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Cite this article: Ditsche P, Summers A. 2019 Learning from Northern clingfish (*Gobiesox maeandricus*): bioinspired suction cups attach to rough surfaces. *Phil. Trans. R. Soc. B* **374**: 20190204.
http://dx.doi.org/10.1098/rstb.2019.0204

Accepted: 11 July 2019

One contribution of 15 to a theme issue 'Transdisciplinary approaches to the study of adhesion and adhesives in biological systems'.

Subject Areas:
biomechanics, biomaterials, biophysics

Keywords:
attachment, biomimetic, suction

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Electronic supplementary material is available online at https://dx.doi.org/10.6084/m9.figshare.c.4588598.

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Learning from Northern clingfish (*Gobiesox maeandricus*): bioinspired suction cups attach to rough surfaces

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While artificial suction cups only attach well to smooth surfaces, the Northern clingfish can attach to surfaces ranging from nanoscale smooth to rough stone. This ability is highly desirable for technical applications. The morphology of the fish's suction disc and its ability to attach to rough and slimy surfaces have been described before, and here we aim to close gaps in the biomechanical understanding, and transfer the biomechanical principles to technical suction cups. We demonstrate that the margin of the suction disc is the critical feature enabling attachment to rough surfaces. Second, friction measurements show that friction of the disc rim is increased on rough substrates and contributes to high tenacity. Increased friction causes a delay in failure of the suction cup and increases the attachment force. We were able to implement these concepts to develop the first suction cups bioinspired by Northern clingfish. These cups attach with tenacities up to 70 kPa on surfaces as rough as 270 µm grain size. The application of this technology is promising in fields such as surgery, industrial production processes and whale tagging.

This article is part of the theme issue 'Transdisciplinary approaches to the study of adhesion and adhesives in biological systems'.

1. Introduction

Several lineages of fishes have evolved suction-based attachment organs to cling to aquatic substrates. These include snailfishes (Liparidae), lumpsuckers (Cyclopteridae), remoras (Echinidae), hillstream loaches (Gastromyzotidae), gobies (Gobiidae) and clingfishes (Gobiesocidae) [1–7]. In clingfish, the suction disc on the ventral side of their body is formed by modified pectoral and pelvic fins [7,8] and enables the fish to attach themselves in strong currents. Northern clingfish (figure 1*a*) inhabit the American Pacific coast from Northern Baja California and Mexico up to Southern Alaska. At low tide, they can be found under rocks above the low tide line.

With its suction cup, the Northern clingfish (*Gobiesox maeandricus*) can attach to smooth and also to rough surfaces, while manufactured suction cups only attach to smooth surfaces [7–9,11,12]. The fish's ability to attach to rough surfaces is highly desirable for technical applications, e.g. concerning the morphology of the suction disc and the variety of substrates *G. maeandricus* can attach to. We know that clingfish attach with forces of 80–250 times their body weight [9,11]. The actual roughness that *G. maeandricus* can attach to depends on the size of the specimen. Larger specimens can attach to surfaces with a grain size of 500–1000 µm, which is about as rough as sandstone [9]. This ability is important for Northern clingfish, as rocks in its natural environment can reach this roughness, and some are even coarser [12]. Other substrate properties, such as wettability or elasticity, have an impact on attachment [13,14]. Aquatic substrates are usually covered with microorganisms, algae and other fouling organisms [15]. This biofilm and

