The Octopus Cometh: A Journey Into the Deep

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Abstract

The creatures of the sea have long awakened awe due to their otherworldly abilities to move, grasp, and manipulate objects underwater. Chief among them is the *Octopus Vulgaris*, whose suckers have long been the study of artists and scientists alike for their marvelous suction and chemo-tactile qualities. The bowl-shaped octopus sucker is composed primarily of a shallow outer cup called the infundibulum and inner cavity called the acetabulum, which work in harmony to create a suction seal to grasp objects. The infundibulum creates a seal on an object's surface, while the acetabulum contracts to reduce internal pressure and generate a tensile force on vastly different surfaces in a wide range of conditions. These properties have inspired drug-loading adhesive patches, underwater suction modules, and the transportation and assembly of industrial parts. Octopus suction cups have been mimicked in various applications, and this review will focus and direct our understanding of their mechanics and incredible potential.

Introduction

Grasping objects is an action often taken for granted by those who do not work with robots. Mechanically, it is simple to "grasp", or fasten two separate parts with a nut and bolt, or to create a threaded surface on a shaft to join metal parts. This method does not work, however, on soft parts, or parts that require a degree of gentleness or complex handling, like delicate ceramics or unwieldy geometries (*1, 2*). This has introduced the age-old problem of gentle object manipulation inspired by biological processes, like a tool that replicates the action of a hand, the claw of an insect, or octopus suckers (*1*). There is an almost overwhelming need to create a universal manipulator that can operate regardless of shape, material, weight, and operating conditions (*5, 6*). These types of manipulators first found traction in rubber suction cups that we see now in toilet plungers and children's toys because they have the ability to generate an anchoring force on rough and smooth surfaces due to a pressure difference, but are a far cry from the remarkable flexibility of octopus suckers (*5, 6*). Other manipulators lack the ability to easily detach from a surface, to generate a significant amount of suction force, and work in wet conditions (*1, 7*). The design of soft robotic grippers and suction cups continues to take inspiration from the structure and actuation of actual octopus suction cups (*8*). There is much research being done on the exciting and ever-evolving world of biomimetic adhesives centered on the complex octopus suction cup to further our mechanics and manufacturing expertise, and to conjoin the creativity of nature with the technology of man.

Structure and function

The octopus sucker is a muscular hydrostat, which means that manipulation is actuated by muscular movement and relies on the incompressibility of water. The muscles in this case not only generate force, but also provide structure for anchoring and movement (*9*). Important musculature terminology denotes that the radial muscles act from the center, or orifice location as shown in in Figure 1 to the outside wall, and the meridional muscles act parallel to the exterior surface of the sucker. As mentioned before, the structure of the octopus sucker relies on two parts connected by an orifice, the infundibulum and the acetabulum (*10*). The infundibulum is funnel shaped, ridged with radial and circumferential grooves, and converges into a constrictive orifice. It is surrounded by an epithelial lip, or rim. This funnel opens into the hollow inner cavity known as the acetabulum, which contains a protuberance on the acetabular roof (*11*). Figure 1 shows the different sections of the octopus sucker. The infundibulum and external sections of the sucker are covered in a chitinous cuticle that helps protect the muscles underneath, but also provides rigidity to the radial grooves (*8, 9*). This chitinous shell has a strength on the order of 60 to 200 MPa and is continuously renewed (*3, 4, 12*). This may be due to the interactions of the infundibulum with rough environments, as the crystallized chitinous material can handle the shearing and tearing forces of everyday octopus life.

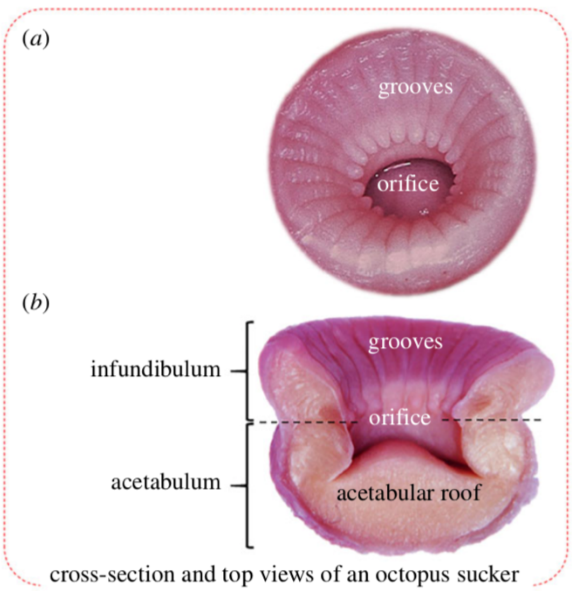


Figure 1. (a) shows the top view of the octopus sucker with particular attention to the radial grooves on the infundibulum. (b) shows the cross-sectional view of an octopus sucker with the infundibulum and acetabulum labeled. (9)

