	symbol	value	unit
length of the BSS	L	290	mm
width of the BSS	b	30	mm
thickness of the BSS	t	0.16	mm
radius of the straight state	$1/k_x$	39.7	mm
radius of the curled state	$1/k_y$	15.1	mm
length of the unwinding pouch	l_1	280	mm
width of the unwinding pouch	w_1	35	mm
length of the coiling pouch	l_2	40	mm
width of the coiling pouch	w_2	30	mm
width of the helical exoskeleton	w_h	35	mm
thickness of the helical exoskeleton	t_h	2.8	mm
pitch of the helical exoskeleton	P_0	80	mm
diameter of the helical exoskeleton	D_1	24	mm
helical angle of the helical exoskeleton	φ	45	degree
length of the supporter	l_s	60	mm
width of the supporter	w_s	35	mm
pitch of the gripper	P_1	36	mm

expressed as Fig. 6 when only the BSS is inserted into the soft helical exoskeleton. To reserve the property of bistable of the gripper, the resilience force of the helical exoskeleton should be smaller than the force of transforming BSS from the open state to the coiling state. Therefore, we have

$$F_{o1} = F_{o2} < F_t \quad (1)$$

where F_{o1} is the resilience force of the helical exoskeleton, F_{o2} is the counterforce of the BSS and F_t is the transition force from the open state to the coiling state.

In coiling state, the pitch of the gripper is decided by the interaction between the helical exoskeleton and the BSS. We have the simplify model of the coiling state (see Fig. 6(b)). The linear elastic springs K_h and K_b represented the simplified model of the helical exoskeleton and BSS, respectively. It has the equilibrium in the coiling state as follow:

$$F_{c1} = F_{c2} \quad (2)$$

$$K_h \Delta d_1 = K_b \Delta d_2 \quad (3)$$

Where F_{c1} and F_{c2} is the resilience force of the helical exoskeleton and BSS, respectively, Δd_1 is the decreased pitch of the helical exoskeleton, and Δd_2 is the increased pitch of the BSS. We can relate the Δd_1 and the pitch of helical exoskeleton as $\Delta d_1 = P_0 - P_1$, where P_0 is the initial pitch of the exoskeleton, and P_1 is the pitch of the gripper. The initial pitch of the helical exoskeleton can be obtained as:

$$P_0 = \frac{K_b \Delta d_2}{K_h} + P_1 \quad (4)$$

From the eq. (4), we can know that the pitch design of the

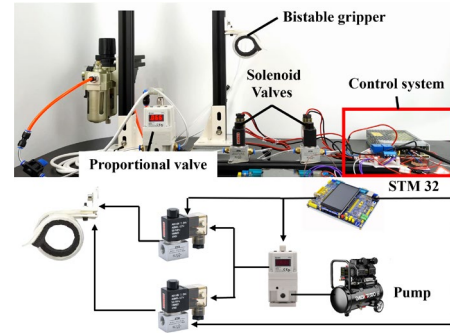


Fig. 7. The experiment setup of the test of the pneumatic transition pressure and the control system of the gripper.

helical exoskeleton is related to the hardness of the material when the material of the BSS is determined. Although higher material hardness of the helical exoskeleton allows a smaller pitch design when combined with the BSS, it may destroy the bistable characteristics of the gripper. On the contrary, if the material of the helical exoskeleton is too soft, the pitch needs to be designed larger to avoid overlap, which would increase the difficulty to the manufacturing of the exoskeleton. Therefore, eq. (4) can provide guidance for the material selection of the helical exoskeleton by measuring the elastic springs K_h .

