

3D-Printed Pneumatically Controlled Soft Suction Cups for Gripping Fragile, Small, and Rough Objects

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A 3D-printed pneumatically actuated soft suction gripper with an elastomer film is proposed. Suction in such gripper is actively controlled by applying a negative pressure behind the film. The elastomeric gripper body is 3D-printed, making it easy to customize and integrate into future robotic gripping systems. The gripper can pick a wide variety of objects, such as delicate fruits, small parts, and parts with uneven loads, with high pull-off forces (over 7.4 N with \varnothing 20 mm/55 kPa). The achieved pull-off forces are significantly higher than the previously reported suction cup grippers with films and more comparable with commercial vacuum grippers. The pull-off forces show no significant differences with surfaces of varying roughness (up to root-mean-square roughness of 5.66 μ m) and the gripper is able to pick and release target objects repeatedly. The gripper is also compared with a commercial vacuum gripper with comparable dimensions. It outperforms the commercial gripper in the case of fragile objects, objects smaller than the gripper diameter, and objects with uneven loads. It can apply high pull-off forces while having controllable release, and is suitable for gripping a wide variety of real-world objects, including heavy, rough, small, thin, and fragile ones.

1. Introduction

An ideal robotic gripper should be gentle, i.e., not deform or break the manipulated object by applying too large stresses on it, grip the object strongly, i.e., be able to lift at least the weight of the object and overcome the adhesion of the object to its substrate, be able to release the object from its grip easily at will, and be able to pick objects of varying sizes, shapes, roughness, and fragility. To fulfill the gentle handling requirement,

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many different soft grippers have been proposed.^[1,2] Gentle gripping methods include capillary forces-based gripping,^[3,4] switchable electroadhesive surfaces,^[5-7] where a voltage applied to electrodes on the gripper induces a charge on the manipulated object, and switchable dry microfibrillar adhesive surfaces,^[8-11] inspired by the adhesive footpads of the gecko. However, capillary grippers and adhesive grippers generally do not achieve a very strong grip of the object: the applied pull-off forces to pick and lift the objects from these grippers are usually small. Strong grips can be achieved with claw grippers^[12-14] and with grippers that can control their shape and stiffness by using shape memory materials^[15-17] and granular jamming.^[18-20] Claw grippers can release the object very quickly, while thermal shape memory materials-based grippers tend to have longer response

times because heating up and cooling down the material is slow. One limitation of claw grippers and granular jamming grippers is that they are limited to objects that they can enclose; flat objects being particularly challenging for both types of grippers. Meanwhile, adhesive and vacuum grippers excel at picking flat objects. Overall, all the different gripping techniques tend to excel in some aspects but have limitations in other aspects. A gripping technique that would excel in all these four different aspects would still be highly desirable.

Vacuum suction-based gripping is a fast and efficient way to handle objects.^[21] In industrial production lines, vacuum grippers are common due to their simple operation principle and fast speed. These grippers generate a negative pressure between the gripper and the target object to achieve a grasp.^[22] Grippers can use either passive or active vacuum for generating the suction effect. In passive vacuum, the adhesion is generated by pushing the fluid from under the gripper, thus creating a negative pressure between the gripper and the target object. In active vacuum, the suction is generated using a pump. Vacuum grippers are suitable for objects with a flat, smooth, and nonporous surface, which is wider than the gripper to achieve proper vacuum sealing.^[1]

Due to many advantages of the vacuum gripping, researchers have proposed different suction cup designs.^[21,23,24] Takahashi et al.^[25] proposed an octopus-inspired suction gripper with a film, using a combination of vacuum and jamming phenomena for

the gripping. They fabricated a 14 mm wide gripper with micro-pumps and glass beads inside the gripper body. The maximum pull-off force they reported was 2.1 N. They also reported the enhancing effect of liquid on the surface^[26] when the same gripper design was used. Horie et al.^[27] reported an octopus-inspired microgripper for medical microelectromechanical systems. Mazzolai et al.^[28] reported an octopus-inspired actuator with integrated suction cups. Their suction cups had three different designs (a suction cup without film, with film underneath the cup, and with curve shaped film underneath the suction cup) depending on the desired function. They reached 3.3 N pull-off forces with the combination gripper.