In the process of adhesion, the soft and flexible infundibulum (E~10kPa) adapts to any surface to create a water-tight seal (*11, 13*). This traps water inside the body of the acetabulum. From this point onward however, there is an ongoing debate on the actual attachment mechanism of octopus sucker cups (*4*). One hypothesis is that the acetabular chamber completely collapses, forcing all the water out of the sucker through the infundibular lip, creating an ersatz vacuum. This theory was criticized because it only accounts for the suction effect of the infundibulum, a passive sucker, similar to the way a suction cup in a shower works. The most recent theory regarding the suction forces of octopus suckers was put forth, in several iterations, by Kier and Smith, which assumes contraction of the radial acetabular muscles, increasing the acetabular cavity volume and putting the water inside the cavity in tension, which reduces internal pressure (*5, 14*). Because of water's high bulk modulus, it acts mechanically like a solid in tension, and this allows transmission of pressure reduction to all contiguous parts of the cavity. After this process, the meridional muscles of the acetabulum contract, thus forcing the protuberance to extend, coming in contact with the orifice and sealing it. In doing so, the octopus sucker has made a firm attachment to the anchoring surface by means of a pressure difference (*3, 11*). From this point onward, the sucker can cease muscular contraction, as the suction force is maintained by the elastic restoration force of the acetabular roof, the cohesive force of the water in the infundibular compartment, and the attachment force of the protuberance and orifice (*4*). This process is shown in Figure 2. The octopus sucker is both a marvel of biology and engineering and the incredible capabilities of natural adhesion devices, and it shows the natural tendency of biological creatures to avoid the redundant use of energy. This is an excellent lesson for engineers, who should take note that there is often a more efficient method to solve a problem than dumping more power into it.

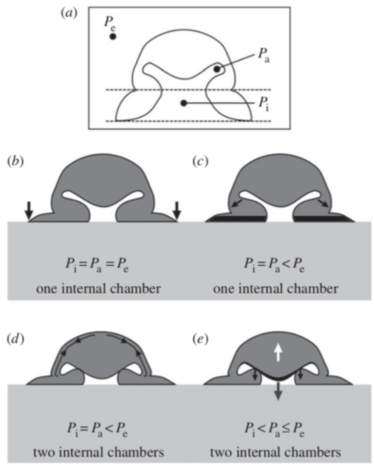


Figure 2. Stages of hypothesized sucker attachment include (b) infundibular contact, (c) acetabular radial muscle contraction, (d) acetabular meridional muscular contraction to extend protuberance, (d) suction maintained (4)

Radial Grooves and Hair-like Structures

The radial grooves in the infundibulum serve to guide the pressure generated in the acetabulum to the entire sucker-surface interface, which helps maintain a stronger attachment, as they also increase the surface area of the pressure-reduced interface (*9-11*).

Figure 3 shows the radial grooves on the surface of the infundibulum created by ridges in the chitinous cuticle (*3*). It is noted that this cuticle has a mean roughness around $11.3 \pm 3.0\ \mu m$ while the maximum depth of the cuticle is $89.5 \pm 20\ \mu m$. This depth allows pressure to be transmitted throughout the entire sucker-substrate interface and is one of the main features that set octopus suckers apart from conventional plastic suction cups (*15*).

Recent observations found that the acetabular roof contains a hair-like microstructure (*16*). Figure 4 shows the SEM photograph of the acetabular roof, along with the sucker sketch and free body diagrams. It has been hypothesized that the hairs serve to seal the gap between the protuberance and orifice. This suggests that the hairs are responsible for the adhesion force between the orifice and the protuberance. The adhesion force together with the cohesive force of the water, counterbalance the elastic recovery force of the sucker. The hair-like microstructure therefore allows the adhesion force of the protuberance with the orifice to be maintained without muscular exertion. This would explain how octopodes can attach themselves to surfaces for long periods of time without tiring. These microstructures would also allow for the acetabular roof and the orifice seal to behave as a valve that opens and closes orifice opening, therefore controlling when to relax or engage against the elastic recovery force of the sucker (*16*).

