A soft gripper with contamination resistance and large friction coefficient

Zuodong Wang1 · Yali Wu1 · Jiayi Yang2 · Honglie Song3 · Khuong Ba Dinh4,5 · Dongguang Zhang1 · Vi Khanh Truong6

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Abstract
With the development of soft gripper systems, food processing, packaging, and processing technology has seen a significant advancement. The soft gripper must be protected from surface contamination and liquid lubrication; hence, a hydrophobic and contamination-resistant surface is used. There is an urgent need for a soft gripper that meets the functions of hydrophobic performance and contamination resistance, but there has been little study. In this study, the two functions are well achieved by introducing a flexible superhydrophobic surface. A novel design of a flexible superhydrophobic surface-based gripper (SSBG) is proposed by the template method. After a series of testing, it was discovered that the friction coefficient between the SSBG surface and the glass plate, cardboard, and steel plate is larger than that of a standard surface gripper (SSG). At the same time, the contamination resistance of SSBG is particularly important. Because of the existence of the plastron layer, the surface was discovered to be able to repel bacterial colonization. Finally, when the usual gripping force of the SSBG is measured on a 250 ml beaker with contamination and liquid lubrication, it can be shown that the gripping ability is improved by at least 100% and 170% compared to the SSG, respectively. As a result, the SSBG has a high potential for utilization in industrial and therapeutic contexts.

Keywords Soft gripper · Superhydrophobic · Surface patterning · Plastron layer · Contamination resistant · Bacteria repelling

1 Introduction
Soft grippers (SGs), which are widely applied in various environments, have been progressively explored in many engineering applications, including soft robotics [1, 2], medical surgeries [3, 4], and rehabilitation devices [5, 6]. Unlike conventional rigid/hard grippers, SGs can easily adapt to a wide range of external loads. In addition, although SGs do not need precise sensing and advanced control system [7–9], SGs can still manipulate dexterously in some constrained environments and have soft contact with objects by utilizing the properties of compliant materials [10–12].

In general, SGs are constructed by soft elements and receive considerable attention due to their ability to deal with deformation and fragile objects [13]. Polymers [14, 15], responsive gels [16], paper [17, 18], and fluids [19, 20] are representative materials for fabricating soft grippers. In comparison, polymers are prevalent materials that can distribute contact loads, and reduce localized stress concentrations. In the meantime, increasing friction through
careful surface selection can aid in achieving force closure during gripper grasping and enabling interlocking between the surfaces. To increase friction between SGs and objects, a number of studies have been carried out. Guo et al. [21] researched data-driven optimization of soft gripper surfaces over a design space based on texture, shape, and compliance. Trinh et al. [22] designed a soft gripper with a friction-tunable function based on the active wrinkles and researched the friction coefficient change under different wrinkle morphologies using a predicted model. Cao et al. [23] investigated a soft pneumatic gripper that can firmly grasp objects with different weights, sizes, and shapes inspired by humanoid fingerprints. Zhao et al. [24] found that the gecko foot has superhydrophobicity and self-cleaning properties through the study of the gecko foot. Furthermore, a liquid crystal elastomer with self-cleaning bionic microstructure based on intelligent muscle drive was designed and prepared. Lanceros-Mendez et al. [25] prepared a PH-induced chitosan hydrogel with good biocompatibility using the 3D printing technology and described the potential for application in soft actuators. Although the methods of surface texturization have been discussed, combining surface texturization with contamination resistance and antibacterial properties has been little studied. However, it is important for SGs execute some manual tasks in the presence of contamination and droplet.

This research focuses on humid and contaminated environments, for example, kitchens, toilets, etc. SGs must grasp an object with a wet and contaminated surface in such an environment. For this purpose, one possible solution to address the issues mentioned above is using the functional surface, especially the superhydrophobic surface (SS) [26–29]. SS is one of the functional surfaces with high contact angle (CA) and low sliding angle (SA). These properties facilitate the complete contact of water droplets with contaminants and remove contaminants. Besides, the roughness of the SS microstructure can ensure a close contact area, which is crucial to generate a sufficient grasping force. At the same time, the SS can repel the adhesion of bacterial biofilm [44].