Despite the many advantages of vacuum gripping, there are still some unsolved shortcomings. Due to the required preload in passive vacuum grippers or negative pressure in active vacuum grippers, the surface of the object cannot be neither soft nor delicate: the negative pressure of a vacuum gripper can leave a print on soft and delicate surfaces. The load of the vacuum gripper should also be even so that vacuum sealing is preserved during the object handling. In addition, the picked object should be able to be released after its transport. Finally, these challenges should be solved without compromising high pull-off forces to be able to carry heavy objects or to maintain grip during fast accelerations.

In our previous works,^[9,29] we proposed designs of soft cup-shaped grippers with thin silicone elastomer films. The adhesion could be actively controlled by applying a negative pressure behind the film. Two different films were demonstrated: a film with a gecko-inspired microfibrillar topography^[9] and a flat non-structured film.^[29] The operation principle of the gecko-inspired gripper relied on adhesion control by equal load sharing, whereas in the flat film gripper, the film acts as a suction cup when a negative pressure is applied behind the film. This, combined with the adhesion of the object to the elastomeric film, creates the force necessary to pick an object. We found that the pull-off forces of the flat film gripper against rough surfaces were larger than those of the gecko-inspired gripper. The fabrication of our previous gripper's body included several time-consuming and complex molding, silanization, demolding, and assembly steps. Also, the achieved pull-off forces were significantly lower than the commercial vacuum grippers of comparable size. To solve these issues, in this article, we propose an improved design of a 3D-printed soft vacuum gripper (**Figure 1a,b**). It is fabricated using direct 3D-printing (Carbon Digital Light Synthesis) with elastomeric silicone resins. The gripper consists of a 3D-printed gripper body with a negative pressure chamber, attached to a soft elastomer film. 3D-printing was selected to speed up and simplify the fabrication process of the gripper body. We were able to modify the design easily and 3D-printed multiple different designs at once. The film material and thickness were selected to be a balanced trade-off between the maximum pull-off force and conformation to rough surface, as reported in our previous study.^[29] The material of the gripper body was also stiffer than the one in our previous study. Unlike in our previous study, where the extremely soft material stretched significantly during the retraction and made the accurate positioning of the objects challenging, in this study the stiffer material reduces the stretching, and also prevents the gripper body to collapse on the soft film immediately after the withdrawal has been started.

We show that the gripper can handle objects smaller than its diameter because the film prevents the objects from being sucked into the gripper. In addition, we demonstrate that it handles highly uneven loads because the adhesion of the film enhances the sealing and thus prevents leaking. The improved gripper design can also achieve significantly higher pull-off forces even when the surface is rough. Finally, due to its softness and film, the gripper can pick soft and delicate objects without damaging them.

The grasping of the gripper is based on the vacuum suction principle. The pressure inside the vacuum chamber is called P_{neg} . Initially, it is same with the atmospheric pressure P_0 and the gripper has a dome shape (I in Figure 1c,d). When gripper is brought into contact with the target object and a preload F_{pre} is applied, small amount of air is captured between the film and the object (II in Figure 1c,d). Pressure in this volume is called P_S . After the preload, a negative pressure P_{neg} is applied inside the gripper by a syringe pump and then $P_{\text{neg}} < P_S = P_0$ (III in Figure 1c,d). When the gripper is retracted from the surface, the pressure between the gripper and the object starts to decrease and $P_{\text{neg}} < P_S < P_0$ (IV in Figure 1c,d). The pull-off force F_{off} is reached when (or a few seconds before) the gripper finally detaches from the surface (V in Figure 1c,d).

To see the effect of the negative pressure P_{neg} on the pull-off force F_{off} , we measured F_{off} against a smooth glass surface while varying P_{neg} from 0 to -55 kPa (Figure 1e). The maximum pull-off force was around 7.4 N, reached when a -55 kPa negative pressure was applied. The pull-off forces are higher with a larger negative pressure; however, the increase is nonlinear and saturates. To capture this nonlinearity, we fitted a second-order polynomial $y = -0.003683 - 0.4171x - 4.49x^2$, excluding the outlier when $P_{\text{neg}} = 0$, with an adjusted R^2 value of 0.996. We also tested linear fits for all the data and by excluding the $V = 0$ case and all these resulted in lower adjusted R^2 values. The good fit of the second-order polynomial implies reduced gains for high vacuums. Note that 55 kPa is already 0.54 atm, ≈ 1 atm being the theoretical maximum in the ambient environments.