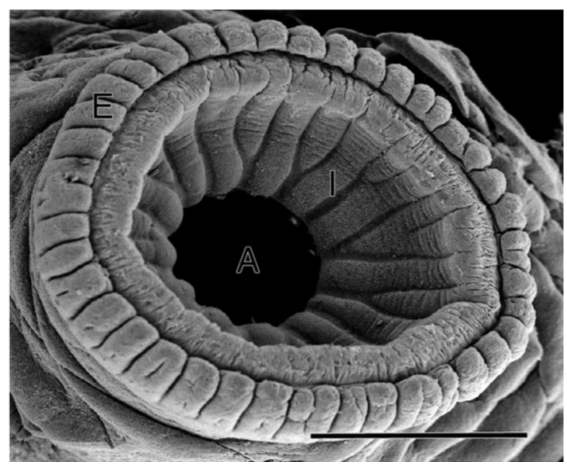
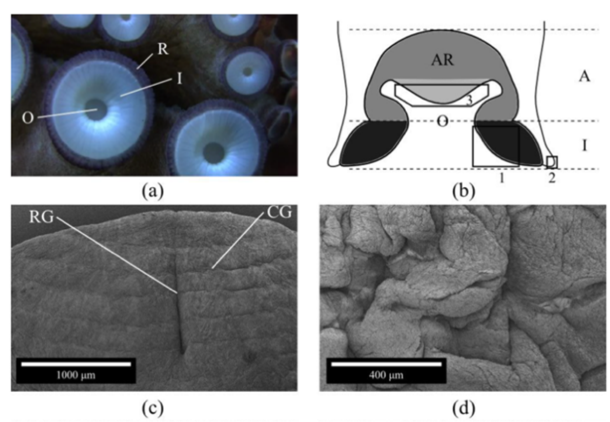


Figure 3. SEM of radial grooves of the infundibulum (3)



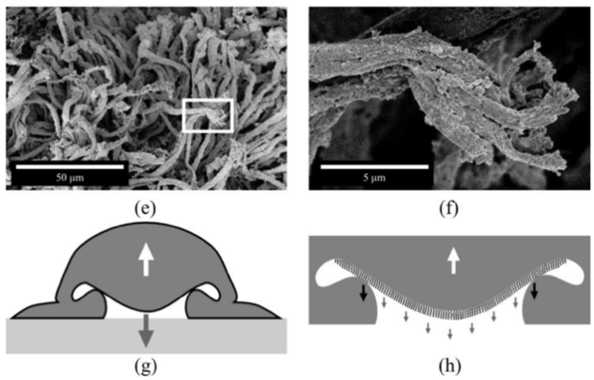


Figure 4. The orifice, rim, infundibulum, acetabulum, and acetabular roof are indicated in (a) and (b). The infundibulum is shown in more detail in (c). The radial and circumferential grooves are indicated as RG and CG, respectively. The rim is shown in (d). The hair-like microstructure of the acetabular roof is shown in (e). The white box in (e) is enlarged in (f). The free body diagram of the sucker is shown in (g). The elastic recovery force of the sucker (white arrow) is counterbalanced by the cohesive force of the water (grey arrows) and the adhesive force of the hairs (black arrows) in (h). (4)

Material Properties and Mechanics

The remarkable adhesive properties of the octopus sucker lie in its ingenious method of using muscular contraction to decrease water pressure and generate suction. Using an indentation unit with a spherical micro indenter, the Center for Micro Biorobotics tested the properties of the different sections of the octopus sucker by a force-displacement graph for a loading, waiting, and unloading phase. The loading and unloading phases were used to measure the elastic modulus of the octopus sucker and the 10 second waiting phase was used to quantify the stress-relaxation of viscoelastic behavior. It is interesting to note that the artificial materials tested as stand-ins for natural tissue did not exhibit this viscoelastic behavior, but rather maintained a constant force over the waiting time, while the octopus tissue experienced a rapid decrease in force (*15*). This experiment found that the elastic modulus of the soft and flexible infundibulum was 7.7 kPa, while the acetabular protuberance was more than double that, at 18.1 kPa (*15*). This is due to the high density of cross connective tissues in the acetabular protuberance, whereas the infundibulum consists primarily of an outside epithelium and radial muscles. We speculate that the high stiffness of the protuberance is needed to maintain the structural integrity of the sucker under tension, as when the sucker is sucking, the muscles relax and the protuberance essentially acts as a column in tension between the orifice and the acetabular roof.

