Inflatable Particle-jammed Robotic Gripper Based on Integration of Positive Pressure and Partial Filling

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Abstract

In this work, we proposed an inflatable particle-jamming gripper based on a novel grasping strategy of integrating the positive pressure and partial filling, in which the positive pressure increases the contact area between the gripper and objects, and the grain package in a partial-filled state provides significant grasping adaptation for the gripper. Firstly, we design and fabricate the inflatable particle-jamming gripper, and clarify its working mechanism. Then three kinds of grippers, including the proposed inflatable gripper, full-filled gripper and partial-filled gripper, are experimentally compared for the capability of grasping objects of various sizes and their performances from four metrics (compliance, reliability, grasping robustness and lifting efficiency) are evaluated as well. Furthermore, a theoretical analysis is carried out for different grasping performances among the three kinds of grippers, in which the inflatable gripper performs a more promising grasping performance. In this paper, by inflating the gripper to an ordered extent with positive pressure, the originally full-filled gripper turns into a partial-filled state. Based on the unique grasping strategy of the proposed gripper, it is possible to achieve a brilliant compliance and robust grasps. Even though the object is located 20mm away from the gripper-centre-axis, valid grasps are observed as well. It is concluded that the proposed gripper could potentially have a wide range of applications in the industry and daily activities.

Key words: soft robotics, jamming gripper, grasping strategy, partially-filled scheme

Introduction

Human hands have advanced dexterity in grasping objects of various shapes and sizes easily without damaging them, which has inspired many researchers in robotic grasping fields (1). A human uses hands, or technically end effectors, to achieve diverse social activities such as grasping, locomotion, and catching (2). Moreover, sensory feedbacks that have been gained through previous tasks could further ameliorate the way that a human deals with similar occurrences. In order to imitate the efficient mechanism of the human grasping, traditional humanoid robotic manipulators featured on anthropomorphism have to face the challenges such as complicated control algorithms, a wide range of joints and elements, and overly intricate sensing feedback networks (3-6). Considering their demanding cost and limited functionalities, these rigid humanoid grippers can hardly satisfy the demands from both industrial and daily life requirements.

Soft biological materials with their inherently characteristic advantage, such as brilliant compliance, versatility and dexterity, have sparked extensive research about soft grippers (7-11). Without many controllable joints and forcing sensors, soft grippers have more powerful adaptability to objects of varying shapes and sizes and can interact with unfamiliar working environment more efficiently and friendly. The main gripping technologies that soft grippers rely on are: actuation, controlled stiffness and controlled adhesion (2). Currently, soft actuators can be actuated by three prevailed techniques: pressurized fluids and compressed air(12-15), shape memory materials(e.g., shape memory alloys)(16, 17) and electroactive polymer(e.g., dielectric elastomer actuators)(18). Although these soft actuators have been applied in many aspects of human life, there are still some unsolved challenges originating from the limitations of the soft material itself. More specifically, insufficient gripping force and low resistance against an external disturbance during the grasping operation are the main problems in many aspects of daily requirements. In order to resolve this shortcoming, soft manipulators with variable stiffness, controllable adhesion, and prominent capability of conforming objects have been developed (19, 20). These grippers can passively adapt to different objects with diverse surface geometries with no need to apply high applied force. Nonetheless, improving the gripping force is still a challenge that should be tackled.

In order to improve the grasping performance, the technical combination of these three grasping technologies, such as actuation, controlled stiffness and controlled adhesion, has been applied in the process of manufacturing the soft grippers (10, 21). Brown*, et al.* (1) integrated pneumatic actuation with variable stiffness phenomenon and innovatively unveiled a universal robotic gripper based on the particle jamming mechanism. The gripper can produce a remarkable force to grasp different objects with a wide variety of shapes, sizes, and weights. It should be indicated that the variable stiffness of the grains within the elastic bag is technically called the "Granular Jamming". A wide range of variable stiffness also qualifies the gripper for grasping fragile objects with intricate surface properties such as raw eggs and foam earplugs. The simplicity of manipulating apparatus provides a path to its commercialization as well. For instance, Empire Robotic Company had launched out a series of products based on the jamming mechanism. However, further investigations showed that jamming-based technology has essential limitations (22).

The satisfactory grasping performance of the jamming gripper is mainly attributed to the friction, geometric interlocking and suction phenomenon(1). Reviewing the literature indicates that many schemes have been proposed so far to further develop the granular manipulator from different aspects, including the configuration design and jamming process. Accordingly, diverse novel manipulator designs based on the jamming mechanism have been explored so far by many researchers. Cheng*, et al.* (23) proposed a snake-shaped jamming gripper driven by a cable-driven system, which is widely applied in surgical tasks. Recently, a refreshing soft manipulator with the jamming mechanism has also been proposed (24, 25). The fibre-reinforced manipulator combined with a particle pack shows a universality of gripping objects. However, more improvement is required to enhance the grasping force. Amend and Lipson (26) proposed the multi-fingered soft robotic manipulator with two ball-typed particle-jamming packages. Inspired by pinching things with thumb and index finger, two actuators and negative pressure are applied to the gripper to catch two grain bags and grasp objects. However, this scheme has challenges originating from the complexity of the humanoid designs.

Some scholars have focused on the effects of granule properties in a purpose to boost the grasping abilities while maintaining the simplicity of the gripper and manipulating system(27). Accordingly, it is found that the threshold of the jamming process can be predominantly determined by the state of particles. Further investigations showed that compliant granular materials have a low jamming threshold while achieving a weak solid-state of the package because of the low friction between inner particles. Among all materials tested in this regard, ground coffee grains are considered as a substance with the best compliance and highest resistance to a rigid load (23). Instead of looking for more suitable particulate materials to improve the efficiency of jamming grippers, Amend, Brown, Rodenberg, Jaeger and Lipson (28) innovatively proposed a granular jamming gripper based on the positive pressure technique. With a burst of positive pressure after the gripper is jammed, the rigid grains will be reset to a fluid and loose state, which achieved a higher grasping force, pushing force and grasping error tolerance. However, due to the consecutive squeezing in vertical direction in order to cover the objects as much as possible, the applied force will increase tremendously, which could cause the counteraction against the deformity of grain bag and the growing contact areas. Consequently, this gripper only can be applied for objects with the diameter within 70% of the grain package diameter (22). Another simple and useful way to approach targets is by incorporating the partial filling technique with the jamming mechanism(29). In contrast to the conventional jamming gripper fully filled with particles, the partially filled jamming grippers have unique advantages, especially in the sampling filed under the deep sea, which greatly reduces the vertically applied force, and more delicate samples could be collected. Although the partially filled package has reasonable compliance and universality, its gripping robustness is adversely affected as the contact area reduces when the jamming occurs.

In the present study, it is intended to integrate the positive pressure and partial filling schemes and propose a universal jamming gripper, which here we called “inflatable gripper”. It should be indicated that considering the simplicity of ball-shaped grippers, this configuration will be applied in the proposed design. The application of the positive pressure equips the gripper in this article with higher dexterity and stability by inflating the gripper to a specific size instead of just modulating a short burst of air. Moreover, the originally full-filled particle package will be modified to a partially filled package with the positive pressure so that when the gripper approaches the target and is squeezed vertically, the partially filled bag of grains improves the deformity and contact area of the gripper. Once the air in the membrane is exhausted, the inflated gripper returns to its full-filled state and the grains begin to jam. Therefore, the grasping ability does not reduce by the initial filling. The transition from the partial filling to the full filling makes the gripper benefit the advantages of both traditional positive pressure jamming gripper and partial-filled jamming gripper. In order to quantify the property of the gripper in this article, we parallelize experiments with three gripper models: traditional full-filled gripper, partial-filled gripper, as well as the inflatable gripper proposed in this paper. The analysis of the improved grasping performance is conducted and comparison with novel grippers proposed by other researchers and the challenges of the inflatable gripper are also addressed. It is expected that the proposed gripper has a promising adaptability and reliable grasp so that it can have potential applications in many engineering fields.

Materials and methods

Aimed to develop a universal jamming gripper with remarkable versatility and reliability, it is intended to design and configure an inflatable jamming gripper based on the positive pressure and partial filling. Moreover, the experimental platform and manipulation are constructed to quantify the grasping performance.

Design and Fabrication

The simplest form of a jamming gripper consists of an elastic membrane containing loose particles and a vacuum-modulated system. Amend, Brown, Rodenberg, Jaeger and Lipson (28) designed the jamming gripper featured on a structure with a collar. Vertical compliance of the gripper is optimized because the collar can guide the particle package as it conforms to objects, thereby achieving greater contact areas between the jamming gripper and objects. This enables the gripper to grasp objects with higher weight and a bigger size. Amend, Cheng, Fakhouri and Culley (22) presented a mature design for the jamming gripper which could satisfy the prioritized demands of potential customers. They theoretically divided the gripper into three modules: including head, base and adaptor plate. Further investigations showed that this design has significant advantages such as high efficiency and simple assembly. With the adaptor plate, the gripper can be fixed on the majority of robotic arms with a weight varying within the range of 5 kg to 10 kg. Meanwhile, head can be replaced rapidly while other elements can remain installed, which is an outstanding point in industrial applications. It should be indicated that the proposed design consists of seven elements, which is less than the number of elements in conventional grippers. Figure 1 illustrates the physical drawing and exploded diagram of the proposed gripper.