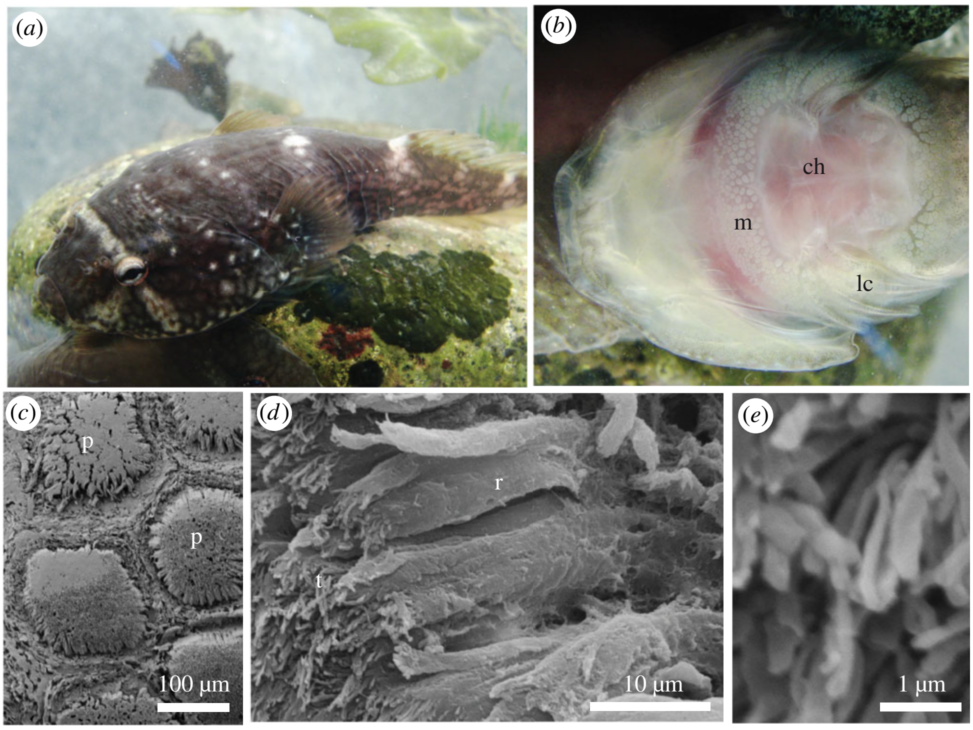

Figure 1. (*a*) Northern clingfish *G. maeandricus* attaching to a fouled rock. (*b*) Ventral view of the adhesive disc with epidermal papillae. (*c*) Papillae cover the disc margin. (*d*) Papillae consist of tightly packed rods, which are divided into tiny filaments at their tips. (*e*) Filaments on the tips of the rods. Abbreviations: lc, lateral cleft; ch, inner chamber of suction cup; m, disc margin; p, papillae; r, rods; t, tips [9]. (Online version in colour.)

periphyton alters the substrate properties considerably [9,10]. For *G. maeandricus*, the tenacity decreases somewhat on some substrate types in the presence of biofilm (up to approx. 25%). However, the tenacity was still about 150 times the fish's body weight [9].

To understand the biomechanics behind the attachment mechanism of *G. maeandricus*, we need to look at the suction cup's morphology. The lower side of the suction cup's margin is covered with hierarchical structures of increasingly finer size (figure 1*b–e*). They consist of papillae (approx. 150 µm) covered with rods (approx. 5 µm), which are divided into tiny filaments at their tips (approx. 0.2 µm) [9]. These specialized structures enable adaptation to differently sized surface irregularities of a substrate. It has been hypothesized that these structures increase the friction properties of the disc margin [11]. The material properties of the suction cup could also contribute to tenacity. Young's modulus of the Northern clingfish's suction cup is low (1.6 ± 2.3 MPa) [16]. The elastic and soft material of the disc rim, in addition to the hierarchical structure, enables adaptation to the surface structure of the substrate. We hypothesize that the unusual morphology of the disc rim is the key feature that enables Northern clingfish to attach to rough surfaces.

Experiments with artificial suction cups of identical shape and varied hardness and elasticity show that a soft suction cup allows the cup to follow the contours of a rough surface, but the softness also allows the edge material to buckle and fail more easily. The latter causes early failure of the suction cup and consequently low attachment forces [16]. This occurs in manufactured single material suction cups, but in clingfish the soft suction cup is supported by underlying bones (basipterygum, dorsal and ventral postcleithrum) [16], which prevent slipping inwards of the suction cup margin. We hypothesize that both the increased friction with the substrate and the combination of soft (disc margin) and hard materials (bone) are key features enabling the fish to attach to rough surfaces. In conclusion, the secret of Northern clingfish's ability to attach to rough surfaces with high tenacities may be the combination of enhanced sealing, increased friction and a composite construction of the suction cup.

The goal of this study is to address these knowledge gaps in the biomechanics of the Northern clingfish's attachment to rough surfaces and to develop suction cups bioinspired by Northern clingfish. We have three goals: (i) test whether the hierarchical structures on the disc rim enable attachment to rough surfaces; (ii) quantify the friction of the disc rim; and (iii) transfer what we have learned from Northern clingfish to a bioinspired suction cup prototype. This last goal will allow us to test our understanding of the biomechanics of the clingfish's suction cup.

2. Methods

(a) Animals

We collected Northern clingfish (*Gobiesox maeandricus*) in the intertidal region of San Juan Island, WA, USA. Live fish were transported to the Friday Harbor Laboratories, where they were kept in tanks with running seawater and rocks for shelter. Immediately before the experiment, we euthanized the fish with MS-222. The procedures used in this study were approved by an Institutional Animal Care and Use Committee protocol at the University of Washington. Length and disc area were determined for each fish specimen. For some parts of the experiments, the outer anterior part of the suction cup (figure 2) was carefully dissected with a razor blade. During this procedure, we ensured that a small section of the disc rim of the suction cup was kept intact. From the anterior outer part of each fish, we cut a rectangular piece for the determination of the friction coefficient.