Testing the mechanical properties of the octopus body, including the suckers and the arms can be rather difficult, especially when attempting to perform experiments *in vivo* because experimentation on live animals is rarely as easy it is on euthanized animals. To measure the mechanical properties of live octopodes, one research team created an apparatus to allow the octopus to reach inside a tube with a single arm to measure its length, elongation ratio, and force generation. By considering the octopus arm as a cone, it was found that due to the muscular structure of the octopus, specimens could elongate their arms to an $\epsilon = 70\%$ for a diameter shortening of only $\epsilon_D = -23\%$ (*17*). The experiment found that octopodes grasp objects at three quarters their arm length; the remaining distal quarter is used as an end effector. A 400 mm octopus arm lengths rendered a mean pulling force of 40 N (*17*). While the mechanical properties of the octopus arm are not necessarily the same as the mechanical properties of octopus suckers, this experiment represents an extremely well-documented case of *in vivo* studies on octopus mechanics, which translates very well to further research on suckers (*17*). Due to the many difficulties with *in vivo* testing, computer simulation is often used to model the functionality of octopus suckers. With the radial muscle stiffness of octopus suckers around $5 \times 10^4 Nm^{-1}$ and the meridional stiffness around $1.23 \times 10^4 Nm^{-1}$, finite element models of octopus suckers, named muscular hydrostat units, can be constructed to create assemblies of up to 300 suckers to replicate and further investigate the properties of octopus suckers on arms (*18*). This is key to the study of directed actuation in soft robotic end effectors and the use of suction to perform specific manipulations cohesively.

While pressure differences account for the suction force of the octopus sucker, the limiting factor may not be the strength of the muscles or energy requirements, but rather the cavitation limit of water inside. Cavitation occurs when fluid pressure falls beneath the vapor pressure, which causes gas bubbles to form and collapse, potentially harming the octopus or dislodging suction. The octopus suction works by inducing a negative pressure relative to ambient by expanding its acetabular cavity, so cavitation presents a limiting factor. For depths around sea level, the cavitation limit occurs between 0 and -100 kPa, while for a depth of 10m, it occurs between -200kPa and -300 kPa. The maximum pressure attainable by octopodes is given by equation (1).

$$p_d = 141 a_s^{-0.19} \qquad (1)$$

Where p_d represents the maximum pressure difference in kPa and a_s is the sucker area in mm^2. For smaller suckers, such as in distal suckers or juvenile octopodes, cavitation represents a significant issue with the ability to suck (*19*). Thus, we can see that there is an external limiting factor on the strength of octopus suction.

Bio-Inspired Solutions

Francesca Tramacere, a renowned expert in the field of octopus sucker mechanics, noted that "mimicry of infundibular morphology by an artificial suction cup should guarantee maximum attachment area and good resistance to shear forces," which is supported by many studies attempting to improve the design of traditional suction cups (*15*). A novel adhesion device that mimics not only the infundibular morphology of the sucker but also its acetabular mechanics uses resin to create the hard acetabular cavity and silicone to model the soft and compliant infundibulum. The infundibulum needs to be able to adapt to any external surface of varying roughness, and the acetabular cavity must be able to maintain its structure under the low pressure difference generated inside the cavity. Instead of using muscular contraction, this adhesion device uses a piston to expand the volume of the cavity and create water tension, and the orifice-protuberance interface is replaced with a valve. After sealing the infundibulum, the valve is opened and the pressure difference is created via the piston, which is transmitted to the infundibulum. At this point, the valve is closed and the infundibulum remains tightly adhered to the surface, regardless of further piston movement (*10*). This represents one of several designs paving the way to a future of efficient, bio-inspired artificial suction cups.

