PNAS

Main Manuscript for

Bioinspired multi-scale adaptive suction on complex dry surfaces enhanced by regulated water secretion

Tianqi Yue[1], Weiyong Si[2,3], Alex Keller[1], Chenguang Yang[2], Hermes Bloomfield-Gadêlha[1] and Jonathan Rossiter[1*]

[1]Department of Engineering Mathematics and Bristol Robotics Laboratory, University of Bristol, Bristol, UK.

[2]Faculty of Environment and Technology and Bristol Robotics Laboratory, University of the West of England, Bristol, UK.

[3]School of Computer Science and Electronic Engineering, University of Essex, Essex, UK.

*Corresponding author

Email: jonathan.rossiter@bristol.ac.uk

Author Contributions:

Conceptualization: TY, HG, JR

Methodology: TY, WS, AK, HG, JR

Investigation: TY, HG, JR

Visualization: TY, WS, AK, CY, HG, JR

Funding acquisition: HG, JR

Project administration: TY, HG, JR

Supervision: HG, JR

Writing: TY, HG, JR

Competing Interest Statement: All authors declare that they have no competing interests.

Classification: Physical Sciences/Engineering.

Keywords: Soft robotics; soft gripper; suction; adhesion

This PDF file includes:

Main Text
Figures 1 to 4

Abstract

Suction is a highly evolved biological adhesion strategy for soft-body organisms to achieve strong grasping on various objects. Biological suckers can adaptively attach to dry complex surfaces such as rocks and shells, which are extremely challenging for current artificial suction cups. Although the adaptive suction of biological suckers is believed to be the result of their soft body's mechanical deformation, some studies imply that in-sucker mucus secretion may be another critical factor in helping attach to complex surfaces, thanks to its high viscosity. Inspired by the combined action of biological suckers' soft bodies and mucus secretion, we propose a multi-scale suction mechanism which successfully achieves strong adaptive suction on dry complex surfaces which are both highly curved and rough, such as a stone. The proposed multi-scale suction mechanism is an organic combination of mechanical conformation and regulated water seal. Multi-layer soft materials first generate a rough mechanical conformation to the substrate, reducing leaking apertures to micrometres (~10 µm). The remaining micron-sized apertures are then sealed by regulated water secretion from an artificial fluidic system based on the physical model, thereby the suction cup achieves long suction longevity on complex surfaces but minimal overflow. We discuss its physical principles and demonstrate its practical application as a robotic gripper on a wide range of complex dry surfaces. We believe the presented multi-scale adaptive suction mechanism is a powerful new adaptive suction strategy which may be instrumental in the development of versatile soft adhesion.

Significance Statement

The adaptive suction ability of biological suckers on dry complex surfaces was thought to rely on their soft body structures, while the critical role of their mucus secretion has largely been overlooked. By studying the function of mucus in biological suckers, we propose a multi-scale suction mechanism which combines mechanical conformation and liquid seal regulation. The multi-scale suction mechanism demonstrates the great potential of liquid regulation in improving suction adaptation and shows strong adaptive suction on challenging complex dry surfaces. It enables a new low-cost, clean and powerful soft adhesion strategy for next-generation robots.

Main Text

Introduction

Improving the adaptation on complex surface topographies, including curvature and roughness, has been a critical challenge for the development of artificial suction cups. Current industrial solutions use always-on air pumps to actively generate the suction (1-3); however, these are noisy and waste energy. With no need for a pump, it is well known that many natural organisms with suckers, including octopuses, some fishes (e.g., suckerfish and remoras), leeches, gastropods and echinoderms, can maintain their superb adaptive suction on complex surfaces by exploiting their soft body structures. It is generally agreed that the highly adaptive suction of octopus suckers is the result of dexterous musculature movement and the soft epithelium, helping them to conform to irregular substrates (4). This has inspired the design of adaptive suction cups, in particular with respect to their mechanical design and mechanically-enabled surface conformation. For example, similar to the musculature movement of the octopus sucker, some research utilises positive-pressure actuated chambers to generate conformation and antagonistic force on the substrate (5, 6) while others utilise a granular jamming bag, i.e., an elastic bag enclosing free-move granules to conform to the surface that is stiffened via vacuum to retain the deformed shape (7-9). Another example is using a sucker pad made from soft materials (10-12) or fabricating micro-denticles at the bottom surface (13), similar to the soft epithelium of the octopus sucker, to conform to surface roughness. The mechanical conformation aims to reduce the leakage gap size via material deformation, and can generate suction on modest irregular surfaces. However, the lack of direct evidence of adaptation to both highly curved (e.g., a saddle surface, to which compliant materials cannot easily conform) and rough surfaces, and the dependence on vacuum pumps (10-12) indicates that the mechanical conformation alone has questionable usefulness on real complex surfaces.

Given the difficulty of mechanical conformation to build a seal on complex surfaces, researchers sought to utilise liquid to fill in the leakage gap. The enhancement of a liquid seal originates from its much higher viscosity than air, which cubically increases the suction longevity (12). Previous research includes restricting the suction cup to underwater environments (14-16), wetting the substrate by *ad-hoc* pre-immersion in water (17), or manually dropping water (9) on the substrate before usage. However, these methods are not applicable for practical use and the principle of liquid seal regulation remains unclear. Biological sucker users seem to use an intelligent mechanism. Mucus glands or cells have been widely found in the sucker rim of octopus (4, 18, 19), suckerfish and remoras (20-26), leeches (27-29), gastropods (30-32) and echinoderms (33). Although the mucus of molluscs has been demonstrated to have functions of assisting protection, predation and locomotion (34), in-sucker mucus, which is at least five times more viscous than water (24), was suspected by biologists to play an important role in enhancing suction (4, 18-33). The mucus secretion has been demonstrated to be actively regulated by neural systems found in biological suckers (35-40), some of which are close evolutionary relations (41, 42). For example, leech suckers were found to secrete five times more mucus when stimulated by an increased impulse frequency (29, 43); the remora suction disc was also found to secrete a large amount of mucus when placed on a grooved substrate (25). The superb adaptive suction ability of biological suckers could therefore be attributed to the organic combination of mechanical conformation and regulated mucus seal; therefore, it is rational to make the following hypothesis: Organisms dexterously deform their soft body to make a rough shape conformation on the substrate; they then use their in-sucker mechanoreceptors to perceive the suction leakage and secrete an appropriate amount of mucus to form an effective mucus seal. This manner not only enhances their suction underwater but also makes it possible to achieve on-land adaptive suction on dry complex surfaces. It paves a new path for adaptive artificial suction on dry complex surfaces; however, no artificial suction cup has been developed with this advanced mucus regulation strategy.