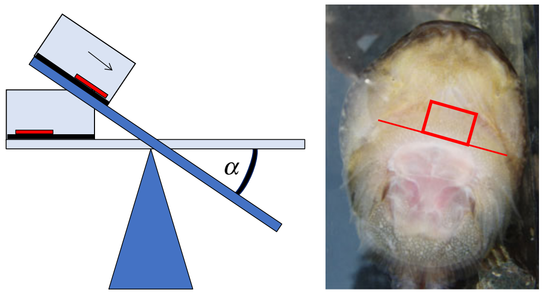

Figure 2. Experimental set-up to measure the friction coefficient. A sample of the disc rim (square in picture and illustration) was placed on a substrate (black in illustration) in a water tank. Substrate and water tank were firmly connected to the tilt table, which was continuously tilted and the angle of attack (α) recorded at which the sample started sliding. From α, the friction coefficient was calculated. (Online version in colour.)

(b) Substrates

We used a moulding technique to prepare substrates of seven different surface roughnesses. Artificial substrates were made from the same material to avoid effects of varying material properties. We cast smooth glass and several different types of sandpaper. Most of these sandpapers were commercial in origin (P600, P400, P320, P280, P180, P120 and P60; Buehler® Carbimet, Lake Bluff, IL, USA, matching average grain sizes of 15, 23, 35, 52, 78, 127 and 269 µm); they were complimented by three sandpapers of our own manufacture. For the latter, we glued sand and little stones of the grain sizes 500–1000 µm, 1000–2000 µm and 2000–4000 µm to cardboard. For the moulding process we used dental wax (President Light Body, Coltene Whaledent, Lagenau, Germany) for the negative mould, and then cast the final surfaces in epoxy resin (Low Viscosity Spurr Kit, SPI Supplies®, West Chester, PA, USA) in accordance with Koch [17].

(c) Measuring the friction properties of the disc rim of the suction cup

Friction is the force which resists sliding of one surface (sample) over another (substrate) [18]. In the classical case, the friction force of a sample is almost independent of the area of contact between sample and surface, but depends on its surface structure, material properties, and the normal force pressing the sample down on to the substrate [19]. However, there are exceptions to these friction laws for soft materials where rubber friction, proportional to area of contact, applies. This is likely to be the case for clingfish's suction cup. Friction between two materials can be described by the static friction coefficient μ. This coefficient can be measured with a tilt table. We made a motorized tilt table of stainless steel, with a stable heavy base and a large (30 × 30 cm) tilting plate (figure 2). This plate is connected to a geared DC motor by a toothed belt. The motor is driven by an Arduino microcontroller that also measured the tilt. We selected a tilting speed of 0.75°s^{-1}. The angle at which the sample starts sliding (sliding angle α) was measured and used for the calculation of the static friction coefficient. Friction measurements were performed with the sample fully submerged to avoid changes in material properties due to desiccation or interference of capillary forces in a wet environment. A transparent box was fixed to the platform of the friction slide. At the bottom of this box was a holder for reversible attachment of the substrates. We used seven different substrates for these experiments, ranging from smooth to a grain size of 4000 µm. For the experiments, the box was completely filled with water. Samples were placed in the middle of the substrate before sealing the box. Each sample used for the friction experiment was cut into a rectangle (figure 2) and attached to a small glass plate of 8 × 12 mm size with the upper and lower end bowed upwards. This way the apparent contact area with the substrate was kept constant for all samples and interlocking effect in sliding directions at the end of the sample were minimized. Each sample was placed in the tilt table so that the anterior side of the suction cup margin pointed in the downhill sliding direction. Tests were performed in random order on all seven substrates, with three repetitions of the test procedure for each sample on each substrate. The friction coefficient μ can be calculated from the angle α:

$$\mu = \frac{F\ \mathrm{friction}}{F\ \mathrm{normal}} = \tan\alpha. \tag{2.1}$$

Friction was measured for 11 specimens of Northern clingfish. The mean was calculated for each sample from the three measurements taken on each substrate type. This mean value was used for data analysis.

(d) Measuring tenacity on different surface roughnesses with and without the disc rim

The attachment force of the clingfish's suction cups was measured with a MTS Synergie 100 materials testing system (Cary, NC, USA) using a 500 N load cell and a water tank with an interchangeable bottom as previously described in detail [9]. The tank was filled with seawater. The fish, harnessed by suturing through the opercular gill openings and through the body of the fish above the suction disc, was connected to the crosshead of the MTS machine (figure 3). The fish was gently pressed onto the substrate to ensure attachment before starting the measurement (preliminary experiments had shown that higher push-on forces did not lead to higher attachment forces). Starting the experiment, the force was continually recorded at 500 Hz while moving the crosshead at a constant speed (1 m min^{-1}) until detachment of the suction cup. The pull-off force, the maximal attachment force of the suction disc before failure, was used for further calculations. Each specimen was tested three times on all seven surfaces in random order. As we were interested in the maximal performance, the highest pull-off force of the three performed trials for each surface–substrate pair was used in further analyses. The same seven substrates as for the friction measurements were used. The whole experiment was designed as a paired experiment—measuring each fish first with the intact suction cup, and again after dissecting the anterior outer part of the suction disc (line in figure 2 picture). Measurements were done on 11 Northern clingfish. Tenacity P was calculated from the attachment force F_a divided by the area of the suction cup A:

$$P = \frac{F_a}{A}. \tag{2.2}$$

(e) Bioinspired suction cups

Four different types of suction cup types were used in this study. The first suction cup type (SC0) was a single material suction cup fabricated out of a stiff silicon material (Young's modulus: 8 MPa) and had a diameter of 6.5 cm. It was used as reference for comparison with the bioinspired suction cup prototypes.