Here, insert figure 1

Figure 1 The structure of inflatable particle-jamming robotic gripper based on the integration of positive pressure and partial filling. **(a)** Configuration of the proposed gripper. **(b)** Exploded diagram of the proposed gripper.

Figure 1 indicates that a tube connector is used to connect the air tube and is fixed to the air-port in the upper base. The positive pressure and the vacuum are adjusted through the air-port and the air can flow through the air filter while particles in the membrane cannot. Tube connector can be easily replaced, which makes it compatible with tubes in different diameters. The upper base and lower bases are assembled by four machine screws. The lower base is divided into two parts, which improves the performance of the assembled membrane. Furthermore, the ball-shaped membrane is stuck between the upper and lower bases so that it is firm and stable during the operation. Considering reasonable jamming characteristics and frequency of use of the ground coffee, it is adopted in the present study as the jamming particle (1, 23, 28).

In order to prepare the experimental prototype, bases are made of PLA by a 3-D printer. It should be indicated that several membrane materials have been evaluated (31). Amend et al. (22) found that membranes made of polychoroprene have excellent compliance with abrasive objects. Accordingly, a latex balloon is used as an elastic membrane due to its simple accessibility and acceptable properties. The thickness and weight of the ball-shaped balloon membrane is 0.26 mm and 1.5 g respectively. Then 26.0 g of ground coffee beads are enclosed in the balloon membrane. The membrane is fully filled but not stretched, which is empirically considered to make the gripper more compliant and robust. The initial diameter of the prototype in a full-filled state is

46 mm.

Inflating method and filling transition

Figure2 illustrates the inflating method and filling transition. Before the gripper approaches to the target, the original gripper is fully filled and no positive pressure is applied. When the grasping task starts, the positive pressure is executed through the tube and the air entering the membrane inflates the gripper to an ordered size. Therefore, the fully filled grain package turns into a partially filled state, in which better flowing of the ground coffee beads is observed. In the inflated condition, the gripper is pushed down to contact and cover objects. Once the contact area increases to the desired level, the vacuum is modulated until the grasping task is accomplished. The integrated positive pressure contributes not only to the transition from the full-filled state to the partial-filled state when grasping, but also causes the refluidization of the jammed particles when the grasping process is done. This is advantageous for high compliance and firm grasps of the gripper.

Here, insert figure 2

Figure 2 Schematic diagram illustrating the grasping process of the inflatable gripper. The transition of the particle package state from full filling to partial filling is actuated by the positive pressure and the jamming is achieved by modulating vacuum.

It is worthy noted that the air inside the elastic membrane should be expelled instantaneously when grasping occurs since the rebound effect of the membrane will seriously affect the grasping effect. Here, we will suppose and investigate two extreme switching cases from inflation to deflation. A parameter t was defined as the switching time from inflation to deflation. When t is close to zero, the particles inside the elastic membrane are fixed quickly before they can recover, and achieve the locking and sucking effect due to the negative pressure. When t is infinite, the gripper will slowly return to its original shape and weaken the grasping ability. Therefore, this reduction in time t is necessary for better grasping performance.

Experimental apparatus and manipulation

For the quantification purpose, the experimental platform is constructed. **Figure 3 shows** the experimental apparatus. The inflatable gripper is mounted on the force sensor (HANDPI Inc., CHN), which can measure and record the stress and tension. Then, the data can be transported to the data terminal through a data cable. The force sensor mounted on the frame records the data at 10 HZ with a resolution of 0.01N. The technical maximum force that the force sensor can allow is 200N. The motion of the force sensor is controlled by manually swinging the handle. When the swing handle is down, the gripper and the force sensor moves down together along the guide of the frame. Once the gripper contacts the object, the value of force is monitored on the screen of the force sensor and data terminal. In consideration of the average error caused by the manual control, all of the operations are performed by one person to minimize the error. The displacement sensor is mounted on the frame as well. When the gripper moves, the value of the displacement is shown in real time on the screen. Once the displacement reaches an ordered value, the movement along the guide of the frame is stopped by a braking device on the frame. The resolution of the displacement was 0.01 mm. The positive pressure is produced by an air pump, which can supply the positive pressure at a flow rate of 165L/min. The air pump is directly connected to a pressure regulator. The regulator was in charge of the switch between positive pressure and negative pressure, regulating the pressure value and releasing the pressure. The vacuum pressure it can modulate is within the range of 0 kPa to -90 kPa. Empirically, the particle package is jammed under -85 kPa negative pressure and is inflated to 120% of its original size by regulating the positive pressure. The real-time pressure is displayed on the regulator screen.

Here, insert figure 3

Figure 3 Schematic diagram of the experimental apparatus. The test platform is composed of a force sensor, a displacement sensor, the inflatable gripper apparatus, objects, data terminal, an air pump and a pressure regulator. The applied force and pulling force are measured with the force sensor connected to data terminal and the real-time force changing curve can be shown on the screen, and the displacement is recorded by the displacement sensor. Both the positive pressure and negative pressure are regulated by the pressure regulator. Objects are placed in the placement area.

In order to investigate the performance of the inflatable gripper, two other different grippers are tested in parallel as reference. As seen in **Figure 4 (a)**, no air flow is sent into the conventional full-filled gripper in red colour before it approaches the target. The membrane in a natural while not very stretched state has a diameter of 46 mm. It should be indicated that 26 grams of ground coffee beads are enclosed in the bag. The membrane of the partial-filled gripper in green colour is filled with 26 grams of ground coffee beads as well, while the diameter of the membrane in the natural state is 55 mm, 120% of the diameter of the conventional full-filled gripper. The membrane is slack and many folds are distributed on the surface of the membrane as shown in **Figure 4 (a)**. The whole particle bag drops down under the gravity. Therefore, an air volume is formed near to the lower base of the cap. The inflatable gripper proposed in this study is also filled 26 grams of ground coffee beads. As the positive pressure isn't executed, the size is the same as the conventional full-filled gripper and the diameter is 46mm. When the positive pressure is modulated, air is sent into the gripper and the membrane is inflated until the diameter turns into 55 mm, 120% of its original size. Unlike the partial-filled gripper, the membrane becomes tense and no fold is found on the surface. The grains flow down under the gravity while the gripper is still ball-shaped. It should be indicated that membranes of all grippers are used in latex balloon membrane and grippers are all reset by executing an air burst at 8 kPa for 2 s.

Clarifying all the grasping mechanisms mentioned in (1) could be prohibitively challenging and demanding especially for an irregular object. To simplify the researching works and make the experiments more practicable, the objects with special shape and texture were designed. In our experiment, cylinder-shaped samples are selected and printed by 3D printer with plastic. The simple objects with cylindered shape eliminated the possibility of forming interlocking phenomenon when the gripper conforms the objects vertically and the inherent surface texture of printed objects is not smooth enough to make an airtight seal around the contact area, which exclude the contribution from the suction mechanism. Therefore, only the friction mechanism is reserved. The test objects are all cylinder-shaped with with the height of 17 mm. Moreover, their diameter ranges from 9.2mm to 55.2mm, which corresponds to the range from 20% to 120% of the original gripper diameter of 46mm. The sample objects are shown in **Figure 4 (b)**.

During the experiment, the lowering and rising of the gripper are controlled by the swing handle. **Figure 5** shows that when the handle is pushed down, the gripper slowly nears the object and rests on it. The applied force is measured by the force sensor connected to the gripper. Since the sensor is reset to 0 after the gripper is hung on the manipulator, the force displayed on the screen is the one gripper has produced. Once the ordered displacement reaches, the gripper stops and the maximum applied force among all the data that has been collected is regarded as the final applied force in every single trial. Objects can be placed or fixed on the placement board, in line with the centre axis of the gripper. When the object is just placed on the board, the jammed gripper rising can grasp the target upward. **Figure 2** shows that when the object is picked up and held in the air for 10s, the grasp is considered successful. When the object is fixed firmly on the board, the jammed gripper moves up and the pulling force shown on the force sensor screen will keep increasing until the gripper loses the contact with the object. The maximum force during this process is considered as the valid pull-off force. For each test, the three different grippers all move from the height of H_1 to H_2. Figure 5 shows that H_1 and H_2 are the distance between the lowest tip point on the lower base and horizontal placement board respectively. H_1 is 63mm and H_2 is 30mm. The moving distance of three grippers is defined as the displacement of H_1 grippers and the displacement of gripper in most of experiments conducted in this paper is $H_1 - H_2 = 33mm$, if there is not a special note to the figure.

Here, insert figure 4

Figure 4 Diagram of three different grippers and sample objects. **(a)** The inner and outer condition of the three grippers. The left gripper with the red membrane is the conventional full-filled gripper. The middle one with the blue membrane is the novel inflatable gripper. The right one with the green membrane is the partial-filled gripper. **(b)** The sample objects. The diameter of objects from left to right ranges from 9.2 mm to 55.2 mm, 20% to 120% of the original gripper diameter which is 46 mm.