In this work, we analyse the above-described biological adaptive suction mechanism in depth, and then propose its engineering analogue, the multi-scale suction mechanism. This is the first time an artificial suction cup combines mechanical conformation and a regulated liquid seal, and successfully demonstrates strong suction and high adaptability to highly curved, rough and dry surfaces such as stone, as shown in Fig. 1E. The mechanical structure mimics the biological sucker's soft body through a hierarchical structure composed of a silicone sponge and a soft silicone pad, reducing the leaking gap below 10 µm. An artificial fluidic system (AFS), mimicking the mucus gland of the biological sucker is designed to secrete water, a readily available and clean "artificial mucus", to form the water seal. We design a control system to regulate the water secretion coupled with theoretical predictions of suction leakage, thus minimizing the water consumed and left on the surface. A series of on-robot non-trivial gripping and manipulation experiments demonstrate that the proposed multi-scale suction can advance soft adhesion strategies across industry, robotics and biophysics.

Results

Multi-scale suction mechanism

The proposed multi-scale suction mechanism achieves adaptive suction with four key components inspired by biological suckers (drawn as an octopus sucker for convenience (4, 19)) as shown in Fig. 1A: i) The supporting tissues or lid connect the sucker to the octopus or robotic arm and support the underlying structures. ii) The musculature or silicone sponge allow the sucker to mechanically conform to the object overall shape to reduce leakage gap (~ mm). iii) The epithelium or soft silicone pad mechanically conform to the substrate asperities to further reduce leakage gap (<10 µm). iv) The mucus cells or AFS are located at the rim of the sucker and secrete viscous glycoprotein fluid or water to seal gaps (<10 µm). The structural details of the suction cup are further shown in SI Appendix, section 1 and Fig. S1. The multi-scale suction cup is actuated by a snap-through (ST) muscle membrane, via the working principle as shown in Fig. S3. By the mechanical conformation (via silicone sponge + silicone pad) and water seal (via AFS), we replicate biological suckers' hierarchical suction mechanism, reducing the sucker-surface gap to <10 µm and fill the gap with water. The longevity of a water-sealed suction cup is approximately 55 times longer than a dry suction cup due to the increased viscosity of water compared to air. However, the longevity of suction decays cubically with the gap size. Therefore, to make the water seal effective (>10 s for typical grasping application) the gap must be reduced to below 10 µm by the mechanical conformation, as Fig. 1B shows, according to our calculation in SI Appendix, section 3. In addition to mimicking the biological suction mechanism, the multi-scale suction cup also employs a similar capture and release mechanism (44), as shown in Fig. 1C.

The adaptability of the multi-scale suction cup is demonstrated in Fig. 1D. Several objects that are challenging for artificial suction cups to grip are successfully picked up and held by the multi-scale suction cup (see Movie S1). Fig. 1E shows a time-lapse sequence using the suction cup to grip a dry, curved, rough and heavy (598.4 g) stone. The actuation of the ST membrane was manually controlled by a syringe (see Movie S1). The actuation of the ST membrane involves an inversion-capture motion which builds the mechanical conformation. Following this, a small volume of water was secreted from the AFS located at the suction cup rim to complete water seal. The stone was successfully held with a strong and stable suction. This adaptive gripping in a dry environment, as demonstrated, has not been achieved by prior suction cups. The suction was then eliminated by simply inverting the ST membrane again. Finally, the syringe pumped a small amount of air into ST membrane to reset the suction cup, ready for the next grasp, as detailed in Fig. S3.

Multi-scale suction cup design and optimization

A series of experiments were implemented to optimize the silicone sponge, silicone pad and AFS design for achieving the mechanical conformation and water seal, respectively. The mechanical conformation is the combined result of the large-scale conformation of the silicone sponge and small-scale conformation of the soft pad. The optimization of the large-scale conformation is shown in Fig. 2A. The conformation ability of silicone sponge comes from its porous structure, which is fabricated by the salt-templating method (see SI Appendix, section 1). The mass ratio (table salt to silicone) determines its porosity and influences the large-scale conformation. A squeezing test on different combinations of mass ratio and hardness (influencing its mechanical property) was used to find the appropriate silicone sponge to achieve large-scale conformation to the substrate's curvature. The normalized conformation, calculated by maximal deformation/original thickness, indicates that the large-scale conformation is optimal when the mass ratio is 4 (when porosity is 0.67). The optimization of small-scale conformation is shown in Fig. 2B. Microscopic images show that a softer silicone pad conforms better to surface small gaps (see details in SI Appendix, section 5 and Fig. S8), and thus Ecoflex 00-30 was used to fabricate the silicone pad. The optimization of water seal is shown in Fig. 2C and detailed in SI Appendix, section 4. It is challenging to spread water uniformly around the whole suction cup rim to prevent air leakage. Three novel features make the artificial water seal possible: six radially distributed thin channels convey water from the central hollow shaft to the rim; hydrophobic silicone is chemically modified to be hydrophilic by adding hydrophilic copolymers - poly(dimethylsiloxane-b-ethylene oxide) (PBP) (45); finally, the silicone pad rim is enclosed with a superabsorbent (SA) porous foam to store and deliver water around the suction cup via capillary force (46, 47). Hydrogel could also be an option for making a hydrophilic pad (48); however, the PBP-modified silicone is highly suited to the current design, considering the tensile strength and elongation ratio requirement during suction. As shown in Fig. 2C, the large sealing ratio (the proportion of the wetted rim, $\alpha_w/2\pi$) and small overflow distance d_o indicate that the designed AFS uniformly generates a water seal around the rim. The spontaneous water spreading can be seen in Movies S2 and S3.

