

Development of a Novel Mechanical Layer Jamming Cable-driven Soft Actuator for Soft Gripper System

Chinvudh Uahchinkul, Satoshi Muramatsu, and Katsuhiko Inagaki, *Member, IEEE*

Abstract— Soft actuators have many advantages, such as flexibility and safe interaction with the environment. Despite these advantages, they still lack the stiffness to carry the high load. The layer jamming mechanism can be applied to the actuator to increase stiffness, and a vacuum can control the stiffness of the mechanism. However, the typical jamming mechanism has a risk of air leakage, and vacuums are bulky to some systems. In order to solve this problem, we have developed a novel mechanical layer jamming for the cable-driven soft actuator in this paper. Our design uses the actuator body to generate the compression force to the layer at the middle of the actuator's body to increase the actuator's stiffness. The result shows the effectiveness of our mechanical layer jamming in increasing the stiffness of the actuator when adding the load to the tip of the actuator. In addition, we have applied our actuator to the soft gripper system, which successfully grasped various objects and changed the stiffness of the actuator.

I. INTRODUCTION

Soft actuators are now an interesting area of research and development. These actuators offer many advantages, such as high flexibility and more friendly interaction with the environment and humans, compared to the rigid parts of traditional robots. For this reason, soft actuators have been developed for various applications, including soft walking robots [1], [2] and soft grippers [3], [4], [5], [6].

In the past, soft actuators have been developed using various actuation methods [7]. The first method involves using pressure for actuation. However, pressure-based actuators have a risk of air leakage, which can cause operational failures, and they require a pressure source that is usually bulky. Another actuation method involves using cables to drive the actuator. Cable-driven actuators do not risk air leakage during operation. Additionally, the cables are typically connected to motors that pull the cables to actuate the soft actuator, resulting in a more compact system compared to pressure sources. Research has also shown that cable-driven actuators can be further improved to be untethered, which can be useful in many situations [1], [4].

Cable-driven soft actuators have shown effective performance in applications like soft grippers. Soft actuators

used as soft grippers have advantages over traditional rigid grippers because they can adapt their shape to hold objects firmly and are safe for grasping objects. However, soft actuators often have low load-carrying capacities due to their low stiffness, making them deform large when carrying heavy loads. Variable stiffness soft actuators have been developed in various ways to enhance the effectiveness of soft actuators for more applications. By changing the stiffness of the soft actuator, it can utilize the advantages of its soft body to adapt to object shapes and ensure safety in low-stiffness states while achieving high load capacity and less deformation under high-stiffness states.

The concept of variable stiffness in soft actuators has been applied in many previous research [8], [9], [10]. One method is to combine the jamming mechanism with soft actuators [11], [12], [13]. The filling inside the jamming mechanism can be based on three main types: granular, layer, and fiber, each of which has its advantages. Typically, the filling is inside the airtight bag and connected to the pressure source, such as a vacuum. By activating the vacuum, the airtight bag shrinks and generates the compression force to the filling material inside of it, which can increase the stiffness of the mechanism. While not activating the vacuum, it still has a low stiffness and flexibility. The stiffness of jamming can be tuned by varying the pressure of the vacuum, which is also an advantage over the other mechanisms that have only two states between high and low stiffness. Each filling has a different advantage. Granular jamming has a granular filling that can move freely and lock in any shape, and layer jamming has a tunable stiffness in one direction, which is suitable for the actuator that bends in one direction, such as a gripper. Moreover, the fiber jamming is tunable in more than one direction, which has been applied to the high degree of freedom actuators such as continuum robots.

Many researchers have demonstrated the performance of the jamming mechanism with soft actuators. The jamming mechanism was previously applied to the soft actuator using pressure-driven and cable-driven. However, jamming mechanisms usually require a pressure source or vacuum to increase the stiffness, which can be bulky and have a risk of air leakage, similar to pressure actuation systems. Mechanical jamming mechanisms have also been developed to avoid the problem of the pressure-based jamming mechanism, such as using cables with granular jamming [14] and mesh sheaths with layer jamming [15]. Additionally, the discrete layer jamming concept has shown great performance [16], [17]. The result shows the performance of discrete jamming mechanisms with only a few clamps applying force to the layer sheets along the entire sheet, which can increase the stiffness of the mechanism.