The first bioinspired suction cup type (SC1) used in this study was a two-material suction cup, where the stiff layer resembles the harder bones in the clingfish suction cup and the soft layer resembles the soft disc rim with its hierarchical structures. SC1 consists of an outer, stiff part, which is equivalent to SC0 and an additional inner 1.5 mm thick layer of a soft and elastic material (Young's modulus: 0.2 MPa). This layer was prepared by moulding a highly elastic silicon (ECOFLEX 00-10, Smooth-On, PA, US) between two smooth glass plates. After hardening this smooth layer was glued with super glue to a

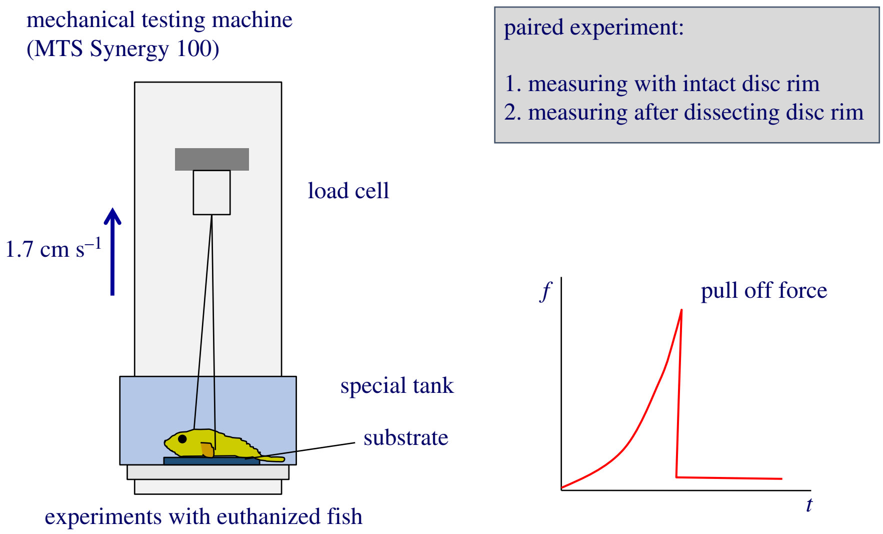

Figure 3. Experimental set-up to measure tenacity of the clingfish. The illustration (left) shows a test specimen connected to the load cell of the material testing machine. Forces are continually recorded while moving the crosshead upwards at 1.7 cm s^{-1}. The graph (lower right) shows an example force–time curve [9]. Experiments were performed twice for each fish, once with the intact suction cup and once after dissecting the anterior part of the disc rim (upper right). (Online version in colour.)

SC0-like suction cup and cut at a distance of about 2 mm from the outer edge of SC0.

The second bioinspired suction cup type (SC2) combines the two-material effect to increase friction with structure designed to increase friction at the rim. Like SC1 the prototype SC2 has an outer, stiff part, which is equivalent to SCO and an additional soft layer. The production procedure was identical to that described for SC1, but to generate a structured outer surface the moulding of the second layer took place between one smooth glass plate and a P180 sandpaper. The latter was glued with the flat side to another glass plate. The overall geometry of SC2 was identical to that of SC1.

The third bioinspired suction cup type (SC3) aims also to increase friction with the substrate, but a different method was used to achieve this goal. SC3 consists of an outer, stiff part equivalent to SC0 and an additional inner soft layer. In this case, the outer surface of the second layer was smooth but had high modulus inclusions which generate increased friction.

The tenacity of the suction cups was measured on the seven substrates ranging from smooth to 269 µm grain size using the method described above for the clingfish suction cup.

3. Results

(a) Suction cups of Northern clingfish: the friction properties of the disc rim

The static friction coefficient of the margin of the suction disc varied with surface roughness (figure 4). It was significantly higher on all but the roughest rough substrates (grain sizes: 35, 76, 276 and 1000–2000 µm) compared to the smooth one (ANOVA, d.f. = 76, $F = 5.54$, $p < 0.001$, Tukey post hoc test). On the rough surfaces (35 to 2000–4000 µm grain size), the median of the friction coefficients measured between 0.62 and 0.77. On the smooth surface, the friction coefficient measured 0.56 (median).