In this study, we introduce an SSBG that is operated by pneumatic force (Fig. 1a–c). Due to its superhydrophobic properties, this surface does not lead to the adhesion of water droplets.

![Figure 1](image_url)

**Fig. 1** Preparation of soft gripper samples: a the photograph of SSBG, b, c the structure of flexible finger, d the fabrication process of the flexible finger, e the molds used in the preparation process, f the experiment and simulation of flexible finger bending, g the topography of S-Finger surface, and h the topography of the N-Finger surface.
on grasping. In addition, the superhydrophobicity ensures that contaminants on the SSBG surface can be easily cleaned off, thus avoiding a reduction in the coefficient of friction. And, the superhydrophobicity also contributes to repel the bacterial adhesion. Finally, we also investigate the characteristics of SSBG. For example, we examine noticeable characteristics of grasping normal force by water droplet contamination and sand contamination. In addition, the ability and performance of SSBG are evaluated by grasping objects of different sizes, which confirm the possibility of usage in industrial fields.

2 Materials and methods

2.1 Materials and fabrication of SSBG

A flexible superhydrophobic surface gripper was prepared using the template method, because its cost was low and the surface morphology could be changed arbitrarily according to the morphology of the template. It not only has good anti-fouling ability but also has some antibacterial ability. It consists of the following four main production steps: (1) fabrication of aluminum alloy base, (2) fabrication of sealing layer, (3) fabrication of cavity, and (4) the assembly of the SSBG (Fig. 1d). As shown in Fig. 1e, the cavity is mainly made through mold-5, and the sealing layer of the flexible finger is prepared through mold-3 and mold-4. Wherein mold-4 was formed by placing the aluminum alloy base in mold-3, and the mold-5 was formed by combining mold-1 and mold-2.

2.1.1 Fabrication of aluminium alloy base

Due to the presence of oxides on the surface of aluminum alloy, polishing by sandpaper is required. Therefore, the 6061-aluminum alloy (Al, Shenzhen, China; main chemical composition: 96.1 wt% aluminum, 1.2 wt% magnesium, 0.8 wt% silicon, et al.) with a size of 118×38×1 mm was polished by #1000 sandpaper. Then, the surface is processed by laser processing method (Laser processing angle: $\theta = 90^\circ$, Laser processing pitch: $d = 0.06$ mm, laser processing power: $P = 24$ W, Laser processing speed: $v = 70$ mm/s, and laser processing wavelength: $\lambda = 1064$ nm). Finally, to reduce the surface free energy of the aluminum alloy base to make it easier to demold. We need to soak the aluminum alloy base in $N$-dodecyltrimethoxysilane (DTS, Shanghai, China) for 20 min and then dry it at 120 °C for 5 min.

2.1.2 Fabrication of flexible polydimethylsiloxane sealing layer

The polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning Corporation, USA) was mixed with the curing agent (weight ratio: 10:1), poured into the mold-4, and then cured at 60 °C for 4 h.

2.1.3 Fabrication of cavity

The Dragon Skin 00-30 (Smooth-on, USA) that is a silicone rubber similar to PDMS was poured into mold-5 and demolded after curing at 60 °C for 0.5 h.

2.1.4 Integration of the SSBG

The strain limiting layer (A4 paper; 100×30 mm) was placed between the sealing layer and cavity and then sealed by PDMS. After these operations, we got a flexible superhydrophobic finger (S-Finger) and the SSBG was completed assembled by two S-Fingers. For comparison, a normal surface finger (N-Finger) is formed in mold-3 and the SSG was completed assembled by two N-Fingers. In addition, the overall size of the flexible finger is 115×15×15 mm and the bending ability is also well (Fig. 1f). Besides, compared to the N-Finger surface, many striped micro-structures on the S-Finger surface can be seen from the scanning electron microscope images (Fig. 1g–h).