Chinvudh Uahchinkul is with the Course of Science and Technology, Tokai University, Kanagawa, 259-1292, Japan (email: 3mtad001@tokai.ac.jp).

Satoshi Muramatsu is with the Department of Applied Computer Engineering, Tokai University, Kanagawa, 259-1292, Japan (email: muramatsu@tokai.ac.jp).

Katsuhiko Inagaki is with the Department of Applied Computer Engineering, Tokai University, Kanagawa, 259-1292, Japan (email: inagaki@tokai.ac.jp).

In this paper, we present a cable-driven soft actuator with a new mechanical layer jamming mechanism that is also driven by cables. This mechanism changes the stiffness of the actuator by using the actuator body to generate compression force on the layer sheets. We will explain the actuator design and the concept of our mechanical layer jamming in detail. The actuator has been tested with external loads to confirm the effectiveness of our design and concept. Furthermore, we have applied the actuator to develop a soft gripper system along with a control system and tested it to grasp various objects. The results of the gripper system's performance are presented in this paper.

II. MECHANICAL LAYER JAMMING SOFT ACTUATOR

A. Actuator Design

In our prototype design, as shown in Fig.1, we developed the actuator based on a cable-driven soft actuator. The actuator is driven by two cables that can be pulled separately to control its bending. The sheets for the layer jamming structure are positioned in the middle of the actuator's body. The actuator design has an octagonal structure, as shown in Fig.2. This structure is designed to bend in two directions when the cables are pulled, similar to a typical cable-driven soft actuator. Additionally, when both cables are pulled simultaneously, the center walls move towards each other, generating compression force on the layer sheets in the middle. This force can work like the concept of typical layer jamming, where force is applied to the layer sheet by an airtight bag with negative pressure. The actuator has eight sections of the octagonal structure along its length, enhancing its versatility for various applications. Each section includes a structure to generate force on the center sheet, resulting in eight points where force is applied along all the sheets.

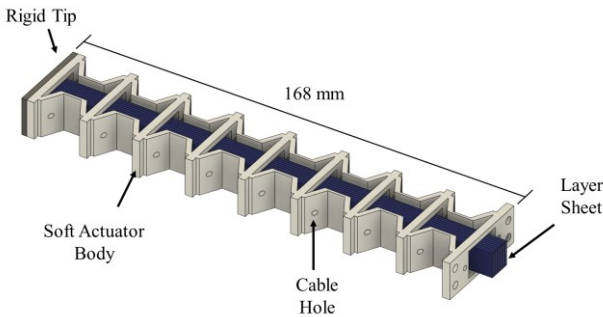
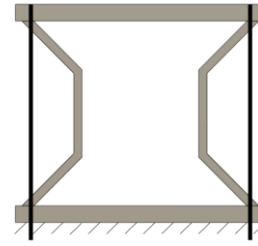
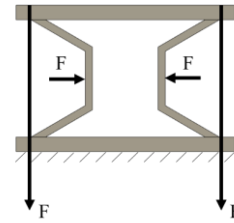


Figure 1. Soft actuator design

Each section of the unit has a length and width of 21 mm. The center wall has a space of 10 mm. With a total of eight sections, the actuator has an overall length of 168 mm. Two cables are connected to the top section of the actuator, and each is positioned 11 mm from the centerline of the actuator. At the top section, we added a small rigid tip to reduce deformation when the cables are pulled. In the middle of the actuator, eight sheets, each with a thickness of 1 mm, a width of 10 mm, and a length of 210 mm, are inserted for the layer jamming structure. Additionally, a shorter sheet is inserted at the bottom part of the actuator, length to the third section of the actuator from the bottom. This compensates for the uneven force distribution, as the top of the actuator generates



(a)



(b)

Figure 2. Soft actuator shape (a) before applying force (b) after applying force

more compression force to layer sheets. By adding the shorter sheet, the force is distributed more evenly. Furthermore, all the sheets are fixed to the base with high compression force while the tip side remains free.