B. Prototype Design

Based on the simplified model of the gripper, the pitch of the gripper can be designed by the pitch of the helical exoskeleton. In order to have a high load capacity, an overlap of the gripper is generally undesirable as it would reduce the contact area between the gripper and the object. Therefore, the pitch of the gripper should be larger than the width of the helical exoskeleton to avoid overlap. We test the $K_h = 74.61$ N/m and the $K_b = 95.05$ N/m by using the universal tensile test machine (ZQ-990L, ZhiQu Ltd., China). The minimum pitch of the helical exoskeleton is 79.59 mm which is obtained based on the eq. (4) without the overlap of the gripper. Accordingly, the helical exoskeleton with a pitch of 80 mm is fabricated by 3D printing as the soft element of the gripper.

The main geometrical parameters of the gripper are listed in Table I. For a larger interaction force between the exoskeleton and BSS, we designed the radius of the exoskeleton is smaller than the radius of the curled state of BSS. The number of helix revolutions of the gripper around the object should be more than one to ensure a stable grasp, so the overall length of the gripper is designed as 300 mm, while the coiling diameter of the gripper range from 40 mm to 60 mm. Based on the parameters listed in Table I, we fabricated a gripper that weight 70 g as the sample to conduct the following experiments.

IV. EXPERIMENTS AND RESULTS

A. Test of Pneumatic Transition Pressure

The experiment set up and the control system is shown in

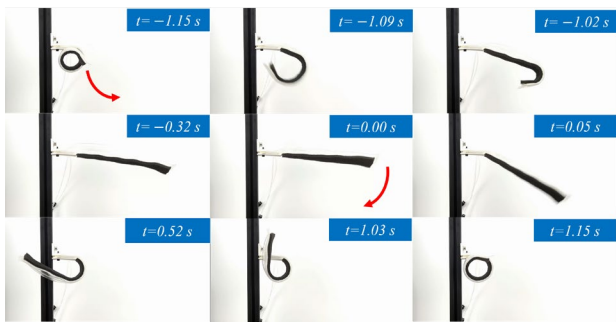


Fig. 8. The transition motion of the gripper and the time required for transitions between its two stable states.

Fig. 7. The STM32 sent the voltage signals to the proportional valve to regulate the pneumatic pressure within the air pouch. Then the solenoid valves were employed as switches to facilitate the inflation or deflation of the two air pouches. In the test, we gradually increase the air pressure input to the air pouch by the proportional valve until the gripper successfully changes its stable state, then record the transition pressure of the gripper. To ensure the controllability of the gripper, the input pressure was considered as the transition pressure only when the gripper achieved a success rate of 90% to change its stable state in the ten tests. Both the transition pressures between the two states are 65 kPa in the test. The testing video can be found in supplementary materials. The test results demonstrate the low energy consumption of the presented gripper, which is suitable for mobile robots. In the future, the gripper can be equipped with a portable pneumatic system for installing on UAV to achieve aerial perching.

In addition, the state of the helical bistable gripper is successfully controlled by the pneumatic system, and the motion of the gripper is reversible. The transition process of the gripper is shown in Fig. 8, and the time required for transitions between its two states is 1.15 s.

B. Grasping Experiment of Two Models

The proposed gripper has two working modes: hanging mode (see Fig. 9(a)) and grasping mode (see Fig. 9(b)). The hanging mode means the gripper attaches an object to support its weight, while the grasping mode is the gripper grasping and transporting a slender object. We conducted different experiment to demonstrate the capability of the

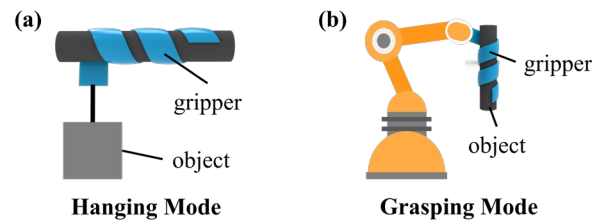


Fig. 9. Two working modes of the helical bistable soft gripper. (a) Hanging mode. (b) Grasping mode.

gripper in different working modes. To verify the ability of the gripper in the hanging mode, we conducted the experiment to test the capacity of the gripper on various slender objects with different surface textures by the universal tensile test machine. The objects included circular PVC pipes and circular wooden bars with different diameters of $\phi 40$ mm, $\phi 50$ mm, and $\phi 60$ mm. The chosen objects are common slender objects such as tree branches and pipes.