Longevity test: flat and rough surfaces

From large scale to small scale, the surface complexity can be described using both the overall curvature and the roughness. To evaluate the adaptive suction on complex dry surfaces, we first test the suction cup on flat and rough surfaces to test the small-scale mechanical conformation (the silicone pad squeezing) and water seal. Later, we will test it on highly curved and rough surfaces to test the multi-scale suction including the large-scale silicone sponge conformation. Flat and rough samples were prepared with 60 (roughest), 80, 120, 180, 220, 360 and 400 (smoothest) grit, as the microscopic photos show in Fig. S8. The experimental setup shown in Fig. 3A is used to apply constant pulling forces (2 N) on the suction cup. The suction cup was tested in three cases: Case 1, completely dry environment; Case 2, underwater (completely wet); and Case 3, dry environment with 1 mL/min water secretion (thereby generating a local wet environment). An unmodified commercial PVC (Polyvinyl chloride) suction cup (denoted S_{PVC}) with the same diameter (30 mm) as the multi-scale suction cup (denoted $S_{MultiScale}$), is also tested on the same setup in Case 1 and Case 2. S_{PVC} exhibits larger hardness (shore 60 A) than $S_{MultiScale}$ (00-30). Detailed experiment procedures are given in Movie S4 and Materials and Methods.

Fig. 3B shows the results of the dry suction test. $S_{MultiScale}$ can maintain suction on samples not rougher than 220 grit up to approximately 38 s, while S_{PVC} cannot maintain suction on any tested rough surface. When moved to underwater environment (Fig. 3C), S_{PVC} has non-zero longevity from 360 grit and $S_{MultiScale}$ performs even better with non-zero longevity from very rough 60 grit. When $S_{MultiScale}$ secretes water on the dry substrate with a rate of 1 mL/min (Fig. 3D), its longevity falls between Case 1 (the expected lower limit) and Case 2 (the expected upper limit).

Longevity test: highly curved, rough and dry surfaces

Three groups of hypersurfaces: ellipsoid (denoted by "E"), hyperbolic paraboloid (denoted by "H") and parabolic cylinder (denoted by "P") are used to represent a range of complex surface shapes. Ellipsoids are convex on both *x* and *y* axes, hyperbolic paraboloids are concave on *x* axis and convex on *y* axis, and parabolic cylinders are flat on *x* axis and convex on *y* axis. Each type of hypersurface consists of five samples with different curvatures, from the highest curved {E_1, H_1, P_1} to the lowest curved {E_5, H_5, P_5}. They are parameterized according to SI Appendix, section 6. The relative radius of curvature (RRoC) of hypersurfaces, defined as $R_{x=0}/r_s$, is used to represent the difficulty for generating suction, where $R_{x=0}$ is the radius of curvature at $x = 0$ in the xz plane (i.e., the contacting site) as shown in Fig. S9, $r_s = 15$ mm is the radius of the suction cup. A smaller RRoC indicates that the surface is more curved and challenging for the suction cup to generate suction. Two of each shape were fabricated, one with smooth surface and another with roughness of 220 grit, a challenging roughness according to the former experiments.

First, the maximal suction force of $S_{MultiScale}$ on smooth hypersurfaces under two cases, dry (same as Case 1) and AFS-enhanced (1 mL/min, same as Case 3), were measured. As shown in Fig. 3E, $S_{MultiScale}$ generated suction on all but the highest curved samples {E_1, H_1, P_1} in both cases. The maximal instantaneous suction force in the AFS-enhanced case is lower than in the dry case (attributed to the instantaneous lubrication from the water before the suction was achieved, causing the loss of van der Waals force – see Discussion section), but showed much longer longevity than the dry case. {E_2, H_2, P_2} and {E_3, H_3, P_3} were then selected for the AFS-enhanced longevity test (1 mL/min) on the same setup. As shown in Fig. 3F, $S_{MultiScale}$ generates suction on samples {E_2, E_3, H_3, P_3} with the larger RROC generating high longevity, including approximately 100 s on E_2 and over 600 s on E_3. The conformation of the suction was exceeded for the most curved samples H_2 and P_2 and no suction was generated.

Picking-up test by a robotic arm

We mounted the multi-scale suction cup on a robotic arm and used it to grip a range of highly curved and rough objects. The three hypersurfaces, hemispheres and hemicylinders with 220 grit roughness were also tested. Each sample was tested three times, and in each test the object was adhered, held and then shaken for 20 seconds. As shown in Fig. 3G, all the samples except for P_2 passed the test. These results prove the practicality of the multi-scale suction cup for picking up curved and rough objects in the real world. More details are shown in Movie S5.

Regulation of the water secretion

To increase suction longevity and minimise water overflow, the water secretion rate should equal the suction leakage rate. The AFS would supply more water on rough substrates and less water on smooth substrates, as the remora does (see Introduction) (25). A constant water secretion rate is liable to result in sub-optimal longevity (if the rate is too low) or excess water wastage (if the rate is too high). Suction leakage is a dynamic process (12), therefore we consider a model-based open-loop calculation of secretion rate to optimize the water secretion rate. We use the leakage model of the suction cup in wet environment from (12): $\dot{V} = L_y u_\mathrm{c}^3 (p_\mathrm{atm} - p_\mathrm{in})/(12\eta L_x)$, where η is the viscosity of liquid, $\dot{V}$ is the leakage rate, L_y and L_x are the length and width of contact area, u_c is the gap size, $(p_\mathrm{atm} - p_\mathrm{in})$ is the pressure differential between the atmosphere and suction region. L_y, L_x, u_c and $(p_\mathrm{atm} - p_\mathrm{in})$ are the unknown parameters. Based on the geometrical and physical model in SI Appendix, section 7, they are all monotonically correlated with h, which is the height of the centre of the suction cup bottom lifted from the substrate. Therefore, by recording h during the longevity experiments on flat and rough samples as shown in Fig. 4A, the leakage rate can be derived. Detailed procedures are shown in Materials and Methods. The approximated $\tilde{u}_\mathrm{c}$ can be derived as shown in Fig. 4B, which is consistent with the former estimation that the leaking gap is reduced below 10 µm. Note that, $(p_\mathrm{atm} - p_\mathrm{in})$ can also be directly measured; however, the inner volume of the measurement system, including the pressure sensor and tubes, will inevitably influence the accuracy of measured suction pressure. We use the measured $(p_\mathrm{atm} - p_\mathrm{in})$ as a characterization of the suction cup performance, as shown in Fig. S14. Results indicate that the proposed suction cup can generate up to -61.4 kPa (dry condition) and -56.1 kPa (wet condition) suction pressure.