The actuator and layer sheet are fabricated using an FDM 3D printer, the Flashforge Adventurer 5m Pro, with 95A TPU filament. Additionally, the base connecting to the servo motor and the pulley connecting the cable to the servo motor is built with PLA filament using the same 3D printer. All TPU parts are printed with 100% infills, while PLA parts are printed with 15% infills. The pulley is designed with a diameter of 30 mm, and the cable used is a fishing line with a diameter of 0.37 mm. The servo motor used is the DSSERVO DS3218, which has a rotation angle of 270 degrees. The pulley mounts to the servo motor and connects with the fishing line to control the cable length.

B. Mechanical Layer Jamming

Typically, layer jamming uses multiple layer sheets inside the airtight bag and increases the stiffness of the structure by using a vacuum to create negative pressure that generates force along the sheets from the airtight bag [13]. The stiffness of the structure can also be adjusted by varying the pressure inside the airtight bag, which varies compression force on the layer sheets. This mechanism can achieve high stiffness until the sheets start to slip and reduce the mechanism's stiffness.

In our design, we have developed a mechanical layer jamming concept for use in our actuator. Unlike typical pneumatic layer jamming, where force is continuously applied along the entire layer sheet, our prototype mechanical layer jamming generates compression force at only eight points along the layer sheet, as shown in Fig.3. When the two cables are pulled simultaneously, the body of the actuator have deformation, then generates compression force from the

middle wall. The force from the middle wall compresses the layer sheet and activates the jamming state. The jamming state of our design can be activated and deactivated by pulling and releasing the cables, respectively. The layer sheets are designed to have some space from the middle wall of the actuator, which lets the actuator bend in a low-stiffness state and switch to a high-stiffness state at any bending angle of the actuator. Furthermore, similar to the typical layer jamming mechanism, where lower pressure and higher compression force increase stiffness, in mechanical layer jamming, pulling cable longer generates higher compression force, resulting in increased stiffness. Our design has several advantages over typical designs and other mechanical jamming systems that were mentioned previously. Notably, it does not require a pressure source or have issues with air leakage. This design also reduces the number of actuation devices by utilizing the same cable to operate both the actuator and the jamming mechanism. Furthermore, the actuator's body compresses the layer sheet at multiple points, making it more similar to traditional designs.

C. Actuation System

The soft actuator is driven by two cables. The cables are tied to the end of the actuator in one end and routed through the cable hole along the actuator. The actuator body connects to the actuation base, and one end of the layer sheets is also fixed to the base. The other end of the cables is connected to the pulley, which connects to the servo motor. We use two servo motors to pull two cables and control the movement of the actuator. Two servo motors are placed and mounted to the base while the servo motor connects to the controller. By pulling one cable, the actuator can bend in one direction, similar to a typical design. Pulling the other cable bends the actuator in the opposite direction. Furthermore, the two servo motors that are used to control the movement of the soft actuator are also used to control the jamming state of the actuator, which lets the actuation system have the same component as the typical soft actuator with control movement by two cables. Two servo motors are controlled by two potentiometers connected to the controller to control the length of the cables.

The model of the cable-driven actuator based on the constant curvature model has been previously solved in [18]. For our design, the actuator has only two cables. The cable length can be calculated from the required bending angle and radius of the curvature of the actuator based on the constant curvature assumption as the following equation

$$l_1 = \theta \cos(R - d) \quad (1)$$

$$l_2 = \theta \cos(R + d) \quad (2)$$

where l_1 and l_2 are the cable length, with l_1 being the shorter cable length and the actuator bending to this cable side, R is the radius of the curvature, θ is the bending angle of the actuator, and d is the distance of the centerline of the actuator to the cable position.