The experimental results are shown in Fig. 10(a), tests were conducted 5 times per scenario. Experiments show that the helical bistable soft gripper has a maximum holding force of 92.67 N while the gripper weighs 70 g, with a load-to-weight ratio of 135.1. Due to the wooden surface being rougher than the PVC surface, which led to higher friction between the gripper and the object, the holding force of the gripper attaching the wooden bars is larger than attaching the PVC pipes of the same size. Besides, the helical bistable gripper appears to be better suited to an object that has a large diameter, with the larger objects yield better results than the smaller one of the same materials. The reason for this phenomenon is that as the radius of the attaching object increases, the elastic restoring force of the BSS increases, which increases the pressure exerted by the gripper on the object. This leads to an increase in static friction between the gripper and the object and enhances the load capacity of the gripper. Therefore, the holding force of the gripper increases as the maximum static friction force and the coefficient of friction increase. Furthermore, we used weights to simulate a load to observe the load capacity of the gripper in practical scenarios, as shown in Fig. 10(b). The helical bistable gripper is manually coiled around the object, and the holding process is without any energy input. The experimental results show that the proposed gripper can coil around on the different slender objects to sustain its weight.

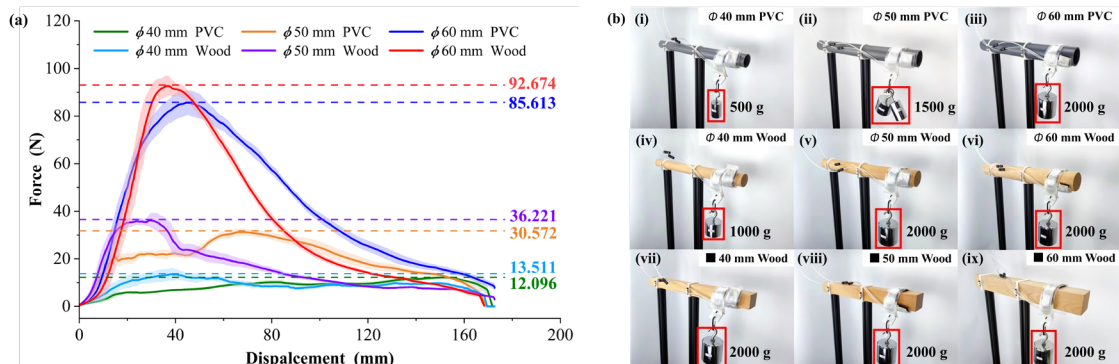


Fig. 10. (a) The experimental results of the holding force of the gripper. (b) The gripper coils around different slender objects to sustain its weight.

TABLE II
COMPARISON OF THE HELICAL SOFT GRIPPERS

Reference	Actuators	Load	Load-to-weight
Geckeler et al. [18]	None	2.7 N	56.0
Meder et al. [15]	Electric	3.1 N	160
Mazzolai et al. [13]	Tendon-driven	3.3 N	3.9
Wang et al. [4]	Thermal	8.2 N	1518
Hoang et al. [10]	Hydraulic	17.6 N	220
Pal et al. [17]	Pneumatic	19.6 N	100
This gripper	Pneumatic	92.7 N	135.1