2.2 Experimental setup and method

The surface morphology of the flexible fingers was measured by scanning electron microscope (MIRA3 LMU, Czech) and super-high magnification lens zoom 3D microscope (Leica DVM6, Germany). The normal force of the SGs under different pneumatic forces was measured by a digital force gauge (ShenCe SC, China). The surface topography of the mold was processed by a laser marking machine (FB30-1, CNI, China). The surface roughness (Ra) was measured by the roughness meter (MarSurf M400, Mahr GmbH, Germany). The surface contact angle (CA) was measured by a contact angle measuring instrument (JY-82C, China). The droplet that was used to measure the CA was 5 μl. The plastron layer was imaged using confocal laser scanning microscopy (CLSM, Zeiss). The substrate was submerged in 1 mM Rhodamine 6G. The existing air layer (plastron) was detected using CLSM. All data measurements were averaged after five cycles. The SLR camera took all physical optical photos (EOS 90D, Japan).

3 Results and discussion

3.1 The design and characterization of superhydrophobic surface

The function of contamination resistance is closely related to the superhydrophobic. To achieve superhydrophobic, we chose PDMS as the sealing layer material [30, 31] and prepared the superhydrophobic surface by the template method (Fig. 2a). At the same time, the superhydrophobic surface
can lead to the formation of air layers due to the presence of micro-nano structures, which can generate an "air cushion", known as the plastron layer. The plastron layer also prevents the surface from contacting the water droplets directly. The model of Cassie-Baxter (Eq. (1)) can describe the phenomenon well

\[
\cos \theta_{CB} = f(\cos \theta + 1) - 1, \tag{1}
\]

where \(\theta_{CB}\) and \(\theta\) are the Cassie-Baxter contact angle and the intrinsic contact angle, respectively, and \(f\) stands for the surface area fraction of the liquid-solid. Equation (1) describes the relationship between \(\theta_{CB}\) and \(f\).

Furthermore, the increase of the liquid-solid contact also lead to an increase of the \(\theta_{CB}\). Therefore, the surface morphology provides the geometric condition for the superhydrophobic surfaces. Therefore, we research the influence of different laser processing parameters on the morphology of the obtained superhydrophobic surface. As shown in Supporting Table S1, we can find that the laser processing speed is the most important factor between the three key factors (Laser processing distance, Laser processing power, and Laser processing speed) by the orthogonal experiment. We further discussed the effect of laser processing speed on the surface. As shown in Fig. 2c, when the laser processing speed is 70 mm/s, the CA reaches the maximum of 156.62°, and the Ra reaches the maximum of 6.173. The maximum CA makes droplets carry away the contaminants easily, and the maximum Ra makes the surface have a greater friction coefficient when it contacts objects. As shown in Fig. 2b and Supporting Table S2, we also measured the groove size of the machined surface by SEM. In addition, as shown in Fig. 2d, Fourier transform infrared (FTIR) results show the hydrophobic groups of SSBG surface, which is also an essential chemical factor that causes the surface to be superhydrophobic. The EDS results also show that toxic fluorides [32–34] used in superhydrophobic surfaces are not introduced, which are significant to grasp (as shown in Supporting Fig. S1).

Fig. 2 The fabrication and characterization of the superhydrophobic surface: a The fabrication process of the superhydrophobic surface, b the groove size of the machined surface, c the influence of processing speed on roughness (Ra) and contact angle, and d FTIR spectra of the smooth PDMS and prepared PDMS
3.2 Friction models and fluid effects on contact

According to the friction model of Coulomb or Amonton’s Law, the friction force $f_s$ is proportional to normal force $F_N$ and friction coefficient $\mu$ (Eq. 2). Surface interactions between silica gel and rigid objects typically match the Coulomb friction model. Therefore, by designing surface topography, increasing the $\mu$ between the SSBG surface and the object can increase the $f_s$, thereby improving the ability to grasp objects:

$$f_s = \mu F_N. \quad (2)$$

However, the presence of a thin fluid film between SSBG and object can create slippery contact and grasp failure when the SSBG surface is contaminated by contamination or liquid. Therefore, the dynamic fluid interactions must be taken into account. The Stefan–Reynolds theory describes the dynamics of fluid films confined between parallel surfaces [35]:

$$F_N = \frac{3\eta R^4 V}{2h^3}, \quad (3)$$

where $\eta$, $V$, and $h$ are the fluid viscosity, closing velocity, and gap height, respectively. The $R$ represents the surface size. This equation (Eq. 3) has also been applied to a range of surface interactions as the first approximation. Keeping all else constant, we can see that the squeeze force $F_N$ is proportional to viscosity $\eta$. In the standard case, the dynamic viscosity $\eta_{water} = 8 \times 10^{-3}$ kg/m·s, but the $\eta_{air} = 2 \times 10^{-5}$ kg/m·s. Therefore, a small squeezing force $F_N$ can cause air to be squeezed out, but it is not easy for water. At the same time, we can also see that decreasing the sizes of a surface exponentially decreases force. It indicates that less force is required to squeeze smaller areas closer together. For a constant nominal contact area, contact consisting of many smaller rectangles rather than one large contact lowers the total squeeze force required. Specifically, the squeeze force for all the contacts force $F_N$ is also proportional to the inverse of feature number $n$:

$$F_N \propto \frac{1}{n}. \quad (4)$$

Typically, the surface rough structure results in higher friction. Therefore, we introduced the superhydrophobic surface with surface microstructure to the soft gripper. Due to the surface microstructure, the surface can result in higher friction between objects and surfaces under loads. In addition, due to the superhydrophobicity of the surface, it can avoid the influence of water lubrication and contamination.

3.3 The performance of the SSBG surface

According to the Cassie–Baxter wettability theory [36], the micro/nanostructure of the superhydrophobic surface can trap a portion of the air, thus forming an air layer called a plastron layer (as shown in Fig. 3a). This plastron layer further enables the surface to present a mirror effect underwater (as shown in Fig. 3b) and makes the surface less adhere to water droplets. Figure 3a and Fig. 3b experimentally verifies the presence of a superhydrophobic surface air layer. The measurement method used in Fig. 3a relies mainly on the confocal microscope and allows the measurement of the exact thickness of the air layer on the prepared surface [37]. Figure 3b, on the other hand, demonstrates the presence of an air layer on the surface by presenting the specular effect through the total reflection of light [38]. However, non-structured surfaces can easily lead to the adhesion of water droplets. As shown in Fig. 3c, d, when SSBG and SSG are cleaned with water, the SSBG surface is less prone to adhere to water droplets due to the presence of a plastron layer, while the SSG surface will adhere to water droplets, resulting in the introduction of a lubrication layer. Therefore, compared with the liquid layer, the plastron layer could be effectively squeezed out under load due to the lower dynamic viscosity, which provides a more effective solid–solid contact and enhances static friction and effective grasp [39–43].

We used enough water (20 ml) and a small amount of water (2.5 ml) to clean the surface of S-Finger (S-Surface-0) and N-Finger (N-Surface-0). As shown in Fig. 4a, b, we artificially placed the SGs on fine sand and then cleaned them with water droplets. Due to the superhydrophobic of the S-Surface, contaminants are more easily carried away by water droplets. Therefore, as shown in Fig. 4c–e, when we used 2.5 ml water to clean the S-Surface and N-Surface, it can be seen that the S-Surface has been completely cleaned clearly (S-Surface-1), but there are many contaminants and water droplets on the N-Surface (N-Surface-2). When we used 20 ml water to clean the two surfaces, it can be found that the S-Surface was as clean as before (S-Surface-1), but the N-Surface still had stubborn contaminants and water droplets (N-Surface-1).

We further tested the ability of SSBG surface can repel the adhesion of bacterial biofilm, which is a collection of surface-adhered cells encapsulated in an extracellular polymeric substance matrix [44]. As shown in Fig. 5, the surface was tested against the colonization of Gram-positive methicillin-resistant Staphylococcus aureus and Gram-negative Pseudomonas aeruginosa, which were responsible for many infections transmission in healthcare settings [45–47]. Figure 3a demonstrates the presence of the plastron layer. These plastron layers are responsible for stopping microbial colonization [48]. The presence plastron layer was reported to minimize the direct contact between solid surfaces and
Fig. 3 Surface characteristics and properties: a the plastron layer, b the mirror effect, c the surface changes of superhydrophobic film under load after water cleaning, and d the surface changes of the flat film under load after water cleaning.