To confirm how the elastic film affects the vacuum gripping forces, we repeated the pull-off experiments with the same gripper design, but without the film (Figure 1e). A fitted straight line had adjusted R^2 value of 0.8425. Without the film, the pull-off forces were always lower and more scattered than with the gripper with the film. The colors related to the applied withdrawal volumes also show that the achieved negative pressures were smaller and more scattered when the film was missing from the gripper. The gripper without the film fails as soon as there is a leakage from the edge, but the gripper with the film prevents the loss of vacuum under the gripper propagating immediately from one side to another. These results indicate that the film enhances the gripping forces. To see the effect of the object surface roughness, we measured pull-off forces against surfaces with varying roughness. To exclude the effect of the material, all surfaces were fabricated from the same material (EpoxAcast 690), by replicating the roughness of original surfaces through replica molding. For reference, we also tested the adhesion against a smooth glass surface. The masters for replicated surfaces were rough steel, 1000 and 2000 grit sandpaper, rough polymer, and concrete. The pull-off force results and R_{rms} (root-mean-squared

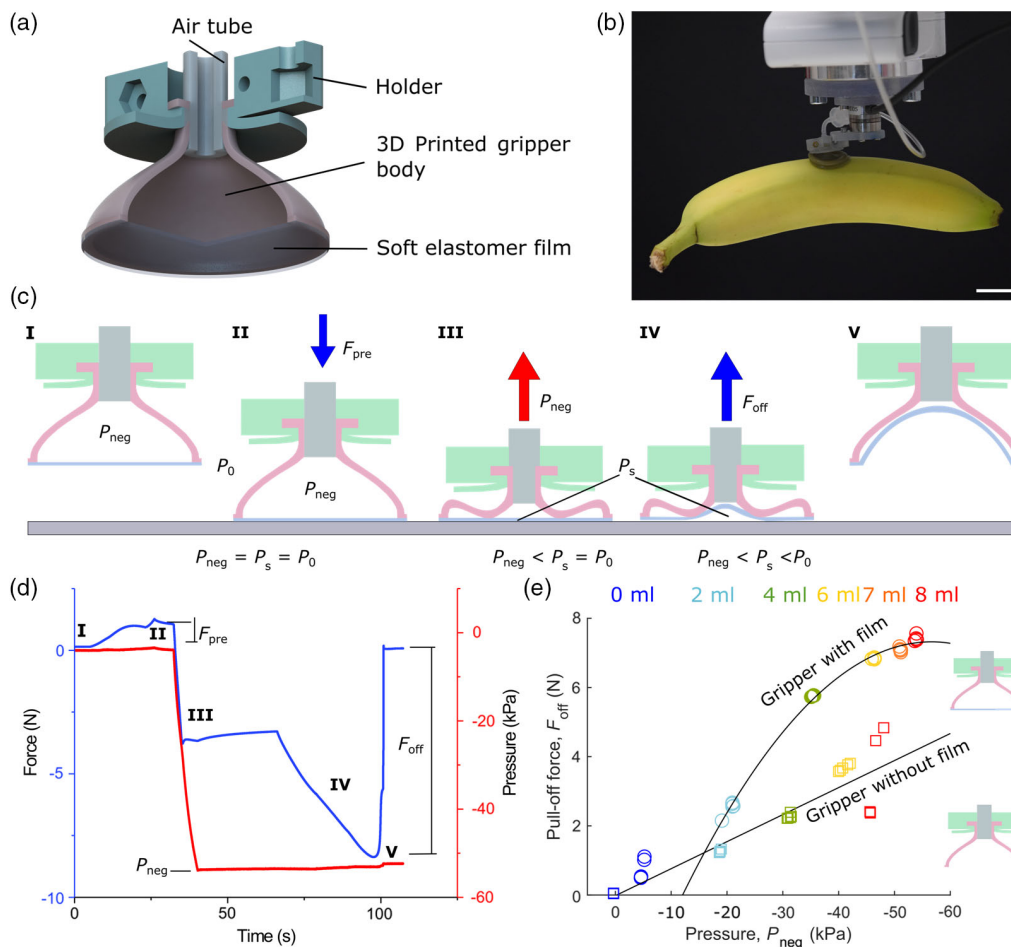


Figure 1. Concept and characterization of the 3D-printed soft vacuum gripper with an integrated elastomeric film. a) Schematic of the gripper and its holder. b) Photograph of the gripper holding a soft and delicate banana fruit (127 g), scale bar: 2 cm. c) Schematic of a pull-off force measurement and d) example data from a pull-off force measurement on a flat glass plate. I) The gripper is approaching the glass plate, II) a target preload F_{pre} (1 N) is applied after contacting the object, III) a negative pressure is applied in the gripper chamber, IV) the gripper is retracted from the object, V) the pull-off force F_{off} (the maximum force measured before the gripper detached from the object) is reached. e) Pull-off forces with different negative pressures on a smooth glass plate for grippers with (circles) and without (squares) the elastomeric film. With the film, the fitted line is a second-order polynomial with zero pressure point excluded. Without the film, the fitted line is linear. Different colors indicate the applied withdrawal volume in each measurement point.