D. Actuator Testing

After developing and building the prototype of the soft actuator with mechanical layer jamming, we tested the variable stiffness of the actuator by activating the layer

jamming. The soft actuator is attached to the base, with two cables routed from the end of the actuator to the pulleys attached to the two servo motors, as mentioned previously. Both cables must be pulled simultaneously to activate the jamming state. The jamming state can be activated at any bending angle, not only the straight position of the actuator. However, when pulling the cable on the other side, the actuator bends backward due to its cable routing. Thus, to activate jamming at a certain bending angle after pulling one cable, both cables must be pulled and adjusted to activate the jamming state while maintaining the same position.

In the first experiment, we tested the actuator in a straight position. To compare the actuator's stiffness, we add an 182 g weight to the end of the actuator when no cables are pulled and when pulling two cables while the actuator is still in a straight position. The results are shown in Fig.4, which show that the actuator still has a low stiffness and flexibility when not pulling the cables. In addition, when two cables are pulled, the actuator body is deformed, generating compressed force to the layer sheet and increasing the actuator's stiffness. The result shows the different displacement of the actuator with the external weight at the end of the actuator, which shows the effectiveness of the novel mechanical layer jamming in this design.

Next, we tested the actuator stiffness in the bending position. The actuator can bend to one side by pulling one cable. With only one cable pulled, the actuator has a low stiffness when adding the weight to the end of the actuator like in the previous experiment, as shown in Fig.5. Two cables need to be pulled to increase the stiffness, as mentioned before, by pulling the other side cable the actuator bends back to the other side. In the experiment, we adjusted the length of the two cables until the actuator bent to the same angle, as in the previous experiment, with only one cable pulled, and tested the stiffness by adding weight to the end of the actuator. The result shows that the actuator has a lower displacement than when only one cable is pulled, which shows the effectiveness of increased stiffness after pulling two cables simultaneously to activate the mechanical layer jamming.

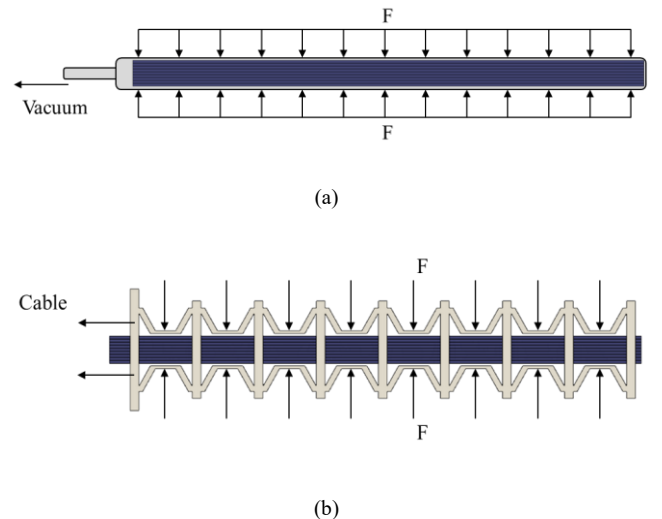


Figure 3. The jamming mechanism (a) typical design (b) our new design



(a)



(b) Jamming Off



(c) Jamming On

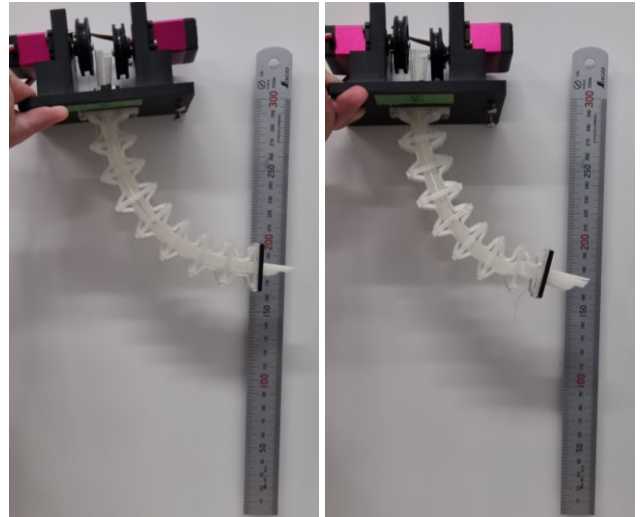
Figure 4. Actuator testing in straight position (a) initial state (b) with external load