Fig. 4 Contamination resistance test: a the contaminated environment configuration, b the contaminated S-Surface and N-Surface, c the S-Surface after 2.5 ml and 20 ml water cleaning, d the N-Surface after 20 ml water cleaning, and e the N-Surface after 2.5 ml water cleaning.
bacterial cells. Bacterial cells remained the air–water interface, which cannot form any firm anchorage points for the biofilm formation.

As shown in Fig. 6a, to facilitate the friction coefficient measurement between the SSBG surface and different objects, a flat plate was placed on S-Finger to distribute the force evenly. And then, we measured the friction coefficient between the three surfaces (S-Surface-1, N-Surface-1, and N-Surface-2) and different objects glass plate (Ra = 0.0437), cardboard (Ra = 3.656), and steel plate (Ra = 1.984). As shown in Fig. 6b-d, the friction coefficient between the S-Finger and the objects under different loads is much larger than that of the N-Finger, proving that the SSBG has a more potent grasping force under other circumstances.

### 3.4 The performance of the SSBG

As shown in Fig. 7a, we tested and verified the bending performance of flexible fingers by simulation and experiment. The result shows that the bending performance has little difference before and after introducing the superhydrophobic surface. At the same time, the bending of the flexible finger can generate normal grasping force. As shown in Fig. 7b, the S-Finger’s normal force has not been weakened compared with the N-Finger (the normal force $F_N$ is about 0.1 N at 2 kPa, and 2.3 N at 36 kPa). Finally, as shown in Supporting Fig. S2, the objects with large size differences also can be grasped stably.

The results of further research (cleaning with 20 ml water) were done. As shown in Fig. 8a, b, before cleaning, it can be seen that the grasping capacity of the SSBG is significantly higher than that of the SSG when the pneumatic force increases. Besides, it can also be seen that the grasping weight of SSBG is more than the SSG one time ranging from 2 to 20 kPa (1.21 times on 2 kPa, 1.45 times on 20 kPa). When the pneumatic force is 16 kPa, the SSBG could grasp a 250 ml beaker (115 g) stably, but the SSG slipped slightly. As shown in Fig. 8c, d, SSG appeared to be obvious slipping after cleaning, and the grasping capacity for 250 ml beakers is lost. At the same time, the weight of SSBG grasping is more than the SSG 1.7 times ranging from 2 to 20 kPa (1.75 times on 2 kPa, 1.99 times on 20 kPa), which also shows the adaptability of SSBG in various conditions and provides a guarantee for the uncertainty application conditions. Moreover, due to the special structure of the SSBG surface, this also provides inspiration for its application to crawling robots. By introducing a superhydrophobic surface on the crawling
Fig. 6 Measurement of friction coefficient under different test conditions: a determination method of friction coefficient, b the influence of load on friction coefficient between finger and glass plate, c the influence of load on friction coefficient between finger and cardboard, and d the influence of load on friction coefficient between finger and steel plate.

Fig. 7 The bending ability and normal force: a the simulation and experiment results of bending angle; b the influence of cavity pressure on the normal force.
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robot, it can not only make it more stable to crawl on land, but also even move on water \[49, 50\].

4 Conclusions

This research designed and fabricated superhydrophobic films to act as a contact surface for soft gripper by the template method. The experiment also verified the contamination resistance ability of the soft gripper. We also show that the surface plastron layer could be squeezed out more quickly due to the smaller viscosity factor \(\eta_{\text{air}} = 2 \times 10^{-5} \text{ kg/m s}, \eta_{\text{water}} = 8 \times 10^{-3} \text{ kg/m s}\). Therefore, the existence of a superhydrophobic surface can provide a more effective solid–solid contact under load. Besides, the fabricated soft gripper surface was tested under various conditions. The results showed that the friction coefficient and grasp ability enhanced with increasing load. Furthermore, under the same conditions, the gripping weight of the S-Finger soft gripper is at least one times that of the N-Finger. At the same time, due to a plastron layer presence, the surfaces were found to inhibit bacterial colonization. These engineering films can be used in many industrial and clinical settings where microbial contamination will be the major issue. Finally, we also demonstrated the grasping capacity of the soft gripper by grasping different objects from 13.8 to 84.3 g.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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