(b) Suction cups of Northern clingfish: tenacity with and without disc rim

The intact suction cup attaches with tenacities of around 35–40 MPa to rough surfaces till a grain size of 500–1000 µm

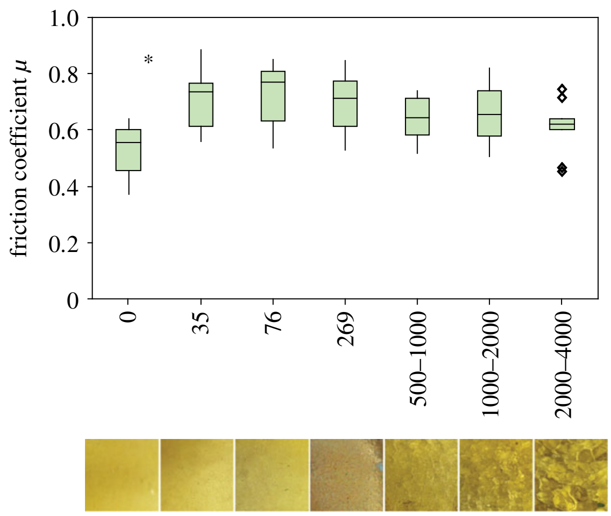

Figure 4. Friction coefficient μ of the disc rim of Northern clingfish (*G. maeandricus*) measured with friction slide on substrates of different surface roughness. The *x*-axis shows the average grain size (µm) of the substrate with images of the substrates below. The friction coefficient is higher on rough surfaces compared to the smooth surface. Boxplots show median, upper and lower quartiles, interquartile range and outliers (diamond). Asterisks indicate level of significance: $^*p < 0.05$. (Online version in colour.)

before the tenacity decreases considerably (figure 5). After dissection of the outer disc rim of the suction cup, the tenacity of the suction cups was significantly lower than in the complete suction cups (paired *t*-test: 0: $N = 10$, $t = 3.2$, $p < 0.05$; 0.035: $N = 10$, $t = 2.65$, $p < 0.05$; 0.076: $N = 10$, $t = 5.55$, $p < 0.001$). However, the suction cups still attach well to the smooth and slightly rough surfaces (tenacities 28–34 kPa). They fail at substrates with a grain size over 76 µm.

(c) Bioinspired suction cups: tenacity of iterative prototype variations

Figure 6 shows the tenacities of the three variations of our suction cup prototypes in comparison to a normal, one

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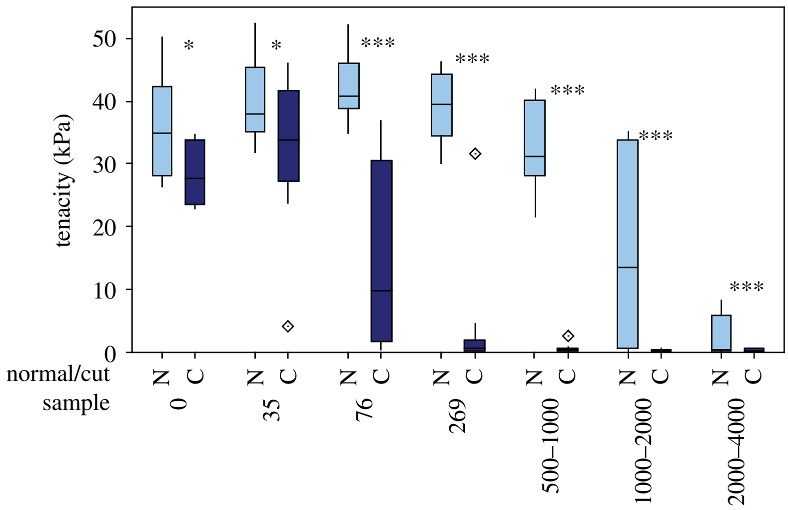

Figure 5. Tenacity of the suction cup of Northern clingfish (*G. maeandricus*) with (N) and without (C) outer disc margin, measured with the MTS mechanical testing machine on substrates of different surface roughness. The suction cups without outer disc margin attach on the smooth and slightly rough surfaces; they fail at an average grain size over 76 µm. On all substrates the tenacity with outer disc margin is significantly higher than without. Boxplots show median, upper and lower quartiles, interquartile range and outliers (diamond). Asterisks indicate level of significance: ***$p < 0.001$; *$p < 0.05$. (Online version in colour.)