III. SOFT GRIPPER SYSTEM

A. Design

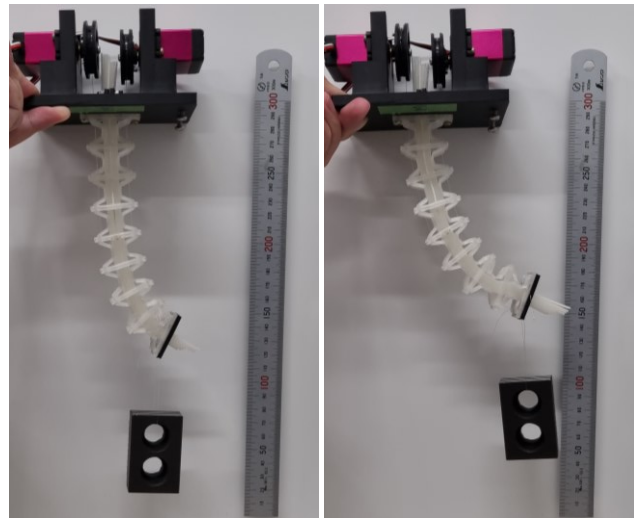
After successfully developing the soft actuator with mechanical layer jamming, we applied it to a soft gripper system. The soft actuator can adapt its shape to match the object's shape, improving the effectiveness of grasping objects. Additionally, with layer jamming, the actuator's stiffness can be adjusted. At a low stiffness state, it is safe for delicate environments, such as handling human contact or fragile objects. When set to a high-stiffness state, the carrying capacity is increased, and we can control the timing of high stiffness by activating the jamming mechanism. To ensure a firm grasp on objects, three soft actuators are used in the gripper system.

To enable the gripper to adjust its bending direction based on the object's shape, two of the soft actuators are connected to rotational bases, allowing them to rotate and change



(a) Jamming Off

(b) Jamming On



(c) Jamming Off

(d) Jamming On

Figure 5. Actuator testing in bending position (a),(b) Initial state (c),(d) with external load

bending direction, as shown in Fig.6. One actuator is connected to the base like in the previous experiment, while the other two are connected to bases that can rotate. The actuators are equally spaced 80 mm from the center and positioned 120 degrees apart from each other.

In our prototype design of the soft gripper, three actuators are used to grasp objects. Each actuator is driven by two cables connected to servo motors, with one actuator requiring two servo motors, as shown in Fig.7. Additionally, two out of the three actuators in the soft gripper are designed to rotate in their bending direction, which is controlled by servo motors connected to the base of the actuators. Therefore, these two actuators have an additional servo motor for rotation. Overall, the soft gripper system uses eight servo motors to control the movement of the three actuators.