Here, insert figure 5

Figure 5 The schematic process of the experimental manipulation. The raising and lowering of grippers are controlled by swinging the handle. The applied force is recorded until the gripper is jammed. When the jammed gripper rises, the pull-off force will be shown on the screen until it loses the contact area with the object in the situation where the object is fixed on the board. Three different types of grippers operate d in the same way and drop down from to H_2.

Results

The performance of the inflatable jammin H_1 g gripper integrated positive pressure and partial filling are is investigated considering the following factors: compliance, reliability, grasping robustness and lifting efficiency.

Compliance

The compliance represents the ability of the soft gripper to deform and adapt to unfamiliar objects with complicated geometry. In this paper, the applied force that grippers produce when they conformed to objects is recorded to evaluate the compliance of the proposed gripper. The test result is presented in **Figure 6**. Eleven cylinder-shaped objects are tested, with the diameter ranging from 9.2 mm to 55.2 mm. However, the horizontal coordinate is presented in the form of a percentage of the original inflatable gripper diameter for a clear elucidation of the relationship between objects and grippers in size(1). It is observed that the applied force produced by the full-filled gripper is much higher than the force produced by the inflatable gripper and the partial-filled gripper. Moreover, the force produced by the inflatable gripper and the partial-filled gripper both grow moderately.. The force of full-filled gripper doesn't increase sharply when contacting the objects within 40% of the diameter. A striking surge appears when the diameter of objects exceeds the 40% of the size. However, intriguingly, the curve tends to level off after the object diameter reaches about 70% of the gripper diameter.

Here, insert figure 6

Figure 6 The applied force produced by three different grippers when contacting to objects in different sizes. All the data points shown in the figure represent the average value recorded from 30 trials. And the error bars indicate the standard deviation (SD for short) of applied force values of 30 trials.

Reliability

In this test, the reliability is evaluated by three parameters: (1) versatility which is represented by the success rate of grasping objects with variable size, (2) error tolerance which is represented by the success rate of grasping objects in a variable displacement off the central axis of the gripper and (3) practicability. Test results from (1) versatility and (2) error tolerance are shown in **Figure 7**. A successful grasp occurs when the gripper can pick up the target and hold it in the air for 10s, It should be indicated that the grasping versatility of the gripper is investigated with this parameter. From **Figure 7(a)** the inflatable gripper shows a preferable grasping success rate than grippers that are fully filled and partially filled, especially when grasping the objects with the size larger than 80% of the diameter. When the object diameter is 100% of full-filled gripper diameter, the inflatable gripper can remain 100% of the grasping success rate, while the other two grippers cannot achieve any successful grasp in 30 trials. Moreover, it is observed that the sharp plunge occurs in both full-filed and partial-filled grippers when objects are in a size of 60% of the gripper diameter while the turning point appears in a size of 100% of the diameter for the inflatable gripper. The error tolerance indicates the capability against error placement of the target. Only the error tolerance of the object in a size of 50% of the diameter is plotted in **Figure 6(b)**. As we can see, inferior to the inflatable gripper, the successful grasping rate of full-filled gripper and partial-filled gripper begins to fall when the off-centre-axis distance is 10 mm and falls to 0% when the distance reaches to 30 mm. It can be observed that the efficient grasp can still be conducted even when the object is in a displacement of 25 mm away from the central axis. This secures the grasping performance even if the precise control system of the robotic arm and the timely sensing feedback are not available.

We also notice that in the real application, the grippers cannot always conform the object only in vertical direction. Instead, it is more frequent to ask the grippe to grasp the object in different directions other than vertical direction. Therefore, the experiments are conducted to explore the practicability of the proposed gripper. In the first experiment, the center axis of the object was set to be deviated from the center axis of the gripper and the deviating degree is 30 degree. The gripper still conforms the object in vertical direction, as shown in Figure 8(a). In the second added experiment, we make the gripper conform the object in other direction other than vertical direction, while the center axis of the object is in line with the direction of gravity. The deviating degree between the center axis of the gripper and that of the object is still 30 degree, as shown in Figure 8(b). It turned out that the grasping failure was not occurred in both experiments. Though the ground coffee beads may cannot be distributed evenly around the object because of the gravity in the second experiment, it is noteworthy that the satisfying grasping performance of the inflated gripper was achieved as well.

Here, insert figure 7

Figure 7 Test results of grasping with different size of object and position. **(a)** Success rate of grasping sample objects with variable sizes. **(b)** Success rate of grasping the target located in a series of off-centre-axis displacements. Only the result from the object of 50% of the diameter is shown. All the data points shown in the figure represent the average of statistics recorded from 30 trials.

Here, insert figure 8

Figure 8. Grasping object with deviating degree between centre axis of object and inflated gripper. The object with 50% of the diameter of the gripper was selected. **(a)** the center axis of the object deviated from the center axis of the gripper and the deviating degree is 30 degree. The gripper still conforms the object in vertical direction. **(b)** the gripper conforms the object in other direction other than vertical direction, while the center axis of the object is in line with the direction of gravity. The deviating degree between the center axis of the gripper and that of the object is 30 degree.

Grasping robustness

Robustness, as a dominant parameter to evaluate the ability of grasping objects and resisting against the external load, is explored by measuring the pull-off force in this experiment. The pull-off force produced by the inflatable gripper is superior to that produced by the full-filled gripper and partial-filled gripper, no matter from the maximum force it can make or from the range it can generate grasping force. We can see from **Figure 9(a)**, the maximum force from inflatable gripper is 38.06±2.52N, which is more than 10 times higher than the maximum force of 3.63±5.53N, produced by the partial-filled gripper and is more than 1.6 times higher than higher than the maximum force of 23.59±1.72N produced by the full-filled gripper. It is found that for all tested sample objects, the force produced by the inflatable gripper is higher than that produced by the partial gripper and the full-filled gripper, except the object in 60% of the diameter. The grasping results from the inflatable gripper turns to more promising especially when the size of objects is larger than 80% of the diameter, while the force produced by other grippers almost falls to 0. The error bars represent a fluctuating level of grasping force around the mean value that is calculated from 30 trials. It is worth noting that a stable grasping performance is observed upon the inflatable gripper among the error bars.

Here, insert figure 9

Figure 9 Force test results under different sizes and displacements. **(a)** The result of the pull-off force from three different grippers**, the** displacement of gripper in the tests is $H_1 - H_2 = 33mm$. **(b)** Ratio of pull-off force to the applied force. The x-axis in Figure 9(b) represents the moving distance between H_1 and H_2. By changing the value of H_2, the displacement of gripper $H_1 - H_2$ is varied from 20mm to 50mm. The sample object is used in 50% of full-filled gripper diameter. All the data points shown in the figure represent the average value recorded from 30 trials and error bars indicate the SD of experimental values recorded.

Lifting efficiency

It is commonly known that achieving a higher grasping force usually requires a higher applied force(22). The grasping efficiency is defined as the numerical correlation between the pull-off force and the applied force. Moreover, a grasp with low applied force while inducing high lifting force is defined as high lifting efficiency. In this test, we individually demonstrate the grasping efficiency through exploring the ratio of the pull-off force to applied force as shown in **Figure 9(b)**. It is observed the ratio increases from zero as displacement grows and peaks arrestingly at a value of 1.54. Moreover, it is found that the applied force keeps increasing steadily, while the pull-off force almost stops growing when the displacement reaches to 40 mm, which results in the reduction of the ratio between the pull-off force and the applied force.

Discussion

Based on the experimental results have presented, we try to explore mechanisms behind the performance and the potential adoption in the future systematically from following expansions.

1. For a specific particle material, the applied force is independent of the volume that the object can take up from the particle package and the compliance of the gripper.
2. Grasping strength is proportional to the efficient contact area.
3. Reasonable grasping performance of the inflatable gripper could have the potential to be used in a wide range of applications in many industries.
4. Properties of the elastic membrane and the inflated extent of the inflatable gripper are still a cannot-be-overlooked investigation in the future.

Analysis for the performance

1. For a specific particle material, the applied force is independent of the volume that the object can take up from the particle package and the compliance of the gripper.

In all groups of the carried out experiment, the design of three grain bags is ball-shaped. The most advantage of this design of it is its structural simplicity and accessible fabrication. However, with this ball-shaped design, the deformation of the particle packed is limited by the surrounding membrane and the cap of the lower base, which stops interior grains inside from further deforming. Consequently, the applied force can significantly increase as the gripper deforms more obviously and a bigger package volume occupied by the sample object. Since the sample objects in the carried out tests are cylinder-shaped, the volume it takes is proportional to the circular contacting area in the vertical direction and the displacement that the package covers the object. When the gripper rests on the object and covers it, the interaction between the deforming package and the object can be elucidated as two contacting models: shearing grains off the whole package and compressing grains against the lower base in the normal direction. The amount of grains sheared from the whole package is subjected to the circular contacting area and the extent that gains can be compressed is determined by gripper displacement. Therefore, the applied force should include two forces generated from these two models, which is mathematically expressed as follows:

$$F = F_s + F_c \tag{1}$$

Where, F is the applied force. Moreover, F_s and F_c denote the shear force and the vertical compressing force, respectively.