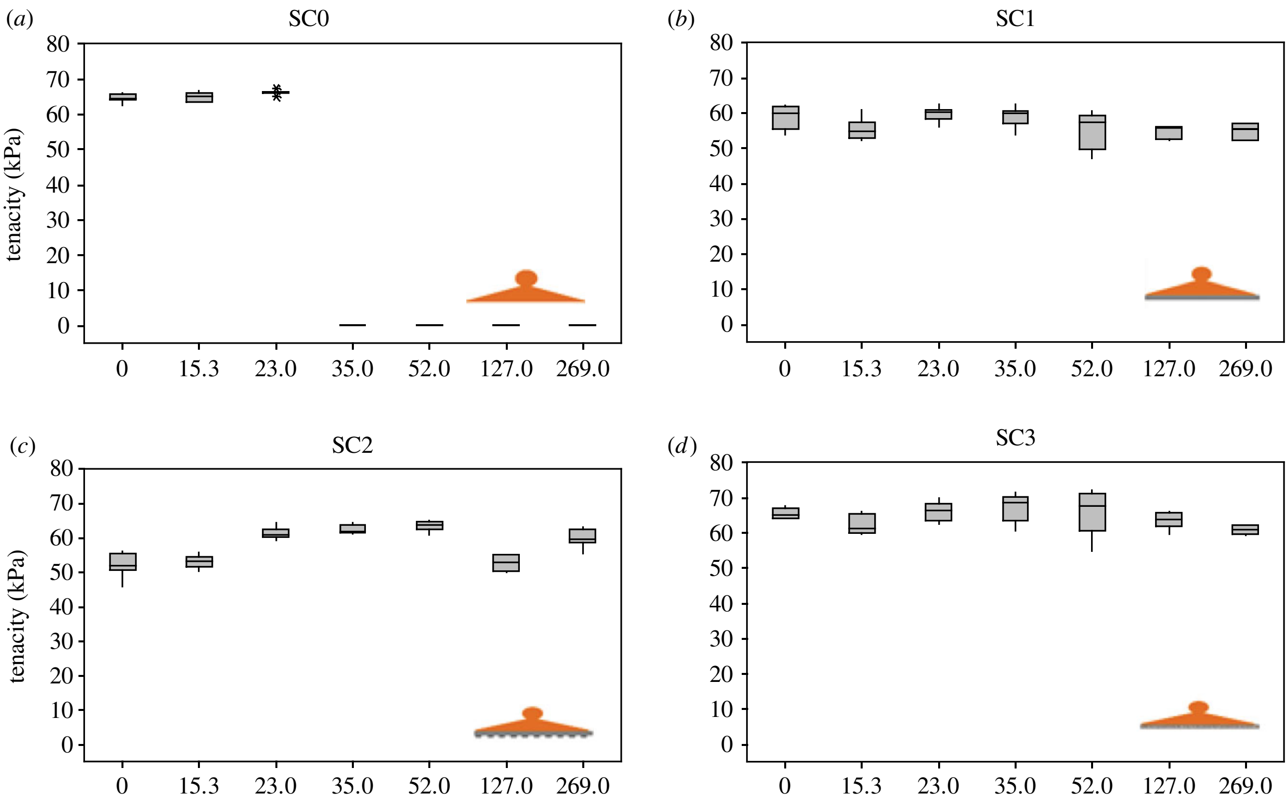

Figure 6. Tenacity of different versions of bioinspired suction cups in comparison to a normal suction cup. The *x*-axis shows the average grain size (µm) of the substrates. (*a*) Normal suction cup (SC0), (*b*) suction cup with an extra stiff and soft-elastic layer (SC1), (*c*) suction cup with a structured soft-elastic layer (SC2) and (*d*) suction cup with a soft-elastic layer with special inner microstructure (SC3). Boxplots show median, upper and lower quartiles, interquartile range and outliers. (Online version in colour.)

material suction cup (SC0). SC0 attaches to smooth and slightly rough surfaces with high tenacities of 65–66 kPa (median), but fails on surfaces with a grain size over 35 µm (figure 6*a*). By contrast, the duo-material suction cup with a smooth soft-elastic layer (SC1) attaches to all tested substrates (figure 6*b*). The tenacity is somewhat lower than that of SC0 (55–61 kPa) (two-way ANOVA for first three substrates: suction cup type: d.f. = 1, $f = 110.2$, $p < 0.001$, substrate type: d.f. = 2, $f = 5.25$, $p \leq 0.01$). Producing the duo-material suction cup with a structured soft-elastic layer (SC2) results in a higher tenacity of (60–64 kPa) on most rough substrates in comparison to SC1 (two-way ANOVA for substrates with 23, 35, 52 and 269 µm grain size: suction cup type: d.f. = 1, $f = 35.29$, $p < 0.001$, substrate type: d.f. = 3, $f = 4.15$, $p \leq 0.01$). On the smooth and slightly rough surfaces (grain size 0 and 15.3 µm) and certain other surface roughness (grain size 127 µm) the tenacity of SC2 is 52–54 kPa, significantly lower than SC1 though (two-way ANOVA for substrates with 0, 15.3 and 127 µm grain size: suction cup type: d.f. = 1, $f = 21.58$, $p < 0.001$, substrate type: d.f. = 2, $f = 1.59$, $p > 0.05$) (figure 6*c*). When the soft-elastic layer has an internal microstructure (SC3) the cup attaches to all tested substrates with high tenacities of 61–69 kPa (figure 6*d*). The tenacity of SC3 is higher than that of SC1 (two-way ANOVA for all substrates: suction cup type: d.f. = 1, $f = 131.74$, $p < 0.001$, substrate type: d.f. = 6, $f = 5.40$, $p < 0.001$).