surface roughness) values of the surface replicas are shown in **Figure 2a**, and micrographs for the corresponding surfaces are shown in **Figure 2b**. The selected surfaces are from the everyday objects, including also highly rough surfaces such as a sandpaper. The surface pattern in each object is different: in the sandpaper, the pattern is small with sharp peaks; in the rough polymer and concrete, the patterns are smoother and larger; and in the steel, there are long grooves and the structures are not as steep as the earlier ones. The measured pull-off forces were practically identical for all different test surfaces. However, the pull-off force did depend heavily on P_{neg} . This indicates that the operation principle of the gripper is mainly vacuum based. Thus, for reliable gripping, controlling P_{neg} is a much more important than the material/roughness of the object being picked, which is a promising result considering the practical applications of the gripper. **Figure 1e** also shows that the forces

start to saturate after the -55 kPa, which limits the maximum pull-force values that can be reached.

The film of the gripper makes it also possible to pick objects smaller than the diameter of the gripper. To demonstrate this, we tested picking of polymethyl methacrylate (PMMA) disks of varying diameters. The smallest disk we were able to pick had a diameter of 6 mm (30% of 20 mm gripper diameter) (**Figure 3f**). However, the gripper could not release this disk, but the disk remained adhered to the film. The smallest disk that we were able to both pick and release had a diameter of 16 mm. To better quantify the ability of the gripper to pick small objects, we measured the pull-off forces against two different diameter glass spheres, 30 mm and 15 mm. Spheres were used in these experiments because spheres do not require alignment of the gripper with the target object. The gripper adhered well to the bigger 30 mm sphere but did not adhere to the smaller 15 mm sphere.