The optimal water secretion rate is adjusted by the open-loop control strategy shown in Fig. 4C, demonstrated by the setup shown in Fig. 4D. Initially, the leaked volume $V(t_0)$ and $h(t_0)$ are assumed zero, and the pulling force $F(t_0)$ is obtained by the load cell. The leaked water volume in next sample interval (0.1 s in this study), $\Delta V(t_i)$, can be derived by the leakage model $L\big(V(t_i), h(t_i), F(t_i)\big)$. The PC controls the syringe pump to secrete water with volume of $\Delta V(t_i)$ to compensate for the leakage, then $h(t_{i+1})$ can be derived by the geometric model $G(V(t_{i+1}))$. The whole iterative loop can be written as:

$$\Delta V(t_i) = L\big(V(t_i), h(t_i), F(t_i)\big),$$
$$V(t_{i+1}) = V(t_i) + \Delta V(t_i),$$
$$h(t_{i+1}) = G\big(V(t_{i+1})\big).$$

Through this strategy, a 500 g weight, covered by a 180-grit rough surface, was successfully picked up and shaken randomly by a robotic arm for 20 seconds, then finally released. Shown in Fig. 4E and Movie S6, the water secretion rate varies with time, while the water border (white reflective curve, recorded by the on-gripper camera) is almost stable without distinct movement from 12.2 s to 21.9 s, indicating that the water leakage and secretion rate are approximately balanced. After release, only a thin layer of water was left on the surface and evaporated quickly.

Demonstrations of practical applications

Two highly curved animal plastic models, a cow and a pig with grooved surface texture, and several building blocks with rough wooden textures are tidied up by using the multi-scale suction cup on a robotic arm. Since the surface topographies of toys are unknown and quite irregular, we chose to use a constant water supply rate of 4 µL/s based on our preliminary tests on these toys, which ensured successful consecutive grasping and did not leave severe water overflow on the substrate. The tricky postures shown in Fig. 4F (i) and (ii) prove that the multi-scale suction cup generated quite strong and stable suction on the two highly curved and rough objects. Some procedures require the suction cup to maintain the suction for a long time, e.g., Fig. 4F (v) to (viii), further demonstrating its longevity on complex surfaces. The video of this experiment is shown in Movie S7.

Discussion

Principles of mechanical conformation

Experiments on curved surfaces demonstrated the effectiveness of the large-scale conformation achieved by the silicone sponge, as shown in Fig. 3E-G. Zero suction force in both dry and wet conditions on $\{E_1, H_1, P_1\}$ shown in Fig. 3E demonstrate that the shape conformation is an essential condition of the small-scale conformation. In addition, the large-scale conformation showed higher effectiveness on the ellipsoids than the other shapes (shown in Fig. 3F), which might be caused by the shape similarity between the suction cup and ellipsoids. Inserts in Fig. 3F show that the sealing on ellipsoids is complete, but a non-contact central region exists for hyperbolic paraboloids and parabolic cylinders. Using the soft silicone pad successfully achieved the small-scale conformation, demonstrated by the experimental results on flat and rough surfaces, as shown in Fig. 3B-C. Soft elastomers also have been utilised in developing adhesive pads based on van der Waals (VDW) force (46, 49). The VDW force is effective for gripping lightweight objects but is significantly reduced in wet conditions (50), which also explains the results in Fig. 3E, where the measured wet suction force is a little lower than dry suction. In contrast, the soft pad in the presented suction cup is used for mechanical conformation on rough surfaces, and will not be affected by wet conditions. This mechanical conformation via soft pad could be explained by the contact mechanics at the suction interface (51). The average gap size $\bar{u}$ that causes leakage has the following relation with the surface roughness (represented by the roughness power spectrum $C(q)$ with respect to roughness wavevector q), the squeezing pressure p, and the equivalent Young's modulus of the suction cup bottom material E^*:

$$\bar{u} \propto C(q), p, E^*.$$

This equation indicates that to reduce the leakage (i.e., reduce $\bar{u}$), a higher squeezing pressure p and a softer bottom (i.e., lower E^*) are required, while the surfaces roughness is not related to the design of the suction cup. The geometry and suction cup skeleton hardness of the two suction cups are the same, while $S_{\mathrm{MultiScale}}$ enables higher squeezing pressure through squeezing the silicone sponge and a much softer bottom (00-30) than S_{PVC} (~60 A). Therefore, the gap of $S_{\mathrm{MultiScale}}$ is much smaller than S_{PVC} and hence $S_{\mathrm{MultiScale}}$ can generate effective dry suction on moderately rough surfaces ($\geqslant$ 360 grit, Fig. 3B) and can generate strong underwater suction on rougher surfaces ($\geqslant$ 80 grit, Fig. 3C). Via the above-mentioned hierarchical mechanical conformation, the proposed multi-scale suction cup leaves less than 10 µm apertures on rough substrates, demonstrated by the results shown in Fig. 4B, which are ready for the water seal. However, we should stress again that the conformation is passively achieved by squeezing the multi-layer soft materials; this is analogous to, but differs in detail from, the mechanical conformation of biological suckers via dexterous muscle movement (4).