The shear force F_s required to cause particle disengaging from the package should vary with the shear area, A_{shear}, and the final shear strength of the material, τ, as shown in **Figure 10**. The shear force is described as follows:

$$F_s = \tau A_{shear} \tag{2}$$

The vertical compressing force F_c to push grains upward should be proportional to the contact area in normal direction, $A_{compress}$, and the ultimate normal strength of the material, as shown in **Figure 10**. Therefore, the vertical compressing force is mathematically expressed as following:

$$F_c = \sigma A_{compress} \tag{3}$$

Correspondingly, the shear area A_{shear} is the contact area around the cylinder-shaped object's side and the normal contact area $A_{compress}$ is the bottom surface of the cylinder-shaped object, respectively. Moreover, it is assumed the displacement of the gripper $H_1 - H_2$ is the depth x that object stuck in particle package (Where $x \leq H_1 - H_2$, because there is still a distance before the operation starts). The A_{shear} and $A_{compress}$ can be described as:

$$A_{shear} = \pi dx \tag{4}$$

$$A_{compress} = \frac{\pi}{4} d^2 \tag{5}$$

Where d and x are the diameter of the sample object and the displacement of the gripper, respectively.
From equations (1-5), the following equation is obtained:

$$\left.\begin{aligned} &F_s = \tau A_{shear} \\ &F_c = \sigma A_{compress} \\ &A_{shear} = \pi dx \\ &A_{compress} = \frac{\pi}{4} d^2 \\ &F = F_s + F_c \end{aligned}\right\} \Rightarrow F = \tau \pi dx + \sigma \frac{\pi}{4} d^2 \tag{6}$$

Here, insert figure 10

Figure 10 The schematic of the parameters involved in equation (6).

We assume that the particle package is an elastic medium. Apparently, shear stress and normal stress s grow with increased stiffness of the particle package. In line with the definition of stiffness, the stiffness level of the gripper can be indicated by the slope of the curve of applied force versus displacement. (31) Therefore, shear stress t and normal stress s should be the function of displacement *τ(x)* and *σ(x)*. However, since the displacement in our tests is all given to $x = H_1 - H_2$, and the particle material in three grippers is τ ground coffee beads, displacement x, shear stress τ and normal stress σ should be a constant for a given displacement x. Therefore, equation (6) presents that the applied force is only affected by the diameter of objects, and the bigger size of the objects grows, the higher force will be applied, which is consistent with the result that we obtained in our experiments, shown in **Figure 6**.

However, with equation (6), we cannot adequately explain why there is an intriguing levelling-off in the curve of the full-filled gripper presented in **Figure 6**. A possible explanation for this unconformity lies in the limitation of the package deformation. As the size of the object increases, it is more difficult for the gripper to cover around the object as we observed during the tests. When the size of the object reaches to a threshold, the full-filled gripper cannot even achieve a shear contact area and the valid normal contact area reaches to its maximum as well, even though the size of the object becomes larger, which results in the levelling-off of the full-filled gripper.

For a given gasping task, the size of the object is often ordered and the size cannot be changed to reduce the applied force. We can see the promising performance in applied force applied by the partial-filled gripper and inflatable gripper in **Figure 6**. The possible reason for it is their low shear stress τ and normal stress σ, which are influenced by the stiffness of the particle package. In order to investigate the stiffness difference technically and explore why there is an obvious different grasping performance among three grippers, we quantified the applied force as a function of displacement. Three grippers were used to conform the object with 50% of the gripper diameter and different applied force was recorded as the displacement x changed. Some snapshots from the experiments are shown in **Figure 11**. We fitted the experimental results as $F_1 = 2.541e^{(0.168x)}$, $F_2 = 2.273e^{(0.052x)}$ and $F_3 = 0.002e^{(0.353x)}$ for corresponding grippers based on the changing tendency of the data we collected as shown in **Figure 10(a)**. However, the exponential tendency of the curves we fit may contradict against the equation (6) which shows that F is linearly proportional to x when the diameter of object is ordered. It can be explained that shear stress τ and normal stress σ are the function of displacement *τ(x)* and *σ(x)*. With the displacement x changed, shear stress τ and normal stress σ could be increased dramatically, which could cause the exponential increasing of applied force as displacement increased. According to the definition of stiffness where the displacement should begin with the height that gripper touches object at the very beginning, the displacement $H_1 - H_2 = 33mm$ we illustrated for the three grippers before is corresponding to $x_1 = 21mm$ for full-filled gripper, $x_2 = 25mm$ for inflatable gripper and $x_3 = 25mm$ for partial gripper. From the slope of three fitting curves where $\frac{dF_1(x_1)}{dx} = 14.54$, $\frac{dF_2(x_2)}{dx} = 6.77$ and $\frac{dF_3(x_3)}{dx} = 0.32$, we can see that the slope of the full-filled gripper could even be more 45-folds than that of the inflatable gripper. Therefore, the stiffness of the full-filled gripper is much higher than that of the other methods in accordance of the definition of stiffness we discussed before, which could explain why the compliance ability of inflatable gripper and partial gripper performed in Figure 6 is more promising.

2. Grasping strength is proportional to the efficient contact area.

Since the geometrical interlock mechanism and suction effect do not contribute to the grasping performance in the tests, the only parameter determining the grasping force F_g is the friction mechanism F_f . Then, $F_g = F_f$ is obtained. When the negative pressure is executed, the jammed grains will contract the object around the side contact area, which generates a stress σ^* over the efficient contact surface(1). The intense contradiction is achieved by modulating the strong vacuum. We assume that σ^* is proportional to the jamming pressure P_j, and can be formulated as $\sigma^* = kP_j$, where k is the coefficient of quantifying the relationship between σ^* and P_j , usually $k \le 1$ (31). Considering the cylinder-shaped sample objects, the efficient contact area A should be equal to the shear area A_{shear} based on the assumption that the contacting area doesn't change during the lifting process. Therefore we have $A = \pi dx$. The normal force, $F_n = \sigma^* A = kP_j \pi dx$, results in the friction F_f against the weight of the object. From definition of friction force F_f , $F_f = \mu F_n$ where μ is the static coefficient of the contact surface. Then, the following equation is obtained:

$$F_g = \mu k P_j \pi dx \qquad (7)$$

For the jamming pressure, $P_j = 85kPa$, the modulating coefficient k should be a constant, same as μ and x. With equation (7), the grasping force is as a function of the diameter of objects. As the diameter of the object increases, the grasping force increases as well, this could explain the upward trajectory of the curves in **Figure 9(a)**. However, equation (7) contradicts against the following steep plunge shown in **Figure 9(a)**. A potential explanation for these highlights the maximum shear area that can be achieved during the grasping process. Due to the same reason, the grasping force stops increasing as illustrated in **Figure 9(b)**.

A significant advantage of the inflatable gripper is that it can form a bigger maximum valid contact area for a specific displacement, compared to the full-filled gripper and the partial-filled gripper. As the gripper rests on an object, the particle bag is compressed as well. The positive air inside the membrane is condensed, consequently, which causes the particle bag inflate around further, and achieve a bigger contact area which doesn't happen in the partial-filled gripper. Therefore, the increased size of the bag cover objects with larger size and heavier weight. Even when the location of an object is farther away from the centre-axis of the gripper, a successful grasp can still be performed.

Here, insert figure 11

Figure 11 Snapshots from experiment of exploring the correlation between the pull-off force and displacement. **(a)** The variation of the pull-off force versus the displacement from the full-filled gripper. **(b)** The variation of the pull-off force versus the displacement from partial-filled gripper. **(c)** The variation of the pull-off force versus the displacement from the inflatable gripper.

Discussion for future application and challenges

3. Promising grasping performance of the inflatable gripper could has the potential to be used in **a wide range of applications in many industries.**

From the test results, it is found that the inflatable gripper outperforms the other two grippers presented in this study considering the parameters of compliance, versatility or grasping reliability. And it is noteworthy that the promising grasping performance is not merely in vertical direction. The satisfying grasping performance was achieved as well when grasping in directions other than the vertical direction. One possible explanation for it may due to the interlock mechanism introduced by the operation from different directions other than vertical direction. In order to evaluate the gripper more comprehensively, it is intended to compare soft grippers that have been presented by other researchers recently. However, comparing grippers based on different technologies with a unified grasping criterion could be prohibitively challenging for us, as scholars could customize a unique standard to make assessment in accordance to the specialities of their grippers, which leads to quite limited statistics for researchers to compare(28). In this study, the range of the selected grippers is narrowed down and eight parameters are filtrated that are commonly adopted to evaluate grippers by scholars and can reflect the grasping performance objectively as well. As shown in **Table 1**, apart from the inflatable gripper proposed in this paper, three grippers based on the jamming mechanism (shown in orange colour) and four grippers based on other technologies (shown in blue colour) are selected. The available performance values show that the inflatable gripper has an advantage considering its reasonable compliance and robust grasp. The weight and the original diameter of the inflatable gripper are just 27.5 grams and 46mm, respectively, which are obviously smaller than most grippers presented in this study. However, the pull-off force that it can produce does not underperform other grippers. We use the ratio of full-off force to gripper weight to act as an evaluating parameter of grasping ability as a gripper with heavier weight tends to have a more promising grasp. The inflatable gripper with a ratio of 141.00 is better than other grippers presented here, such as Printable Pneumatic Actuator with the ratio of 18.42, which has been considered as the quite preferable gripper(32). Additionally, the proposed gripper here is an early prototype, and the maximum grasping force it can make excludes the attribution from the suction phenomenon and especially geometry interlock mechanism which plays a significant role in grasp when the gripper totally covers the object. Therefore, the inflatable gripper can be potentially competent at many industries in the future.