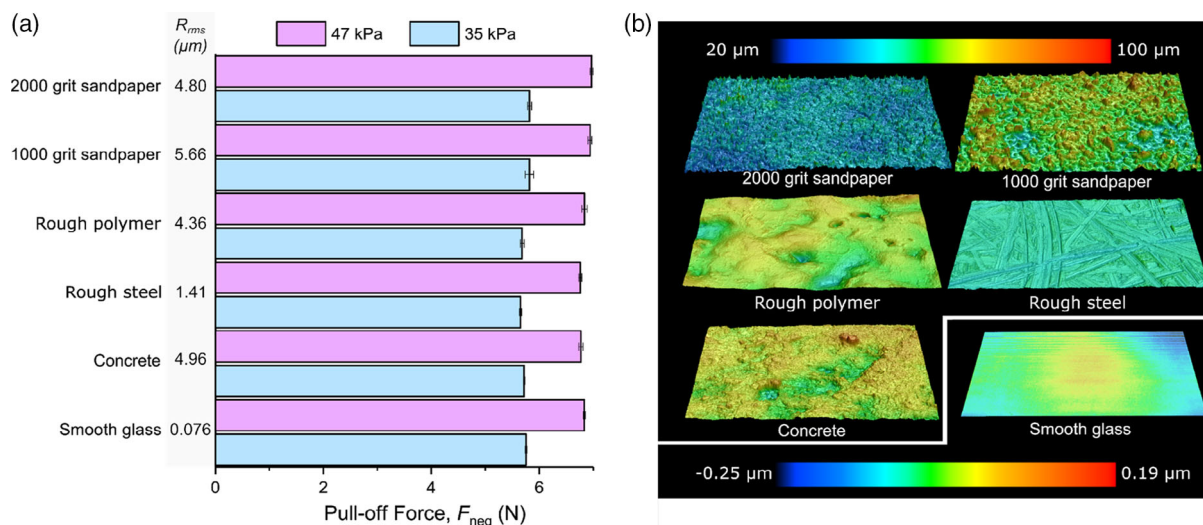


Figure 2. Pull-off forces for surfaces with varying roughness. a) Pull-off forces with smooth glass and replicas of rough surfaces (2000 and 1000 grit sandpaper, rough polymer, rough steel, and concrete) and R_{rms} values of the corresponding replicas. Pull-off force measurements were conducted with 35 and 47 kPa negative pressures. Each bar indicates an average of five measurements, and error bars show standard deviation. b) 3D topographies of the surfaces measured by a laser confocal microscope.

This is shown in Figure S3, Supporting Information. The results indicate that the gripper is able to grip small, flat, and light parts, due to its soft film, but would fail with highly curved objects.

The repeatability of the gripper was tested by attaching the gripper to a robotic arm with a three-axis force sensor (Figure 3c). The pick-and-place operation (Video S1, Supporting Information and snapshots in Figure 3b) was repeated 15 times for the same five surface replicas as before and two small PMMA parts with diameters of 18 and 16 mm. The target objects were selected to be light (≈ 10 g), to test the adhesion of the gripper to the objects. Even in the absence of vacuum, the gripper might adhere to the object simply due to van der Waals and capillary forces (sticky finger phenomenon). An example (concrete replica) of the force data recorded during one of these repeatability experiments is shown in Figure 3a. In each pick-and-place cycle, the force profile stays similar and the gripper was able to reliably and reproducibly pick and release every tested object. This shows that the gripper would not be limited only to smooth surfaces in potential future applications and it is capable to release also light objects.

To test whether the gripper leaves marks or dints on surfaces, we picked two delicate objects: a pear (170 g) and a banana (130 g), as shown in Figure 1b and 3e. Picking and releasing the fruits was successful, and the gripper did not leave any visible dints on the surface. We attribute that as the gripper, including the gripper body, is entirely soft, there is no risk of local high stresses and thus the gripping is gentler. As a control experiment, we did the same manipulation tasks with a commercial suction cup (Bellow suction cup SPB4 20 SI-55 G1/8-AG, Schmalz GmbH, Germany). The commercial suction cup was used with a vacuum generator (Vacuum Unit VER 15, Schmalz GmbH, Germany), set to -60 kPa pressure as recommended by the manufacturer for continuous suction. Figures S1a,b, Supporting Information, show that the commercial suction cup left visible prints on both surfaces. To test if

the gripper leaves visible contamination on picked surfaces, we picked a cleaned glass plate and a silicon wafer with the gripper (Figure S4, Supporting Information). Both surfaces and the gripper were cleaned before the picking with acetone, isopropyl alcohol, and deionized water. We did not observe any visible contamination on the surfaces after inspecting them with an optical microscope. However, silicone elastomers are known to contaminate surfaces in nonvisible ways,^[30] which can be reduced, for example, by oxidating the silicone elastomer before picking.^[31] We conclude that our gripper can handle significant loads without leaving visible dints on the soft surfaces of the objects that can be easily damaged. Also, it does not leave visible contamination marks on the clean surfaces.

Thin objects and films are often a challenge to robotic grippers: both grasping and suction grippers may inadvertently wrinkle or even crumple the film. To demonstrate that our gripper can pick thin objects, the gripper was used to flip the pages of a book (Video S2, Supporting Information and snapshots in Figure 3g). The gripper managed to grip and release the pages, without leaving visible crumples on the pages of the book.