Role of regulated water secretion

Although biological mucus is typically at least 5 times more viscous than water which enables longer suction longevity (24), water is simpler, cleaner and low-cost. The 1 mL/min water secretion experiments on flat and rough surfaces demonstrated the effectiveness of the water seal, as shown in Fig. 3B-D. Comparing Fig. 3B and Fig. 3C, we draw two conclusions: 1) Water helps suction adhesion on rough surfaces, and 2) water enhancement is much more effective for roughness of >120 grit (the gap size is deemed to be reduced below 10 µm). In Fig. 3D, the 1 mL/min rate places suction longevity between the dry and underwater conditions, indicating that the 1 mL/min water secretion rate has formed an effective local wet environment on the dry surface but not enough to match the stability of underwater suction. The standard deviation of Case 3 is larger than the other two cases due to the manual pre-wetting at the start of the test. The model-based strategy successfully tuned the water supply rate to address this problem on the flat and rough surfaces. Maintaining a constant flow rate is also a potential means to simplify the system, mitigating the need for a load cell and real-time computation. A sufficiently high flow rate would enable the gripper to generate suction on surfaces with unknown roughness but at the expense of excessive water residue, as we used in the tidy-up-toys experiment. The value of the constant supply rate should therefore be approximately calculated or tested in advance to minimise the water overflow, based on an estimate of the maximum leakage rate. Future development of the AFS will involve embedding in-sucker sensors (e.g., strain sensors as reported in (52, 53)) to give feedback of leakage state, adjusting the water secretion rate in real-time on substrates with unknown features. Although the wet environment causes a little reduction of suction force due to the loss of VDW force (Fig. 3E), its benefits, including application across a wider range of surfaces and significantly improved suction longevity (> 5500%), far outweigh this limitation. Wet adhesion has also been demonstrated to be beneficial to capillary adhesion (46, 47). However, the fundamental difference in adhesion principle makes a water-enhanced suction cup generate higher adhesive force, while the capillary adhesive pad can be applied on permeable surfaces.

Conclusions

In this article, we present a novel bioinspired multi-scale suction mechanism to address the difficulty of generating adaptive suction on dry and complex surfaces. Our hypothesis is that the superior adaptive suction of biological suckers is the result of the combined action of the movement of their soft bodies and a neuro-regulated mucus seal. Following this hypothesis, the proposed multi-scale suction mechanism successfully demonstrates its adaptive suction on highly curved, rough and dry surfaces. The presented artificial suction cup employs a multi-layer soft structure for generating a mechanical conformation to the substrate and an artificial fluidic system for generating an effective water seal. We present a regulated water secretion strategy based on a physical model, thereby the suction cup achieves long suction longevity on complex surfaces with minimal water consumption and overflow. We demonstrate its practical applications as a robotic gripper on a wide range of complex dry surfaces, showing its great potential in industry, robotics and advancing the development of soft and wet adhesion strategies.

Materials and Methods

Design and fabrication of the suction cup

The lid (top blue component in Fig. S1) is 3D printed by resin (Photon Mono X, Anycubic). The ST membrane (amber) beneath the body is made by casting PU rubber (PT Flex 60, Polytek), and its structure is optimized through the method presented in SI Appendix, section 8. The constraining ring (black) beneath the ST membrane is 3D printed from ABS (F270, Stratasys). The silicone sponge is made by salt templating method. The sucker skeleton is made by casting the PT Flex 60 PU rubber. The fabrication of the PBP-silicone pad is presented in the following section. Details of fabricating silicone sponges, sucker skeleton and PBP-silicone are presented in SI Appendix, section 1. The SA foam is a commercial super-absorbing foam (Spunj) with 1.8 mm thickness, cropped into 4 mm height and 94 mm length. The length of SA foam is a little shorter than the perimeter of the suction cup to leave enough space for swelling. The commercial silicone film (LMS) has 60 A shore hardness and is 0.5 mm thickness. Assembly of the body, ST membrane and constraining ring is by rigid gluing (Precision Max, Loctite). The assembly between other components is by soft gluing (Sil-Poxy, Smooth-On). Before assembling the SA foam, the SA foam is pre-wetted and wound on a tube with diameter of 30 mm. After drying out, SA foam is in the form of a circular shape.

Measurement of the longevity on rough samples

The rough sample (including the flat and rough samples and the curved and rough samples) to be used is connected to one end of the load cell (SB, JL-maxwell), as shown in Fig. 3A. The sampling frequency of this load cell is 10 Hz. The pulling force is applied by a suspended weight through a pulley system. Water secretion is provided by the syringe pump (NE-1000, New Era Instruments). The longevity is measured as the time difference between when the force signal turns from negative (suction cup is being squeezed) to positive (suction begins) and from positive to zero (suction cup breaks). The following steps were used: i) Use an air pump to generate a negative relative pressure differential to invert the suction cup. ii) Place the suction cup onto the rough sample by hand, and apply a squeezing force to ensure a solid contact. iii) Reverse the direction of the pump to generate a positive relative pressure differential to let the suction cup capture the rough sample. The pump is then turned off, and suction is maintained by the stresses within the stable state of the ST membrane. iv) Remove hand so that the weight exerts a constant pulling force on the suction cup. The pulling force is recorded in real-time by the load cell. v) After a period, the suction cup will suddenly break away from the sample. The real-time force information is used to quantify the longevity of this test. In Case 3 of Fig. 3A, before step iv) we let water secretion run for 2 seconds, so that approximately 33 µL of water will overflow on the substrate (the SA foam is pre-saturated by default). This is to ensure the water seal is formed in advance of pulling test.

Leakage model of the proposed suction cup

The contact region (where the suction cup bottom tightly conforms to the substrate to form the seal) is a circular ring-shaped region. The outer diameter of this region is denoted as d_{out} and the inner diameter is denoted as d_{in}. L_x and L_y in the leakage model, are defined by

$$L_x = \frac{d_{\mathrm{out}} - d_{\mathrm{in}}}{2},$$
$$L_y = \frac{\pi(d_{\mathrm{in}} + d_{\mathrm{out}})}{2}.$$