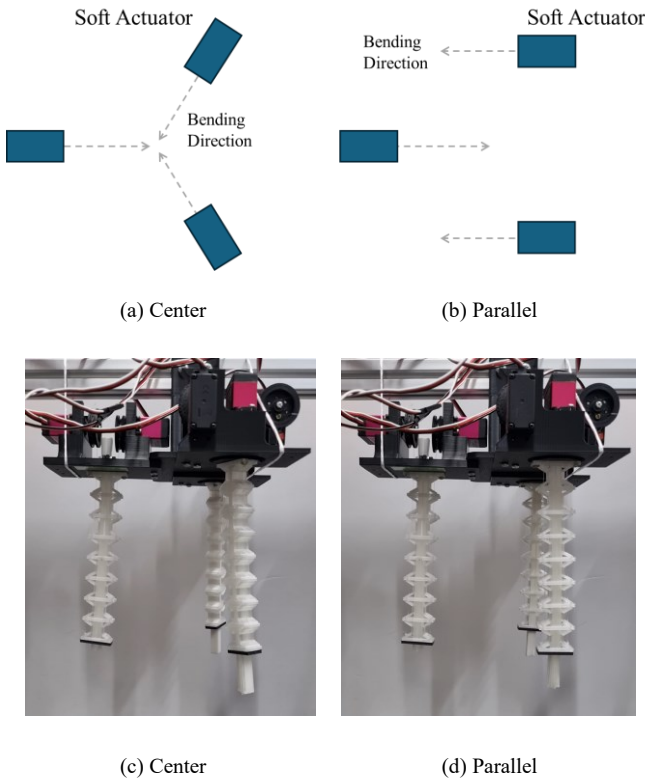


Figure 6. Actuator position when changing bending directions

B. Control System

All the servo motors are connected to the Arduino Uno, which controls the rotation angle by sending PWM signals to each servo motor. The power source for the servo motors is provided by an external power supply, as shown in Fig.8. In our prototype design, the PWM signals are controlled using potentiometers. Two potentiometers control the servo motors that bend the actuators, while one button switch is used to rotate the actuator base angle to change the actuator configuration, as mentioned earlier. One potentiometer controls all servo motors that bend the actuators toward the center of the gripper. Another potentiometer controls the servo motors to bend the actuators to the opposite side and is also used to activate the layer jamming system. Currently, our system is humanly controlled to grasp and change the actuator configuration.

C. Soft Gripper Testing

After building the soft gripper, we tested it to hold various object shapes and weights, as shown in Fig.9. With only one cable pulled, the actuator makes a curvature in which the maximum carry weight of the gripper is low, and all the actuators remain in a soft state. By pulling two cables and adjusting the bending angle of the actuators, the stiffness increases, allowing the gripper to hold heavier objects. Moreover, due to the soft actuator's ability to adapt its shape to the object, pulling only one cable causes the actuator to adapt to the object's shape. Since the actuator body is not at a constant curve shape and some deformation occurs, compression force is generated on the layer sheet, activating

the jamming state and increasing stiffness. Additionally, pulling the cable further increases stiffness as the force on the layer sheet increases with more deformation. From the experiment, we found that with appropriately shaped objects, the compression force on the layer sheet increases, increasing stiffness and enabling the gripper to carry more weight with only one cable pulled. In our experiment, the cylindrical shape could hold a weight of up to 803g without the actuator deforming and dropping the object. In the other object shape, the actuator drops the object at a lower external weight and deforms mainly in the near base section.

However, the experiment showed that due to the non-uniform compression force on each section when pulling two cables simultaneously higher at the end of the actuator where the cables are tied, sections with low compression force remain in a soft state and cannot lock shape when external weight is added. In this situation, the actuator can easily bend under external force in that section, reducing the carrying capacity, which must be improved in future designs.

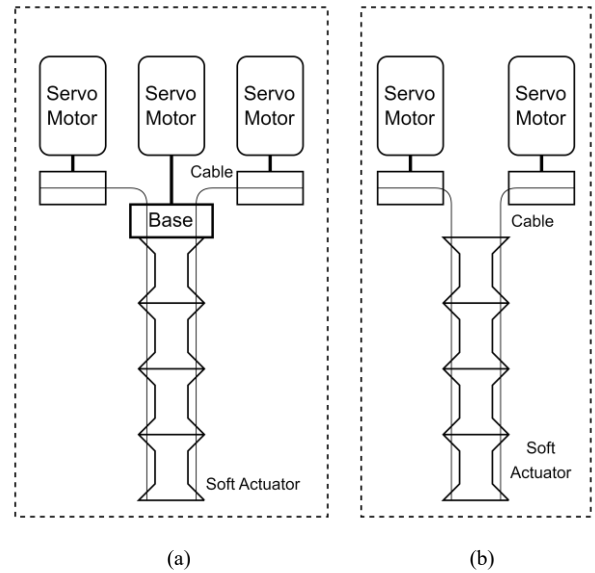


Figure 7. The gripper configuration (a) with rotational base (b) without rotational base