Another avenue of biomimicry is through dielectric actuators. The dielectric elastomer (DE) actuators were designed to mimic the radial muscles of the acetabulum and were chosen due to their softness and ability to generate high pressures (*20, 21*). The actuator was designed with an acrylic material (VHB 4905, 3M) with electrodes made of silver conductive grease (Circuit Works CW7100, Chemtronics). The passive membrane was made following the same procedure, but no electrodes were used. The artificial suction cup was composed of an actuation unit embedded inside the acetabulum which was connected to a passive artificial infundibulum made of silicon. Figure 5 shows the proposed suction cup (*20*).

Experiments measured the maximum pressure generated, just under 7 kPa, when the applied voltage was 2.5 kV and the volume of water inside the acetabulum was 80 mm^3. The speed of attachment was also investigated and found that the first 80% of the pressure difference is achieved within 100 ms (*20*). Improvement in the artificial infundibulum geometry and, consequently, improvements in the pressure difference, could allow this model to revolutionize suction technology.

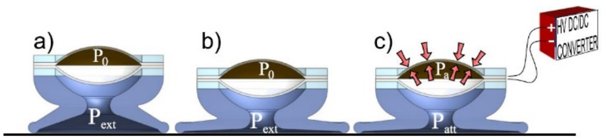


Figure 5. Attachment method proposed. (a) The suction cup approached the surface; (b) the seal is formed on the surface; (c) the actuator is activated, reducing the pressure inside the suction cup. The electrostatic forces that generate the change in pressure are represented by the arrows in (c). (20)

Adhesive patches inspired by octopus suction cups have also been investigated (*22*). Baik et al. developed four different types of adhesive patch geometries: perforated cylinders, cylindrical pillars, cylindrical holes, and octopus inspired architectures (OIAs). Their normal adhesion was compared for different substrate conditions (dry, moist, under water, and under oil) and different loading conditions. Figure 6 shows the results obtained (*23*).

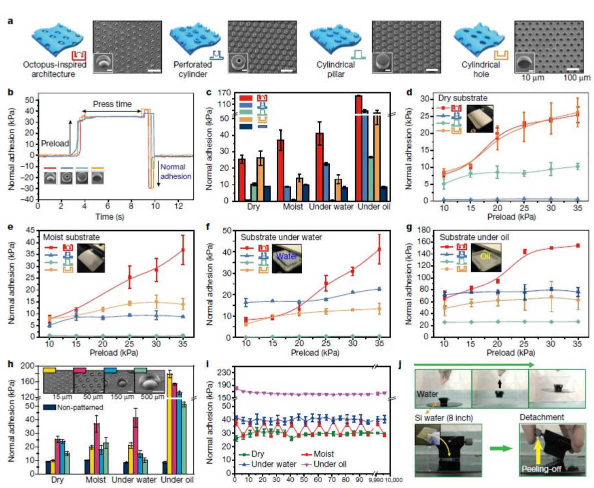


Figure 6. Adhesive geometries (a). Time response (b). Dry, moist, under water, and under oil substrates adhesion strength (c)-(g). Pull-off strength (h). OIA adhesion for over 10000 cycles (i). Wafer transport using OIA patch (j).(23)

The OIA was found to have the highest adhesive strength for moist, under water, and under oil conditions and the highest pull-off strength for dry, moist, and underwater conditions (*23*).

Summary and Conclusion

This paper has explored the many varied characteristics of the morphology and mechanics of the octopus sucker. It is important to note that despite the myriad studies done on the octopus suckers, it is difficult to get a clear picture of their exact mechanisms due to the difficulty associated with mechanical testing on octopodes *in vivo* because of the limitations of current imaging techniques. Nevertheless, octopus suckers from euthanized octopodes have become the *de facto* method by which studies have been undertaken to study the mechanical properties of octopus suction cups, but with better microscopy techniques being developed every day, the breakthrough to a fuller understanding of the mysteries of the deep is well on its way. Massive advancements in the understanding of bio-inspired suction mechanics have taken place in the past decade, especially regarding the passive suction and attachment that eluded previous theories. We believe that further study of octopus suckers and their mechanics are key to finding solutions in the fields of muscular hydrostat-inspired soft robotics and manipulator attachment on non-uniform surfaces. Models based on the geometry and materials of the octopus sucker will lead to better, more efficient and tenacious suckers, and these suckers will unlock the vast potential of biological ingenuity. We are very much on the cusp of massive breakthroughs in octopus-inspired adhesion, which may well lead to the next revolution in adhesive medical technology, robotic manipulators, and underwater actuation. Are you in?

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