4. Discussion

While on smooth surfaces usual artificial suction cups reach higher tenacities (50–80 kPa) [20] than the suction cups of Northern clingfish (30–40 kPa), Northern clingfish can attach to rough surfaces, where normal suction cups fail. Transferring the biomechanical principles, our bioinspired suction cup can attach well to smooth and rough substrates (up to 270 µm grain size). The tenacities of the bioinspired suction cup are 60–70 kPa, which is higher than the biological model.

(a) The role of the disc rim

While the broad disc rim increases tenacity on smooth surfaces, it is not needed to attach to smooth surfaces. By contrast, on rough surfaces the broad disc rim is crucial for Northern clingfish's ability to attach. From these results, we can conclude that the specific morphology of the rim is the determining factor for clingfish's ability to attach to rough surfaces. We propose that the soft-elastic disc rim with its hierarchical structures is important in two ways: (i) adaptation to the surface structure of the substrate and (ii) increasing friction with the substrate.

Adaptation to the irregular surface structure of rough substrates is crucial to seal the suction cup. Sealing is important to maintain the pressure difference between the cavity of the suction cup and the ambient liquid (be it air or water). Even small gaps lead to leakage, which cause failure of the suction cup [21]. The morphology of the disc rim adjusts to surface irregularities. First, the soft margin of the suction cup allows adaptation to the general surface topography of the substrate. Then, on a finer level, the hierarchical structures of the disc rim adjust to the finer surface asperities. The papillae should be able to adjust to surface irregularities in a size range of approximately 150 µm, the rods (on the papillae) to surface irregularities in a size range of approximately 5 µm and the tiny filaments at the tips of the rods to surface irregularities in a size range of approximately 0.2 µm [9]. Hierarchical structures have been described to allow adjustment to the surface irregularities of the substrate in other attachment devices [22], and geckos are probably the most famous case. Their setae, which are highly branched in some gecko species, end in spatulae: flattened tips which make direct contact with the surface and its irregularities [23]. The setae allow adjustment to the surface irregularities at one size range, the spatulae allow adjustment to smaller surface irregularities. In general, there are two main types of attachment devices (for insects): one is hairy, the other is smooth [24]. Adjustment to small surface irregularities by smooth attachment pads can, for example, be found in tree frogs, grasshoppers or stick insects, often in combination with secretions [19,25,26]. All the examples above, however, are not used in conjunction with suction, but with other attachment mechanisms such as van der Waals or capillary forces. Van der Waals forces and capillary forces do not normally apply under water. The octopus uses suction under water, and achieves perfect adjustment to the irregularities of the surface structure of the substrate with a very soft outer material of its suction cups [27]. The suction cups of octopus are often much smaller than in Northern clingfish though, so they do not need to adjust to coarser surface topography. In general, the size of the suction cup has an impact on the surface roughness to which they can attach [9].

We show increased friction for the suction cup margin on rough surfaces compared to smooth ones. The friction coefficient (figure 4) shows basically the same pattern as the tenacity of the whole biological suction cup on the same test surfaces (figure 5), suggesting that friction is determining the failure force. The mechanism for this follows from the normal failure mechanism of suction cups. During detachment, the force normal to the surface causes the margin of the suction disc to slide centrally. This leads to a decrease in disc diameter and compression in the edge of the disc. The compressed margin eventually buckles, letting in outside fluid. In the clingfish, the increased friction forces on the rough surfaces resist the forces pulling the disc margin centrally. Consequently, the increased friction of the disc margin delays failure, and increases attachment forces. Friction in combination with suction is also applied by remoras [4], where the spinula of the remora adhesive disc enhance attachment on rough surfaces [28]. In remoras, suction is almost solely relevant on smooth surfaces, but decreases considerably on rough surfaces, where friction contributes more to the attachment force [4]. In remoras, the friction enhancement seems particularly important to withstand shear forces [28], while in clingfish the increased friction properties lead to increased pull-off forces. Understanding the importance and function of the disc rim for attachment to rough surfaces made it possible to transfer these qualities to a technical, bioinspired suction cup.

(b) Bioinspired suction cups

Our inspiration for bioinspired suction cups had three sources. (i) The harder and stiffer outer layer of the suction cup prototype resembles the bones underlying the suction cup in Northern clingfish. These bones provide stability to the biological suction cup and resistance against sliding centrally of the soft suction disc when the suction cup is pulled in a normal direction. (ii) The very soft layer mimics the elasticity and softness of the disc rim and its hierarchical structures, which enable adaptation to surface irregularities of the substrate. (iii) Enhanced friction of the rim of the suction cup provides resistance to the cup edge slipping inwards. Enhanced friction delays failure of the suction cup and also increases attachment forces and tenacity.