Objects with uneven load distribution are difficult for many robotic grippers, as such loads results in torque, leading to an uneven stress distribution between the gripper and the object. To see if our gripper can pick uneven loads, we tested picking a fluid-containing bottle (429 g) from the edge of the bottle (Figure 3d). For comparison, we tested gripping the bottle using the same commercial vacuum gripper as before (Video S3, Supporting Information and snapshots in Figure S1c, Supporting Information). Our gripper could pick the bottle from the edge, i.e., when the load was uneven, whereas the commercial gripper could grip the bottle only from the middle, i.e., when the load was even. This ability to grip uneven loads could be from the soft silicone film that maintains the seal between the gripper and the object, preventing a small opening developing into a catastrophic loss of vacuum. This reduces the need to carefully plan

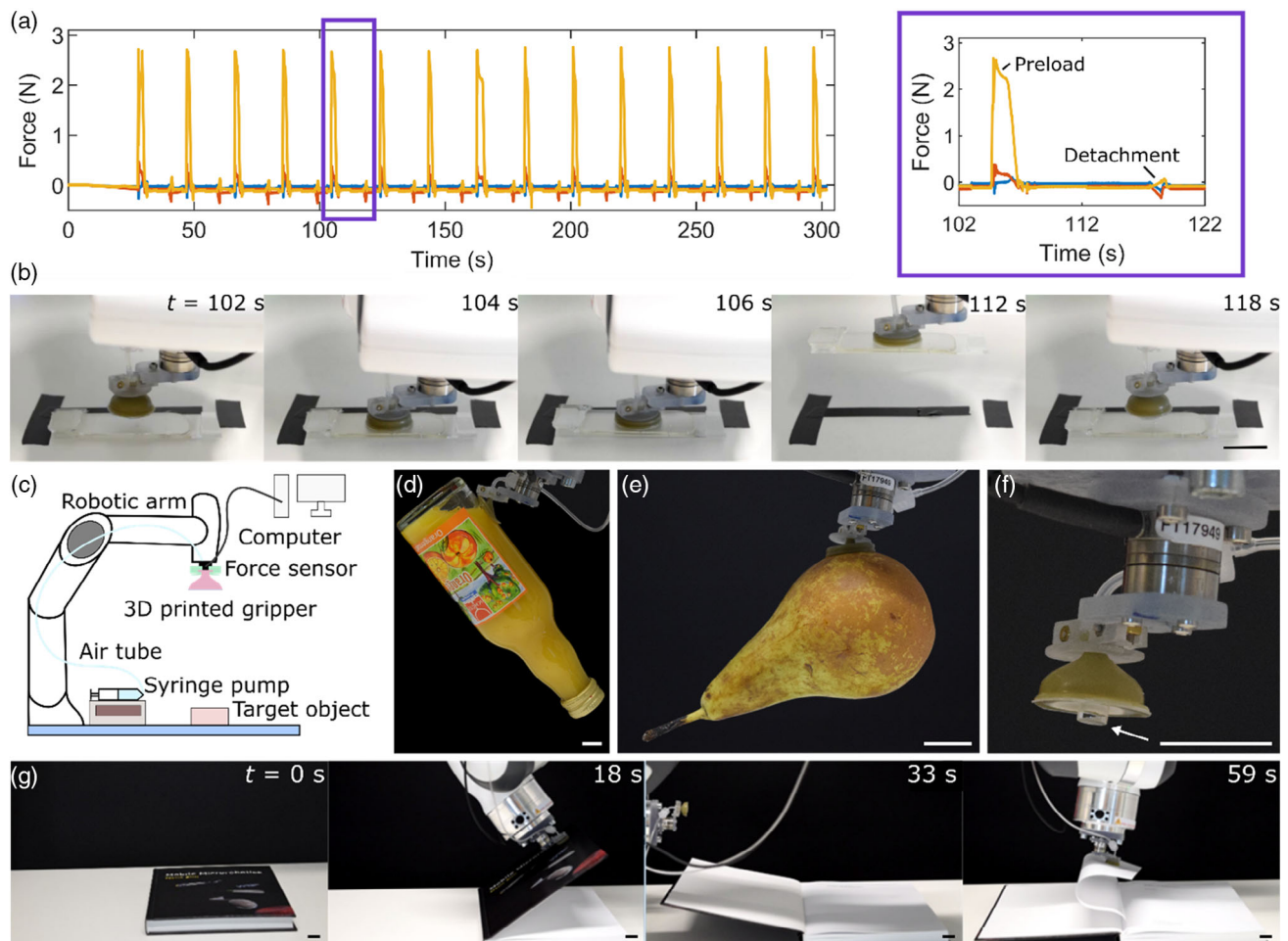


Figure 3. Pick-and-place repeatability tests and demonstrations using a robotic arm. a) Three-axis force data ($x = \text{blue}$, $y = \text{red}$, and $z = \text{orange}$) from the 15 repeated measurements with concrete replica and inset of that data. b) Snapshots from a repeatability measurement. At $t = 102 \text{ s}$, the gripper is approaching the target object. The gripper contacts the object with preload at $t = 104 \text{ s}$, and then a negative pressure is applied inside the chamber ($t = 106 \text{ s}$). At $t = 112 \text{ s}$, the object is carried, and then released ($t = 118 \text{ s}$). c) Schematic of the robotic arm setup: gripper is mounted at tip of the robotic arm and connected to the syringe pump using silicone tubing. A force sensor is between the gripper and the robotic arm, and the sensor is connected to a computer. d–g) Demonstration with the robotic arm: d–f) photographs of the gripper holding different objects: an orange juice bottle (429 g, highly uneven load), a pear (167 g), a soft object, and a small object (6 mm). g) Snapshots of the video: the gripper turns the pages of a book. Scale bar in all photographs: 2 cm.

the gripping. The angle and spot to grip the object do not have to be exact, making it especially suitable for situations where visual inspection of the object is limited.

In conclusion, we fabricated and characterized a 3D-printed soft suction cup gripper with a thin film underneath it. 3D-printing the gripper is faster and simpler than our previously^[9,25,28,29] reported casting techniques: there are less fabrication steps, they take less time to complete, and they are more reproducible. This rapid prototyping also makes it easier to integrate our gripper into future applications in fully 3D-printed soft robotic systems including actuators and sensors. The design of the proposed gripper is closed unlike in traditional suction cup grippers. The closed design prevents particles from entering and clogging the pneumatic channel, making the gripper more reliable in dirty environments. The design also allows the gripping of objects smaller than the gripper diameter. The soft gripper