We also assume $d_{\mathrm{in}}(h)$ and $d_{\mathrm{out}}(h)$ are functions of h, and they are obtained through the method in SI Appendix, section 7. The force balance of the suction cup is

$$F_{\mathrm{p}} = F_{\mathrm{s}} + F,$$

where F_{p} is the pressure differential force applied on the suction cup, F_{s} is the squeezing force applied by the suction cup to the substrate and F is the external pulling force. F_{s} is mainly contributed by the deformation of suction cup geometry, i.e., the compression of the silicone sponge and the bending of the skeleton and the silicone pad. F also slightly changes the suction cup geometry, but this influence on F_{s} is negligible. Under this approximation, the suction cup geometry change is only related to h, indicating that $F_{\mathrm{s}}(h)$ is the function of h. The measurement of $F_{\mathrm{s}}(h)$ is also included in SI Appendix, section 7. The region inside of d_{in} shares the same p_{in} and largest relative pressure differential $\Delta p(d < d_{\mathrm{in}}) = p_{\mathrm{atm}} - p_{\mathrm{in}}$. The region outside of d_{out} connects to the atmosphere therefore $\Delta p(d \geq d_{\mathrm{out}}) = 0$. We simply assume that the pressure is linearly descending in the radial direction in the contact region. Therefore, the pressure differential force applied on the suction cup is the sum of the pressure differential force from the inner sealed suction region and the pressure differential force from the contact region,

$$F_{\mathrm{p}} = \frac{\pi d_{\mathrm{in}}^2 (p_{\mathrm{atm}} - p_{\mathrm{in}})}{4} + \int_{d_{\mathrm{in}}}^{d_{\mathrm{out}}} \frac{\mathrm{d}d \cdot \pi d \Delta p(d)}{2}.$$

Then we obtain $(p_{\mathrm{atm}} - p_{\mathrm{in}})$.

Geometric model of the proposed suction cup

Water is assumed to be an incompressible fluid, and at any time the proposed suction cup is assumed as a cone with a flat rim around it. The water volume leaked into the suction region V is

$$V = \frac{1}{3}[S_1(h + h_0) - S_0 h_0],$$

where $S_0 = \pi r_0^2$ and $S_1 = \pi r_1^2$. By similarity, $r_1 = (h_0 + h)r_0/h_0$, where $h_0 = r_0/\tan(\pi/2 - \alpha)$. Note that, $r_1 \neq d_{\mathrm{in}}/2$. The diagram of the geometric model is shown in Fig. S10.

Calculation of gap size $\tilde{u}_c(h)$

The following assumptions are made to further simplify the model: i) L_x, L_y, which are only related to h, can be experimentally measured. ii) u_{c} is related to the q (surface topography) and h, and iii) $(p_{\mathrm{atm}} - p_{\mathrm{in}})$ is related to h and the pulling force F. The model of leakage rate is therefore,

$$\dot{V}(q, h, F) = \frac{L_y(h) u_{\mathrm{c}}^3(q, h)\big(p_{\mathrm{atm}} - p_{\mathrm{in}}(h, F)\big)}{12\eta L_x(h)}.$$

The surface topography q cannot be readily derived, and it is affected by the fabrication methods and materials used. $u_{\mathrm{c}}(q, h)$ is the function of surface topography q, therefore different surfaces have different $u_{\mathrm{c}}(h)$. To eliminate q, we obtained $u_{\mathrm{c}}(h)$ for different samples by the following method. The experimental setup used is the same as shown in Fig. 3A Case 2. A weight is used to apply a constant pulling force $F(t) = const$ (here we use $F = 5$ N). A camera is used to record the lifted height $h(t)$. Once $h(t)$ is obtained, $\dot{V}(t)$ can be calculated by the geometric model and $\big(p_{\mathrm{atm}} - p_{\mathrm{in}}(t)\big)$, $L_x(t)$ and $L_y(t)$ are also obtained by fitted curves. Since all the other parameters have been determined, $u_{\mathrm{c}}(t)$ can be inversely calculated by the leakage model. Once $u_{\mathrm{c}}(t)$ and $h(t)$ are known, $\tilde{u}_{\mathrm{c}}(h)$ can be obtained by eliminating t. The same process can be conducted on different samples to obtain different $\tilde{u}_{\mathrm{c}}(h)$. In addition, $\tilde{u}_{\mathrm{c}}(h)$ exhibits an irregular shape, and is not readily fitted to a simple model. We used the MATLAB function `slmengine()` to generate a fitted spline and to retrieve the value quickly during the real-time experiments.

Acknowledgments

We thank Toby Tate-Druiff and Andrew Stinchcombe for helping with suction cup fabrication and we thank Ben Baker for helping with the PBP-silicone wettability measurements.

References

1. K. Tai, A.-R. El-Sayed, M. Shahriari, M. Biglarbegian, S. Mahmud, State of the Art Robotic Grippers and Applications. *Robotics* **5**, 11 (2016).

2. J. Shintake, V. Cacucciolo, D. Floreano, H. Shea, Soft Robotic Grippers. *Advanced Materials* **30**, 1707035 (2018).

3. Piab (2023) Suction cups and soft grippers.

4. W. M. Kier, A. M. Smith, The Structure and Adhesive Mechanism of Octopus Suckers. *Integrative and Comparative Biology* **42**, 1146-1153 (2002).

5. A. Giri, C. Girerd, X. Luo, R. Broderick, T. K. Morimoto (2022) Modeling and Design of Soft, Positive-Pressure Actuated Suction Cups for Anchoring in Minimally Invasive Surgery. in *2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)* (IEEE), pp 01-08.

6. S. X. Yang (2013) Positive pressure induced channeled suction cups. (Massachusetts Institute of Technology).

7. J. R. Amend, E. Brown, N. Rodenberg, H. M. Jaeger, H. Lipson, A Positive Pressure Universal Gripper Based on the Jamming of Granular Material. *IEEE Transactions on Robotics* **28**, 341-350 (2012).

8. M. Fujita *et al.*, Development of universal vacuum gripper for wall-climbing robot. *Advanced Robotics* **32**, 283-296 (2018).

9. T. Tomokazu, S. Kikuchi, M. Suzuki, S. Aoyagi (2015) Vacuum gripper imitated octopus sucker-effect of liquid membrane for absorption-. in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (IEEE).

10. S. Song, D. M. Drotlef, D. Son, A. Koivikko, M. Sitti, Adaptive Self‐Sealing Suction‐Based Soft Robotic Gripper. *Advanced Science* **8**, 2100641 (2021).

11. H. Tsukagoshi, Y. Osada, Soft Hybrid Suction Cup Capable of Sticking to Various Objects and Environments. *Actuators* **10**, 50 (2021).