Table 1 Comparison of the grasping performance among different grippers.

Here, insert table 1

Note: Values in the table do not reflect the exactly optimized performance for each gripper. However, the most satisfactory results are presented in the corresponding paper (11, 15, 18, 22, 23, 32, 33). N/A is not applicable for short. Object size and error tolerance are quantified as the same as what has been described in this study.

4. Properties of the elastic membrane and the inflated extent of the inflatable gripper are still a cannot-be-overlooked investigation in the future.

Although the promising grasping performance has been displayed by the inflatable gripper in our test, we have to admit that some functional loss is caused by the applied positive pressure as well and there are still challenges for the proposed gripper.

For an effective operation of inflatable gripper, the grain bag must be inflated by executing positive air into it and be condensed by the modulating vacuum, which could easily result in the fatigue failure of the membrane, as shown in **Figure 12(a)**. Investigating for the suitable material of the membrane with higher resistance against fatigue failure is a necessary future research.

Apart from exploring the grasping ability of the inflatable gripper which is inflated to 120% of the size of the full-filled gripper, an experiment is conducted to discuss the correlation between the pull-off force and the inflatable extent of the gripper. **Figure 12(b)** shows that although the grasping force grows as the extent of inflation increases, there is still a levelling-off. Furthermore, although the successful grasp of the tiny objects can be observed, it is noticed that the grasping enhancement towards the tiny objects is not as satisfying as that towards objects with larger size when adding positive pressure to inflate the gripper to different sizes as indicated in our experiments. Therefore, when grasping objects with different size investigating the specific inflated extent is significant for improving the grasping performance and optimizing the economic benefits.

Here, insert figure 12

Figure 12 Force test results under different displacements and inflated extents. **(a)** Curve fitting of the applied force versus displacement. Three functions are fitted with 95% confidence. The marker points (25.97,214.53) and (32.61,200.55) are the test values shown in **Figure 9 (b)** Result of pull-off force versus inflated extent of the gripper. As the inflatable extent increases the pull-off force increases and then levels off. Only the results from sample objects with 100% and 40% diameter are displayed.

Conclusion

In this effort, an inflatable particle-jamming gripper based on a novel grasping strategy of integrating the positive pressure and partial filling is proposed. The cooperated design equips the inflatable gripper with reasonable compliance and promising grasping robustness. The inflation of the gripper is impelled by the executing positive pressure. Therefore, the originally full-filled gripper turns into the partially filled gripper. The positive pressure causes a higher limitation of the deformation when gripper rests on objects, which qualifies the inflatable gripper to achieve a larger efficient contact area for a specific displacement. The grains in partial-filled state show a preferred capability of flowing, resulting in a low-threshold deformation and adaptability. Three grippers are tested to quantify the grasping performance from four aspects. Compared with the full-gripper and the partial-filled gripper, the proposed gripper shows reasonable performance in compliance, reliability, grasping robustness and lifting efficiency. When grasping a series of objects with variable sizes, the inflatable gripper is more capable of lifting the sample with a larger diameter and apt to generate a higher grasping force successfully. Even when the location of object is 20mm away from the central axis of the gripper, a valid grasp can be made as well. Therefore, a looser requirement of precision for robotic arms to control the manipulator is required. Another benefit of the proposed gripper is its structural simplicity and accessible fabrication. Moreover, design of separating the lower base into two parts makes the membrane be assembled easily and firmly.

It is worth noting that although the inflatable gripper has performed well in several experimental metrics, the proposed gripper is still an experimental prototype and there are some problems to be addressed. For instance, the inflatable gripper still cannot lift flat objects up efficiently, which is the main weakness for such ball-shaped jamming grippers. Moreover, it is found that inflating and jamming the gripper can speed up the process of the fatigue failure of the membrane. Moreover, how to automatically balance the inflated extent and objects in different sizes to induce the optimized grasping and economic performance is a challenging issue. It is our hope that the present study can motivate more researches on the issue of the jamming gripper. Therefore, inflatable gripper can be potentially superior at service from industry and daily activities in the future.

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Author Disclosure Statement

No competing financial interest exist.

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Table 1

Grippers based on jamming mechanism
Grippers based on other grasping technology

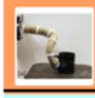
	Gripper	Weight of Manipulator (g)	Size of Manipulator (mm)	Applied Force (N)	Pull-off Force (N)	Object Size (%Gripper diameter)	Error Tolerance (%Gripper diameter)	Ratio of Pull-force to Weight	Responding Time(s)
	Inflatable Gripper	27.5	d=46	6-35	>38	~20%-110%	<65%	141.00	~0.1
	Commercialized Jamming Gripper (22)	600	d=90	22-66	~44	~30%-70%	unknown	7.48	0.1
	Partial Jamming Gripper at Deep Sea (33)	unknown	d=75	<5	~20	unknown	unknown	unknown	unknown
	Cable-driven Jamming Gripper (23)	345	l=380	N/A	~7.5	N/A	N/A	2.22	0.2
	RBO Hand 2 (11)	178	~human hand	unknown	~5	N/A	N/A	2.87	unknown
	Printable Pneumatic Actuator (34)	277	unknown	N/A	~50	N/A	N/A	18.42	<0.4
	Dielectric Elastomer Actuator (18)	0.6	unknown	unknown	~0.1	N/A	N/A	17.01	unknown
	Starfish Gripper (15)	unknown	l=90/140	unknown	~3	unknown	unknown	unknown	unknown