conforms to the 3D shape of the object, which reduces the need to position the gripper accurately when picking objects. Because of these features, the gripper can have future various industrial manipulation or assembly applications, where the objects often have varying sizes and the position of the target objects may vary, for example, when they arrive on a conveyor belt. Finally, compared with previously reported soft suction grippers,^[9,29] the pull-off force of our gripper is significantly higher (7.4 N), as shown in **Table 1**. The pull-off force was also higher when compared with the gripper diameter and area normalized pull-off forces. The exception is the gripper proposed by Tomokazu et al.,^[26] which has higher pull-off force and diameter normalized pull-off force. However, their measurements were conducted with liquid enhancing in the gripper-object contact so the comparison is not straightforward. We attribute the higher pull-off forces are due to improved design and materials of the gripper

Table 1. Comparison of the proposed 3D-printed suction gripper and previously reported suction-based grippers.

Gripper name	Diameter [mm]	Pull-of force per area $[[\text{N}] \text{mm}^{-2}]$	Pull-off force per diameter $[[\text{N}] \text{mm}^{-1}]$	Pull-off force [N]	Fabrication method	Max. Surface roughness picked (R_{rms}) [μm]	Reference
Dielectric suction cup	12	–	–	–	Thin films stacked together	–	[21]
Magnetically switchable gripper	10	0.012	0.09	0.9	Casting	–	[23]
Octopus-inspired gripper	14	0.014	0.15	2.1	Casting	–	[25]
Octopus-inspired gripper with liquid membrane	60	0.016	0.77	46 ^{a)}	Casting	1.2	[26]
Micro sucker	3–10	0.0035	0.03	$\approx 0.1^{\text{b)}$	Casting	–	[27]
Octopus-inspired gripper	9–14	–	–	3.3 ^{c)}	Casting	^{d)}	[28]
Soft suction gripper	18	0.011	0.15	2.7	Casting, bar coating	1.6	[29]
Commercial Suction gripper	20	0.035	0.55	11	–	–	Schmalz
3D-printed soft suction gripper	20	0.024	0.37	7.4	3D-printing, bar coating	5.66	This work

^{a)}Force measured with a liquid membrane between the gripper and the object; ^{b)}Measurement was conducted with a chicken breast (wet), estimated from Figure 4 in ref. [27]; ^{c)}Measurement was conducted by using the whole robotic arm and many suction cups, the whole diameter not known; ^{d)}Rough surfaces tested, where $R_z = 36.5 \mu\text{m}$.