12. A. Tiwari, B. N. J. Persson, Physics of suction cups. *Soft Matter* **15**, 9482-9499 (2019).

13. G. W. Hwang, H. J. Lee, D. W. Kim, T. H. Yang, C. Pang, Soft Microdenticles on Artificial Octopus Sucker Enable Extraordinary Adaptability and Wet Adhesion on Diverse Nonflat Surfaces. *Advanced Science* **9**, 2202978 (2022).

14. F. Tramacere, A. Kovalev, T. Kleinteich, S. N. Gorb, B. Mazzolai, Structure and mechanical properties of<i>Octopus vulgaris</i>suckers. *Journal of The Royal Society Interface* **11**, 20130816 (2014).

15. B. Mazzolai *et al.*, Octopus‐Inspired Soft Arm with Suction Cups for Enhanced Grasping Tasks in Confined Environments. *Advanced Intelligent Systems* **1**, 1900041 (2019).

16. G. Meloni, O. Tricinci, A. Degl'Innocenti, B. Mazzolai, A protein-coated micro-sucker patch inspired by octopus for adhesion in wet conditions. *Scientific Reports* **10** (2020).

17. L. Li *et al.*, Aerial-aquatic robots capable of crossing the air-water boundary and hitchhiking on surfaces. *Science Robotics* **7**, eabm6695 (2022).

18. W. M. Kier, A. M. Smith, The morphology and mechanics of octopus suckers. *The Biological Bulletin* **178**, 126-136 (1990).

19. G. Accogli, G. Scillitani, D. Mentino, S. Desantis, Characterization of the skin mucus in the common octopus Octopus vulgaris (Cuvier) reared paralarvae. *Eur J Histochem* **61**, 2815 (2017).

20. M. Beckert (2015) Mechanics of remora adhesion. (Georgia Institute of Technology).

21. M. Beckert, B. E. Flammang, J. H. Nadler, A model of interfacial permeability for soft seals in marine-organism, suction-based adhesion. *Mrs Advances* **1**, 2531-2543 (2016).

22. O. Gona, Mucous glycoproteins of teleostean fish: a comparative histochemical study. *The Histochemical Journal* **11**, 709-718 (1979).

23. S. M. Pinky, J. Ojha, A. K. Mittal, Scanning electron microscopic study of the structures associated with lips of an Indian hill stream fish Garra lamta (Cyprinidae, Cypriniformes). *European Journal of Morphology* **40** (2002).

24. S. D. Roberts, M. D. Powell, The viscosity and glycoprotein biochemistry of salmonid mucus varies with species, salinity and the presence of amoebic gill disease. *Journal of Comparative Physiology B* **175**, 1-11 (2005).

25. R. B. S. Sewell, The Adhesive Apparatus of the "Sucking-fish". *Nature* **115**, 48-49 (1925).

26. K. L. Shephard, Functions for fish mucus. *Reviews in fish biology and fisheries* **4**, 401-429 (1994).

27. T. Kampowski, L. Eberhard, F. Gallenmüller, T. Speck, S. Poppinga, Functional morphology of suction discs and attachment performance of the Mediterranean medicinal leech (Hirudo verbana Carena). *Journal of The Royal Society Interface* **13**, 20160096 (2016).

28. T. Kampowski, L.-L. Thiemann, L. Kürner, T. Speck, S. Poppinga, Exploring the attachment of the Mediterranean medicinal leech (Hirudo verbana) to porous substrates. *Journal of the Royal Society Interface* **17**, 20200300 (2020).

29. C. M. Lent, Retzius cells: neuroeffectors controlling mucus release by the leech. *Science* **179**, 693-696 (1973).

30. A. McKee, J. Voltzow, B. Pernet, Substrate attributes determine gait in a terrestrial gastropod. *The Biological Bulletin* **224**, 53-61 (2013).

31. A. M. Smith, The biochemistry and mechanics of gastropod adhesive gels. *Biological adhesives*, 177-192 (2016).

32. M. Pembury Smith, G. D. Ruxton, How fast is a snail’s pace? The influences of size and substrate on gastropod speed of locomotion. *Journal of Zoology* **314**, 12-19 (2021).

33. J. Smith, The structure and function of the tube feet in certain echinoderms. *Journal of the Marine Biological Association of the United Kingdom* **22**, 345-357 (1937).

34. M. S. Davies, S. Hawkins, "Mucus from marine molluscs" in Advances in marine biology. (Elsevier, 1998), vol. 34, pp. 1-71.

35. P. Graziadei, H. Gagne, Sensory innervation in the rim of the octopus sucker. *Journal of morphology* **150**, 639-679 (1976).

36. F. W. Grasso, The octopus with two brains: how are distributed and central representations integrated in the octopus central nervous system. *Cephalopod cognition*, 94-122 (2014).

37. K. M. Gamel, Using a bio-inspired model to understand the evolution of the remora adhesive disk. (2017).

38. K. E. Cohen, B. E. Flammang, C. H. Crawford, L. P. Hernandez, Knowing when to stick: touch receptors found in the remora adhesive disc. *Royal Society open science* **7**, 190990 (2020).

39. K. E. Cohen *et al.*, Sucker with a fat lip: the soft tissues underlying the viscoelastic grip of remora adhesion. *Journal of Anatomy* **237**, 643-654 (2020).

40. D. G. Emery, Fine structure of olfactory epithelia of gastropod molluscs. *Microscopy research and technique* **22**, 307-324 (1992).

41. A. Hejnol *et al.*, Assessing the root of bilaterian animals with scalable phylogenomic methods. *Proceedings of the Royal Society B: Biological Sciences* **276**, 4261-4270 (2009).

42. S. A. Smith *et al.*, Resolving the evolutionary relationships of molluscs with phylogenomic tools. *Nature* **480**, 364-367 (2011).

43. C. M. Lent, Serotonergic modulation of the feeding behavior of the medicinal leech. *Brain research bulletin* **14**, 643-655 (1985).

44. F. Tramacere, N. M. Pugno, M. J. Kuba, B. Mazzolai, Unveiling the morphology of the acetabulum in octopus suckers and its role in attachment. *Interface Focus* **5**, 20140050 (2015).

45. M. Yao, J. Fang, Hydrophilic PEO-PDMS for microfluidic applications. *Journal of Micromechanics and Microengineering* **22**, 025012 (2012).