Figure 1

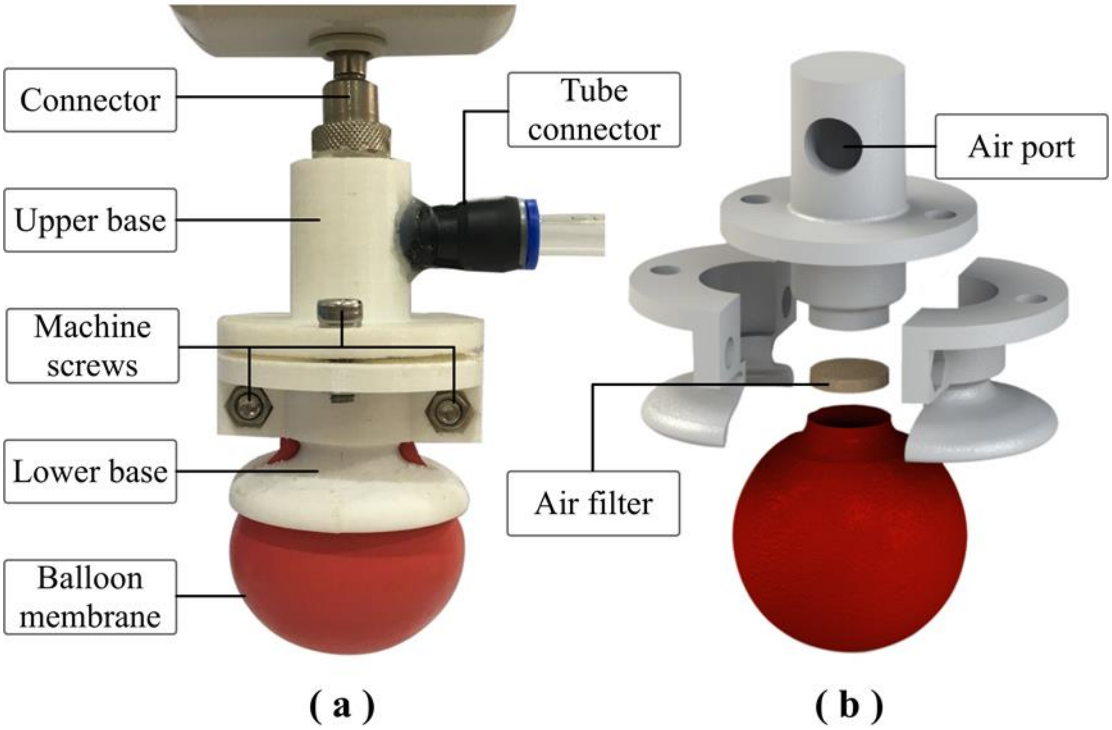


Figure 2

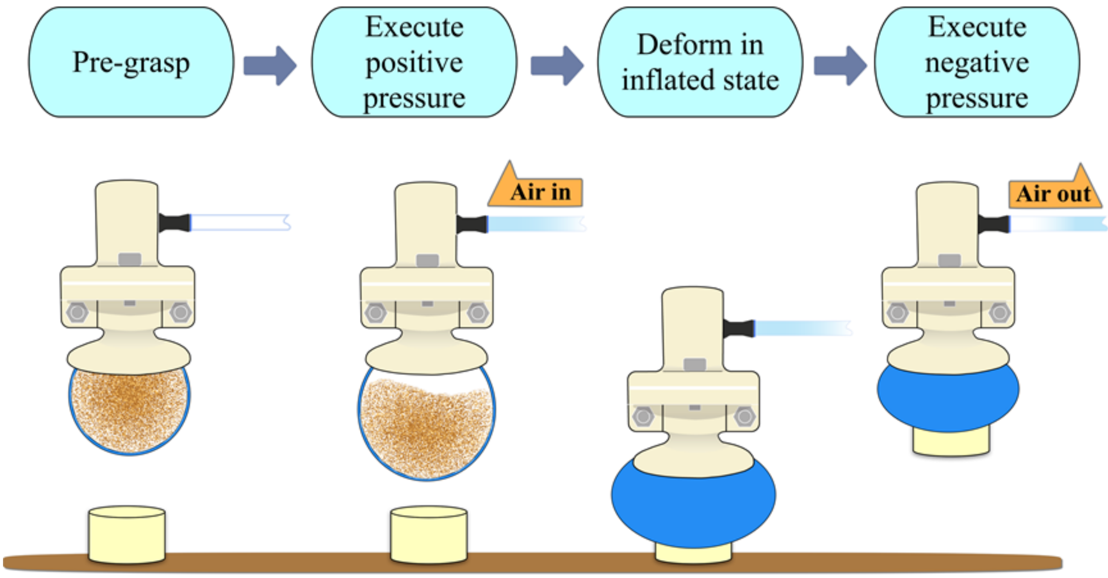


Figure 3

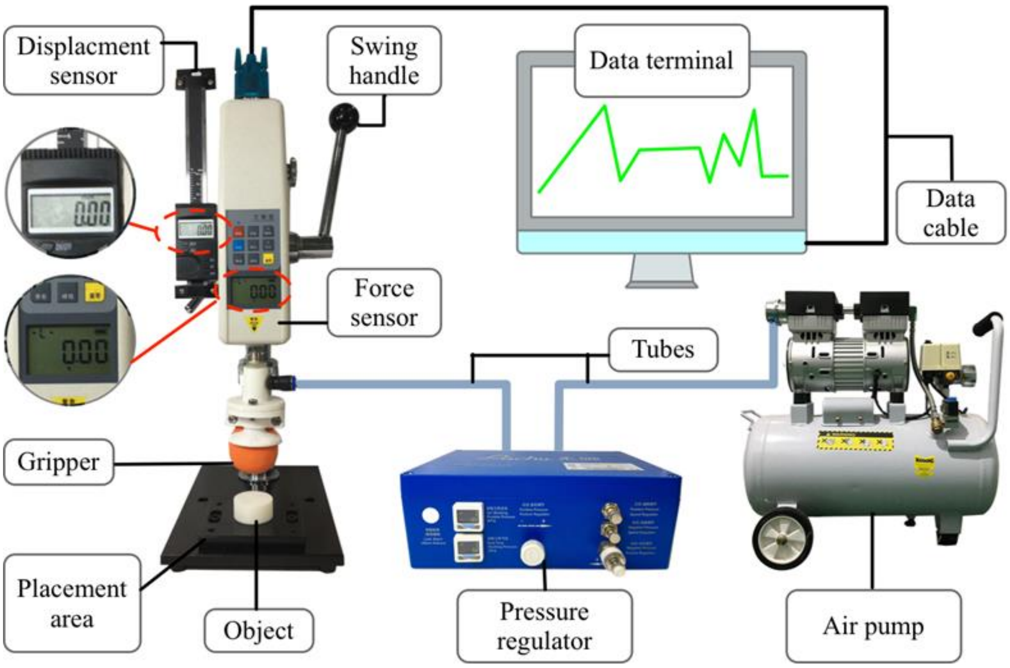


Figure 4

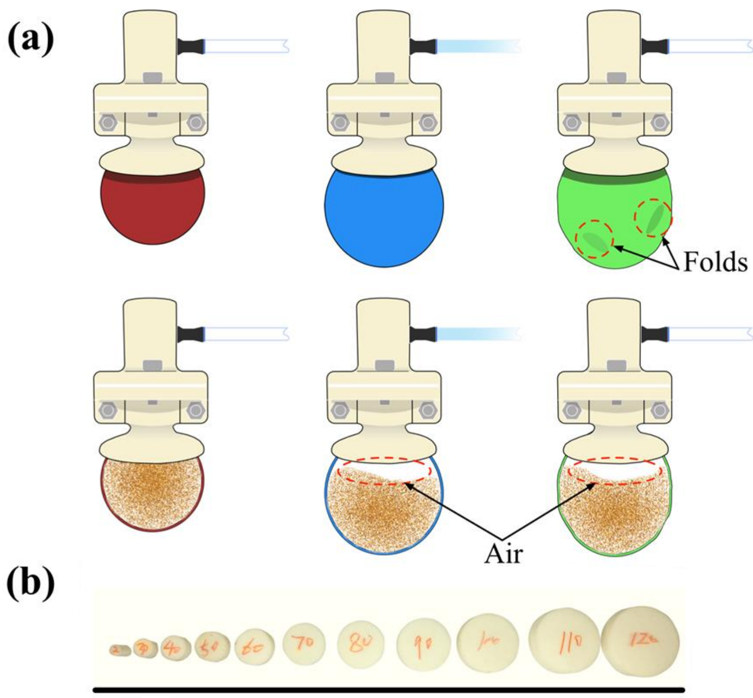


Figure 5

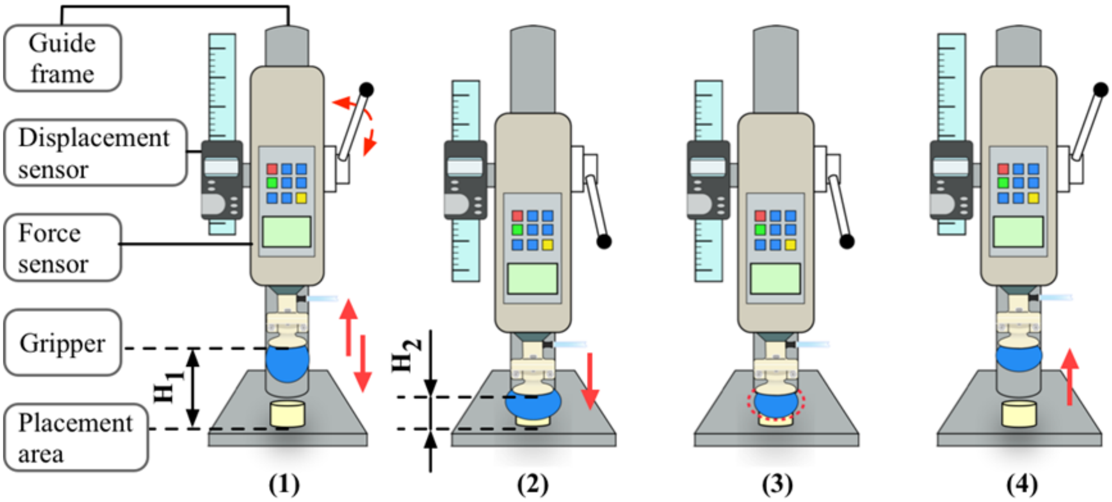


Figure 6

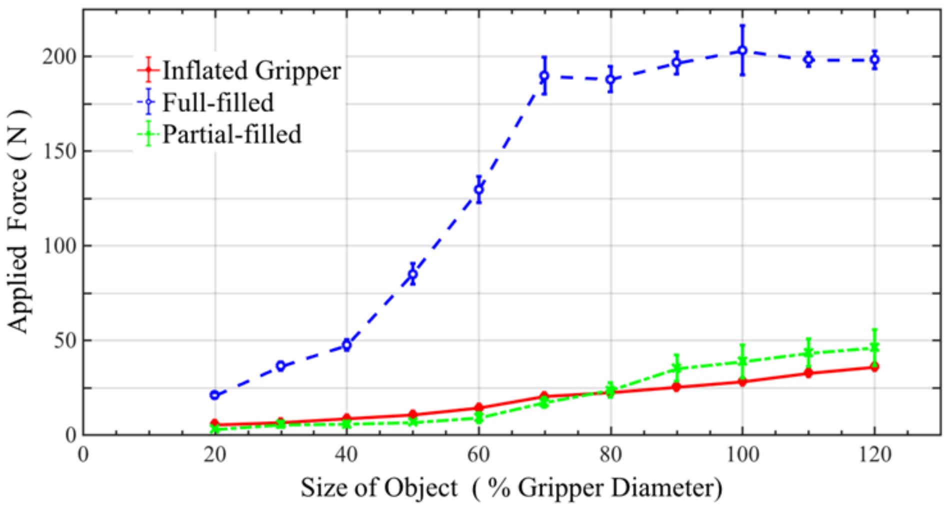
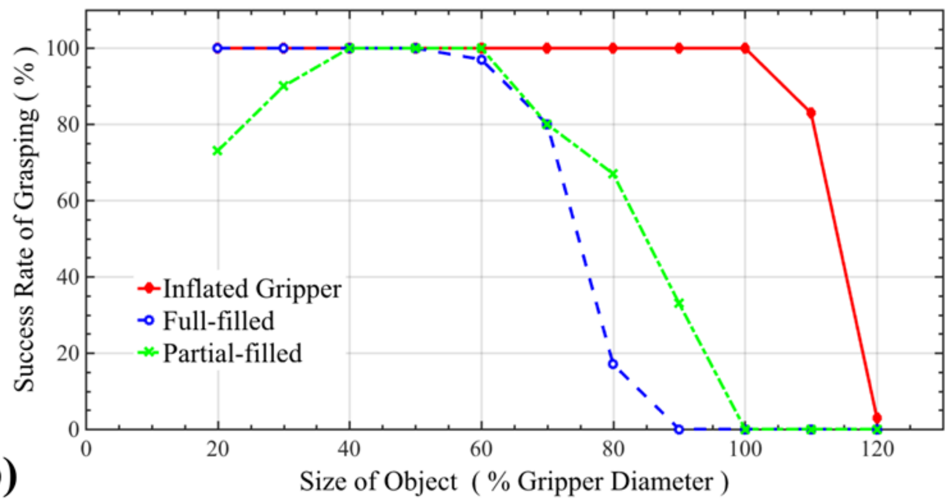