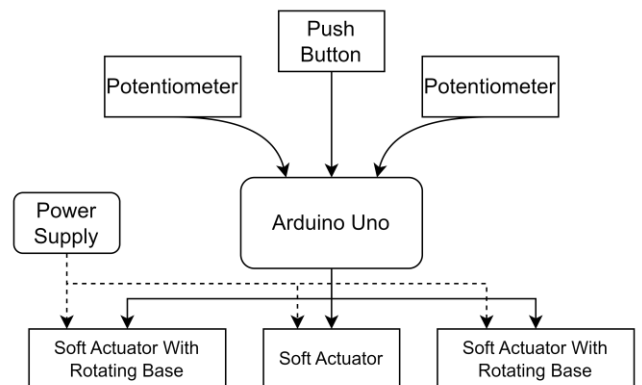


Figure 8. Control system of the gripper system

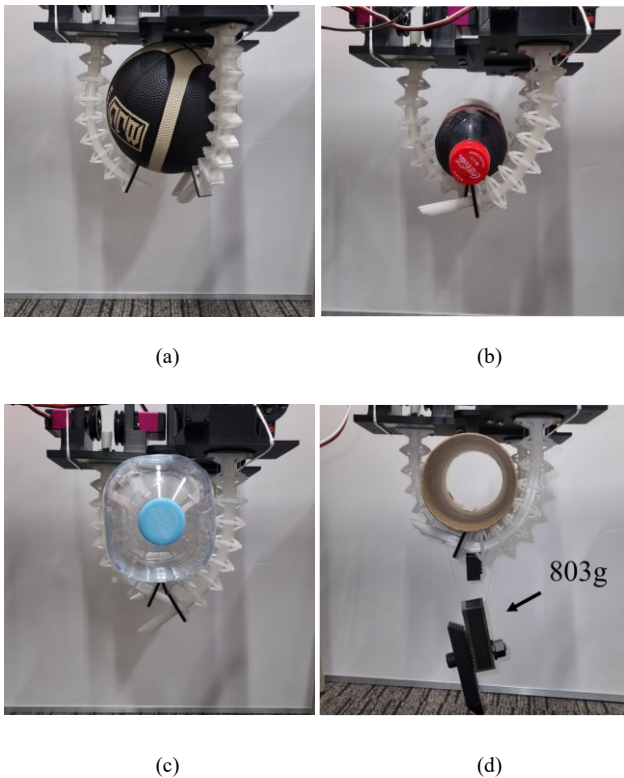


Figure 9. The result of the gripper holding different objects

IV. CONCLUSION

In this paper, we have developed and demonstrated a novel mechanical layer jamming mechanism for a cable-driven soft actuator. The prototype actuator is driven by cables connected to servo motors and can vary stiffness by activating the jamming structure. This is achieved by using the actuator body to generate compression force on the layer sheet in the middle by pulling two cables simultaneously. The results show that our structure effectively increases the stiffness of the soft actuator and reduces displacement when external weight is added to the end of the actuator.

Additionally, we applied our prototype actuator to a gripper system. In the gripper system, three soft actuators are used, and they can change their bending direction between parallel and center directions to adjust the configuration based on the object to be grasped. The results show that the maximum carry weight is 803g with a cylindrical shape. From the experiment, we also found that when the actuator changes its shape to follow the object, some actuator's body deformation occurs, activating the jamming mechanism and increasing stiffness with only one cable being pulled.

In the future, the actuator design can be optimized to maximize performance, such as by improving the materials of the actuator body and layer sheets, adjusting the thickness of the layer sheets, and increasing the number of layer sheets inserted in the middle of the actuator. Without the need for a pneumatic source, untethered designs might be easier to develop and useful in certain situations. Additionally, further

increasing the degrees of freedom of the soft actuator or adding more sections can enhance its versatility, allowing it to change posture in various ways and be used in a broader range of applications.

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