46. L. Xue, A. Kovalev, A. Eichler-Volf, M. Steinhart, S. N. Gorb, Humidity-enhanced wet adhesion on insect-inspired fibrillar adhesive pads. *Nature communications* **6**, 6621 (2015).

47. Y. Chen, Z. Zhu, M. Steinhart, S. N. Gorb, Bio-inspired adhesion control with liquids. *Iscience* **25** (2022).

48. J. Hua, P. F. Ng, B. Fei, High‐strength hydrogels: Microstructure design, characterization and applications. *Journal of Polymer Science Part B: Polymer Physics* **56**, 1325-1335 (2018).

49. S. Kim *et al.*, Microstructured elastomeric surfaces with reversible adhesion and examples of their use in deterministic assembly by transfer printing. *Proceedings of the National Academy of Sciences* **107**, 17095-17100 (2010).

50. Y. Wang *et al.*, Water as a “glue”: Elasticity-enhanced wet attachment of biomimetic microcup structures. *Science Advances* **8**, eabm9341 (2022).

51. C. Yang, B. N. J. Persson, Contact mechanics: contact area and interfacial separation from small contact to full contact. *Journal of Physics: Condensed Matter* **20**, 215214 (2008).

52. H. J. Lee *et al.*, An electronically perceptive bioinspired soft wet-adhesion actuator with carbon nanotube-based strain sensors. *Acs Nano* **15**, 14137-14148 (2021).

53. E. Shahabi, F. Visentin, A. Mondini, B. Mazzolai, Octopus - Inspired Suction Cups with Embedded Strain Sensors for Object Recognition. *Advanced Intelligent Systems* **5**, 2200201 (2023).

Figure Legends

Figure 1. The proposed suction cup achieves bioinspired adaptive suction by multi-scale suction mechanism. (A) The adaptive suction concept achieved by a biological sucker (an octopus sucker (19) shown here) and the multi-scale suction cup. (B) Estimation of the longevity of a suction cup in dry and wet (water) environments with varying gap sizes. Water environment makes suction usable for practical applications when the gap is reduced to ~8 µm, but for dry suction this requirement is more difficult to achieve (~2 µm). (C) The action of the multi-scale suction cup is analogous to an octopus sucker. (D) The adaptability of the multi-scale suction cup. i: A screwdriver (76.4 g, with dimples). ii: A cow model (116.6 g, with grooves). iii: A hammer (905.3 g, with rust and contaminated by machine oil). iv: A stapler (122.5 g, with grooved texture). More of picking up irregular objects are provided in Movie S1. (E) A time-lapse sequence shows how the multi-scale suction cup grips a dry, curved, rough and heavy stone (598.4 g). The timeline at the bottom records the key time and states during the operation.

Figure 2. The multi-scale suction cup design. (A) The large-scale conformation achieved by silicone sponge. Left top: the diagram of the porous structure of silicone sponges with different mass ratio. Left bottom: the diagram of the measurement of the large-scale conformation of silicone sponges. Right: measured conformation of silicone sponges with different mass ratio. (B) The small-scale conformation achieved by silicone pad. Left: conformations of silicone pads with different hardness on a same rough sample by a same squeezing force (10 N). Scale bar: 500 µm. Right: 00-30 silicone pad (the one used for making multi-scale suction cup) conformation on different rough samples. Scale bar: 100 µm. Microscopic images see Fig. S8. (C) The water seal achieved by the AFS. Left: design of the AFS. Blue arrows indicate water flow direction. Right: influence of the AFS design on water seal, showing the case with one fluid channel. More information is provided in SI Appendix, section 4. All photos taken after 1 mL/min water supply for 20 seconds.

Figure 3. Evaluation of multi-scale suction on dry complex surfaces. (A) The experimental setup of test on flat and rough surfaces. The suction cup is suspended by a tendon above the rough sample. The tendon passes through pulleys (f) and is pulled by a mass (e) with pulling force of 2 N. A rough polyurethane (PU) substrate sample (b) is attached to a load cell (a) for recording the force in real time. c: inlet/outlet to the air pump. d: inlet to the syringe pump. g: water tank. (B) Longevity test results of S_{PVC} and $S_{\mathrm{MultiScale}}$ in Case 1. (C) longevity test results of S_{PVC} and $S_{\mathrm{MultiScale}}$ in Case 2. For $S_{\mathrm{MultiScale}}$, the longevity on 360 and 400 grit surfaces are more than 600 s. (D) Longevity test results of $S_{\mathrm{MultiScale}}$ in Case 1, Case 2 and Case 3. (E) The maximum suction force measured on smooth hypersurface samples in dry and AFS-enhanced (1 mL/min water secretion) environments. (F) The longevity measured on $\{E_2, E_3, H_2, H_3, P_2, P_2\}$ with roughness 220 grit, 2 N pulling force for $S_{\mathrm{MultiScale}}$ at 1 mL/min water secretion. Inserts are the bottom view on transparent hypersurfaces. Dark regions (enclosed by dashed lines) indicate tightly sealed regions and bright regions indicate non-contact regions. (G) Pick-up tests of two groups of curved and rough objects by $S_{\mathrm{MultiScale}}$.

Figure 4. Demonstrations of applications on a robotic arm. (A) Measured $h(t)$ curves on three samples with different roughness under a 5 N pulling force. (B) The experimentally derived $\tilde{u}_{\mathrm{c}}(h)$ on three samples. (C) The open-loop control strategy for achieving water leaking-secreting balance. (D) The experimental setup for verifying the automation application on a robotic arm. (E) Time-lapse of the on-gripper camera view shows the water border is stable during the lifting. t = 0 s: initial state, t = 2.4 s: sucker inverted, t = 9.4 s: object captured, t = 12.2 s: object lifted, t = 21.9 s: the middle of the object lifting task, t = 31.0 s: the object is released. The curves below show the contact force (red) and water secretion rate (blue) during this test. The straight line of water secretion from 7 s to 10 s is the pre-wetting before the gripping. (F) The tidying-up-toys task is

completed by the multi-scale suction cup on a robotic arm. Time marks on the right corner of sub-images are the holding time of each toy.