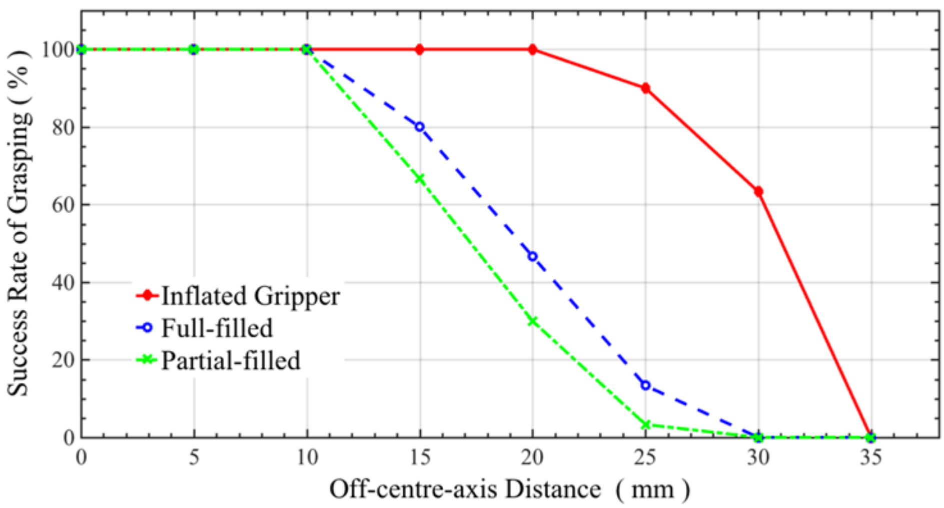
Figure 7

(a)



Success Rate of Grasping (%)
Size of Object (% Gripper Diameter)
Inflated Gripper
Full-filled
Partial-filled
0
20
40
60
80
100
120

(b)



Success Rate of Grasping (%)
Off-centre-axis Distance (mm)
Inflated Gripper
Full-filled
Partial-filled
0
5
10
15
20
25
30
35

Figure 8

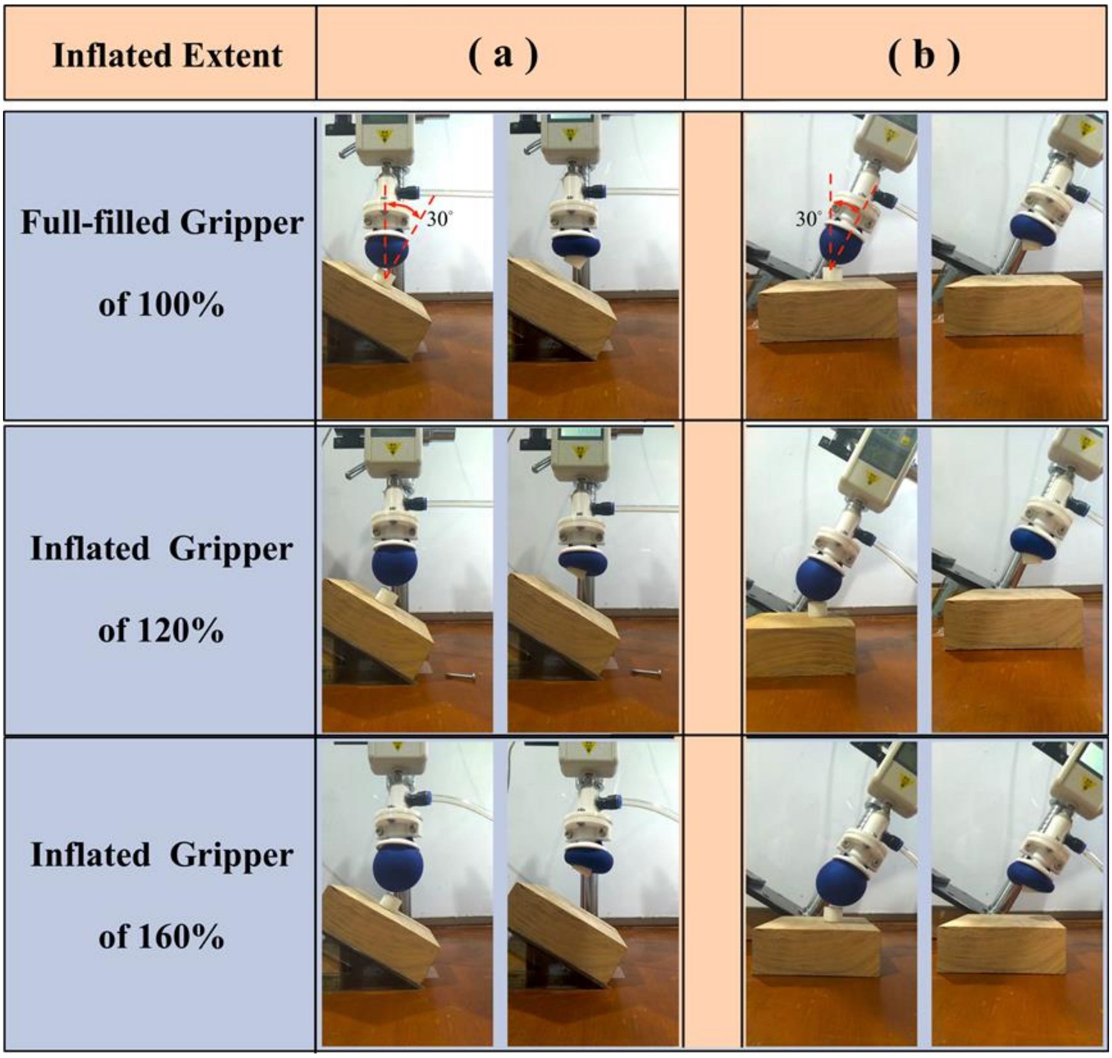

Inflated Extent
(a)
(b)
Full-filled Gripper of 100%
30°
30°
Inflated Gripper of 120%
Inflated Gripper of 160%