body which were able to achieve due to fat fabrication methods. This pull-off force is comparable with industrial suction grippers and that is why we compared our gripper to the same size commercial suction cup gripper with 11 N pull-off force. We demonstrated that our gripper can perform the same tasks as the commercial gripper in the given pull-off force limit, but additionally our gripper could perform tasks that are challenging for the commercial gripper, such as picking uneven loads, delicate surfaces, and smaller objects than the diameter of the suction cup. The operation speed of our 3D-printed gripper is slower than the commercial suction cup. The speed of the proposed gripper is currently limited by the used vacuum pump, and by changing the vacuum unit, the operation speed can be increased. Because of such versatility of our gripper, we believe that it could find use in future warehouse applications, where objects can be expected to vary in surface material, size, and shape.

2. Experimental Section

Design and Fabrication of the Soft Gripper. The fabrication steps of the soft gripper are shown in Figure S2, Supporting Information. The gripper consists of a 3D-printed soft gripper body with 700 μm wall thickness, a soft silicone film, air tubing, and a rigid 3D-printed holder. The diameter of bottom part of the body is 20 mm with 0.3 mm wider outer ring to enhance the sealing when in contact. The inner volume of the gripper is 1.4 mL. The 3D-printed part was fabricated by using Carbon Digital Light Synthesis (Carbon DLS) and M2 Printer (Carbon, CA, USA) by using a soft silicone urethane resin (SIL 30, Carbon, CA, USA. Shore hardness: A35). 3D-printer had a 75 μm xy-resolution and 100 μm z-resolution. After the 3D-printing, the parts were cleaned with isopropyl alcohol to get rid of any residual resin. Then, the parts were placed in the oven for 8 h at 120 °C. After that, the supporting structures were removed from the gripper bodies. Then, the 3D-printed gripper body was bonded onto 400 μm -thick bar-coated soft silicone film (Ecoflex, Smooth-On Inc., USA. Shore hardness: 00–50) with a silicone adhesive (Sil-PoxyTM, Smooth-On, USA). Then air tubing was attached into upper part of the gripper and sealed by using the same silicone adhesive. Finally, the gripper was attached to a 3D-printed rigid plastic holder designed for the gripper.

Fabrication of the Rough Surface Replicas: The rough surface replicas were fabricated by first creating a negative mold of the original surface, by pressing a glass plate with a layer of uncured vinylsiloxane polymer

(Flexitime medium flow, Heraeus Kulzer GmbH) onto the original surface. The mold was cured for 5 min at room temperature, and then removed from the surface. Next, a positive replica of the original surface was made by casting clear epoxy (EpoxyAcast 690, Smooth-On Inc., 10:3 ratio by weight) into the mold, with another glass plate pressed on top. The positive replica was cured for 48 h before removing it from the mold.

Adhesion Measurements: To characterize the adhesion and pull-off forces of the gripper, the gripper was attached to a high-resolution load cell (GSO-1K, Transducer Techniques), measuring the reaction forces normal to a smooth glass substrate. High-precision piezo motion stages (LPS-65 2", Physik Instrumente GmbH & Co. KG) were used to move the gripper vertically. The interface between the gripper film and the glass substrate was observed from below using an inverted optical microscope (Axio Observer A1, Zeiss) with a video camera (Grasshopper3, Point Gray Research Inc.). A programmable syringe pump (Legato 210p, KD Scientific, USA) was used to control the pressure inside the gripper body.

Repeatability Tests and Demonstrations: The repeatability of the gripper was tested with 7 degrees of freedom robotic arm (Franka Emika, Panda Research, Germany). Figure 3c shows the measurement setup. We attached the gripper and the holder to a six-axis torque sensor (Nano 17 Titanium, ATI Industrial Automation, USA) which was attached to the tip of the robotic arm. In these experiments, we used the same syringe pump as before to apply the negative pressure inside the gripper chamber. In the repeatability tests, the robotic arm was programmed to pick and place the objects 15 times and the syringe pump was operated accordingly.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

adhesion, pick and place manipulation, soft grippers, soft robotics, vacuum grippers

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