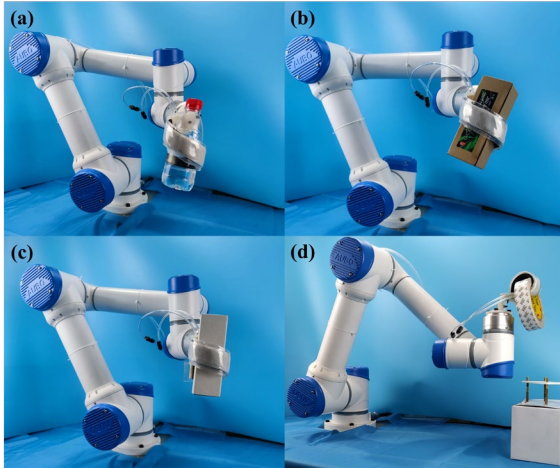


Fig. 11. Grasping test on various objects: (a) Water bottle ($\phi 60$ mm): 221.6g. (b) Battery box (50×60 mm): 121.8g. (c) White box (40×44 mm): 66.2g. (d) Double-sided tape: 203.8g.

The load capacity of some existing helical soft grippers was demonstrated to evaluate the performance of the proposed grippers, and the comparison of these load capacity is presented in Table II. The gripper distinguishes itself with the high holding force of 92.674 N without any energy input, whereas most of the other designs have a relatively low load capacity or need continuous energy input to sustain the payload. Even though they perform well in terms of the load-to-weight ratio, their load capacity is far below than the proposed helical soft gripper. Besides, the maximum holding force of the gripper can be further improved by extending the length of the gripper.

As shown in Fig. 11, various objects with different shapes and weights were grasped by the gripper to test the capability of the gripper in grasping mode. The test objects were a double-sided tape and three slender objects that including a water bottle with a circular cross-section and two square boxes of different sizes. We install the gripper on the robotic arm and remote control the robotic arm by the controller to grasp the target object. The gripper coils around and transports the object when the robotic arm approaches the target object. During the grasping process, the pneumatic system was only used to control the gripper coiling around or loosening the object. The gripper exhibits the ability to conform to various objects, with its maximum grasping weight reaching 221.6 g while in the grasping mode.

The magnitude of friction between the gripper and the object depends on the coiling force. In the hanging mode, the

weight added to the gripper can increase the coiling force under gravity. But in the grasping mode, the coiling force is mainly provided by the small residual force of the BSS. Therefore, the maximum holding force of the gripper is 92.67 N in the hanging mode, while the maximum grasping weight of the gripper is 221.6 g in the grasping mode. This experiment demonstrated that the proposed gripper could be used for attaching slender objects to support its weight or grasping objects, while most helical soft gripper has only one function.

V. Discussion & CONCLUSION

In this work we proposed a helical bistable soft gripper with a high load capacity and holding objects without energy consumption. We combined the soft helical exoskeleton and the bistable steel shell to improve the load capacity of the soft gripper, and the gripper had the functions of high load capacity, bistability, and reversible helical motion. The states of the gripper can be reversibly controlled by the pneumatic actuator, and the gripper has two working modes hanging or grasping. This gripper demonstrated good adaptivity that successfully coiled around different slender objects with diameters from 40 mm to 60 mm. Moreover, the maximum holding force of the gripper was 92.67 N in the hanging mode, which allowed the gripper to hold more than 131 \times than its mass (70 g). The excellent performance and versatility make it an ideal candidate for mobile robots perching on slender objects to save energy and extend the functioning time, and this design may provide references for future UAV perching mechanisms.

While the proposed gripper exhibits excellent load capacity, it is still an early-stage design with several limitations. Firstly, due to the constraints of the helical grasping mechanism, the gripper is primarily used for grasping slender objects and is hard to grasp spherical or flat objects. Moreover, while the maximum grasping radius of the gripper is determined by its overall length, but it is hard to coil around some slender objects with small diameters due to the constraint of the deformation shape of the BSS. Furthermore, the proposed gripper faces challenges in operating within narrow spaces. We will explore solutions to these problems in the future.

In the future, a model to predict the pneumatic transition pressure and the maximum holding force of the gripper will be developed. An important next step is installing this helical bistable soft gripper on mobile robotics such as UAV by designing a portable and lightweight pneumatic system. The UAV equipped with this gripper can achieve perching functionality to extend its working time, thereby broadening its range of applications.

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