Figure 9

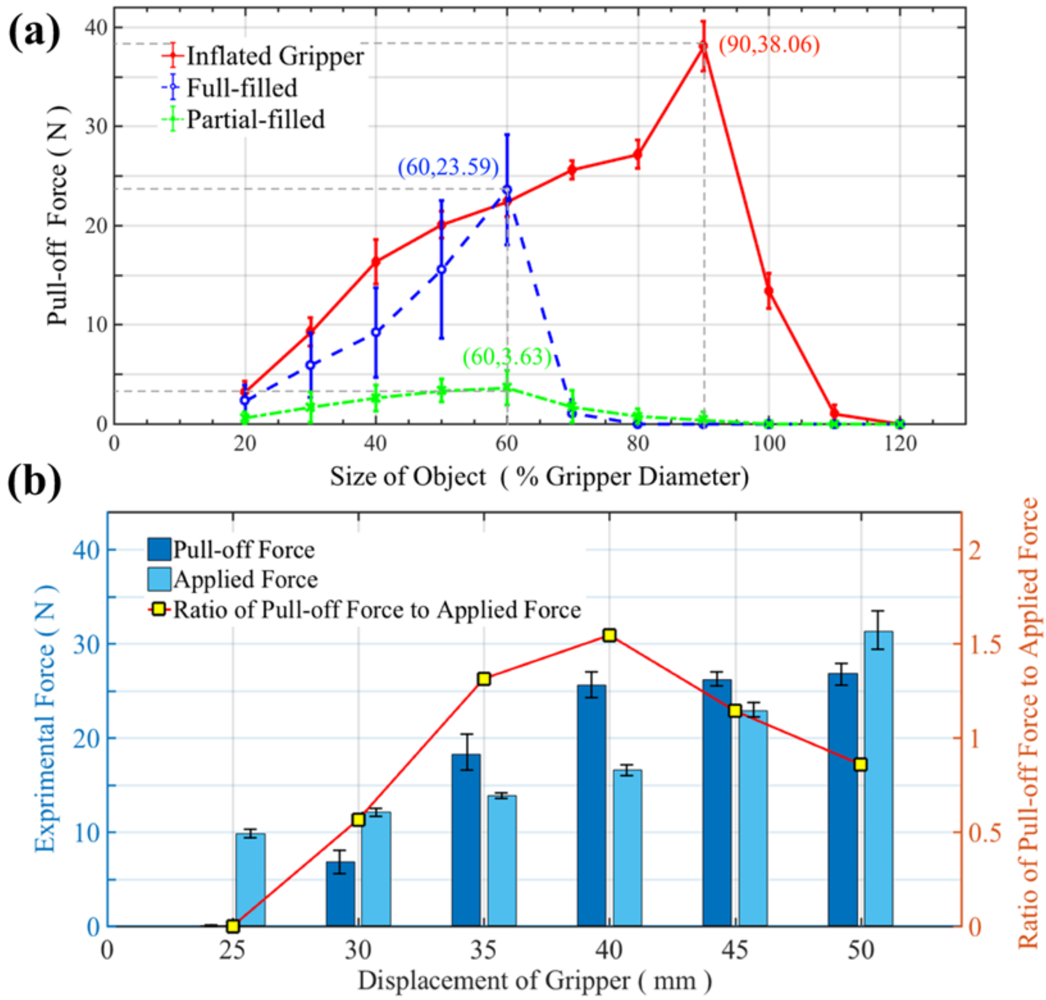

(a)
Inflated Gripper
Full-filled
Partial-filled
(90,38.06)
(60,23.59)
(60,3.63)
Pull-off Force (N)
Size of Object (% Gripper Diameter)
(b)
Pull-off Force
Applied Force
Ratio of Pull-off Force to Applied Force
Exprimental Force (N)
Ratio of Pull-off Force to Applied Force
Displacement of Gripper (mm)

Figure 10

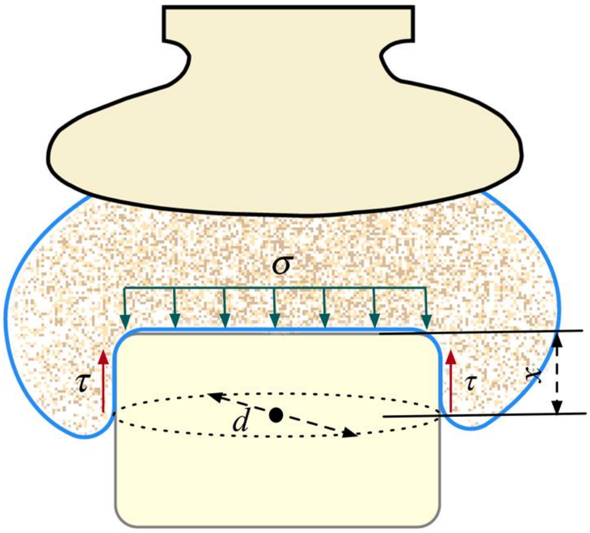


Figure 11

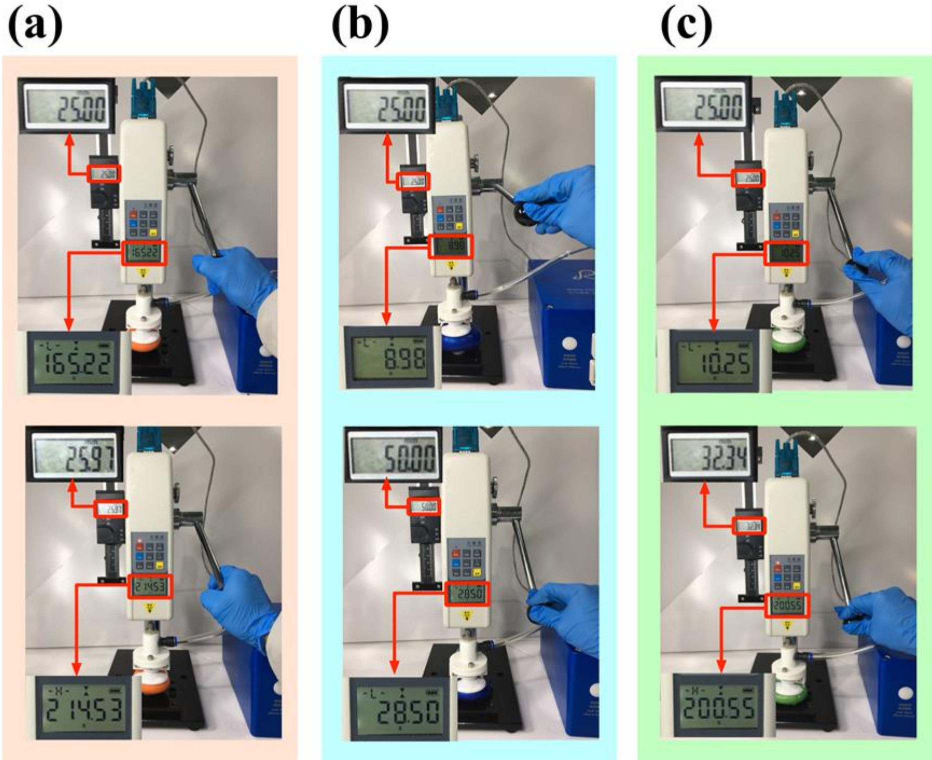
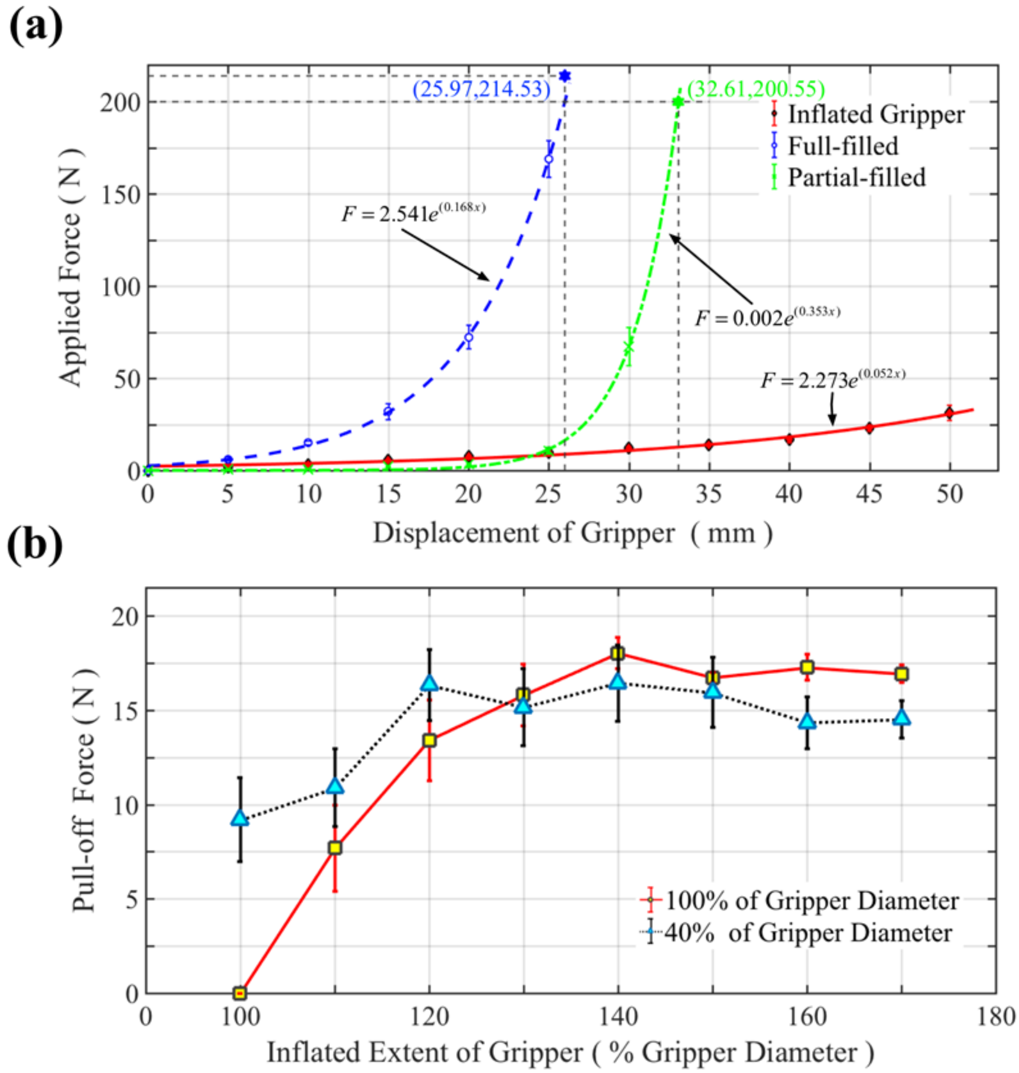


Figure 12



(a)
(25.97,214.53)
(32.61,200.55)
Inflated Gripper
Full-filled
Partial-filled
$F = 2.541e^{(0.168x)}$
$F = 0.002e^{(0.353x)}$
$F = 2.273e^{(0.052x)}$
Applied Force (N)
Displacement of Gripper (mm)
0
50
100
150
200
0
5
10
15
20
25
30
35
40
45
50
(b)
100% of Gripper Diameter
40% of Gripper Diameter
Pull-off Force (N)
Inflated Extent of Gripper (% Gripper Diameter)
0
5
10
15
20
0
100
120
140
160
180