Variations of the bioinspired suction cup prototype demonstrate the importance of combining all three described aspects. The two-material suction cup prototype SC1 combines aspects (i) and (ii) providing stable suction cups, which can adjust to rough surfaces. The advantage of attaching to rough surfaces, however, comes with the price of somewhat lower attachment forces. The latter is likely caused by the soft material of the second layer of SC1 giving in more easily to the forces directed in a central direction of the suction cup while pulling in a normal direction. To counterbalance this effect, structuring the soft layer of the disc rim increases

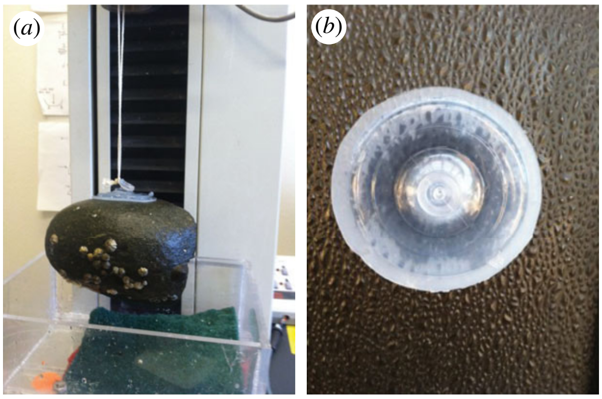

Figure 7. Bioinspired suction cup prototype SC3 (*a*) holding a rock (about 5 kg) in the mechanical testing machine and (*b*) attaching to a very rough surface. (Online version in colour.)

friction in SC2. The structures in SC2 have a single level of hierarchy. Limitations in the moulding technique did not allow production of more complex structures. On smooth surfaces, the structuring leads to a reduction of the real contact area, which explains the reduced tenacity. To avoid these problems, we alternatively provided the smooth (unstructured) soft layer with an inner microstructure (SC3). The latter increases friction only under pressure, which is exceeded by the applied suction cup itself. This method ensures a large real contact area and increases friction on all tested rough and even on smooth surfaces, resulting in a high tenacity of 60–70 kPa.

These are high tenacities for adhesion on rough surfaces. For comparison, the tenacity of a biomimetic remora adhesive disc prototype developed tenacities of 58 kPa on smooth surfaces and 16–22 kPa on rough surfaces [20]. Considering that suction in water is limited by cavitation [29], the tenacity of our bioinspired suction cups might come close to its natural limitation. While at sea level the cavitation threshold is considered 100 kPa, cavitation is also impacted by the substrate properties and particles or chemicals in the water leading to a lower realized cavitation threshold [29].

In addition to tenacity, the duration time of attachment is promising. In first tests, SC3 attached up to three weeks on rough substrates (270 µm grain size) in a preliminary experimental setting under water (P Ditsche 2016, personal observation). Moreover, these bioinspired passive suction cups attach not only to technical surfaces, but also to natural surfaces such as rocks and even whale skin (figure 7). Attachment solutions are needed for various tasks such as attaching sensors and other technical devices to ships or other aquatic substrates, for under water robots or to tag aquatic animals. These are just some examples of where our clingfish-inspired suction cups could solve the problem of attaching reversibly but stably to wet and rough surfaces.

Ethics. The procedures used in this study were approved by an Institutional Animal Care and Use Committee protocol at the University of Washington.

Data accessibility. The datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' contributions. P.D. and A.S.: conception, design, interpretation of the findings, drafting and revising the article and final approval. P.D.: execution and analyses.

Competing interests. The authors declare no competing financial interests.

Funding. The National Science Foundation (IOS-1256602) supported this study financially. The Seaver Institute also provided funding.

Acknowledgements. Molly Pane helped with some previous versions of the artificial suction cups, which gave us insights to develop the finally working bioinspired suction cups. Max Kessler built the tank which we used for the measurement of the attachment time of the bioinspired suction cups. P.D. also thanks her daughter Celine for her continued patience and encouragement during developing these bioinspired suction cups.

References

1. Gerstner CL. 2007 Effect of oral suction and other friction-enhancing behaviors on the station-holding performance of suckermouth catfish (*Hypostomus* spp.). *Can. J. Zool.* **85**, 133–140. (doi:10.1139/Z06-199)
2. Maie T, Schoenfuss HL, Blob RW. 2012 Performance and scaling of a novel locomotor structure: adhesive capacity of climbing gobiid fishes. *J. Exp. Biol.* **215**, 3925–3936. (doi:10.1242/jeb.072967)
3. Gibson RN. 1969 Powers of adhesion in *Liparis montagui* (Donovan) and other shore fish. *J. Exp. Mar. Biol. Ecol.* **3**, 179–190. (doi:10.1016/0022-0981(69)90016-1)
4. Fulcher BA, Motta PJ. 2006 Suction disk performance of echeneid fishes. *Can. J. Zool.* **50**, 42–50. (doi:10.1139/Z05-167)
5. Zou J, Wang J, Ji C. 2016 The adhesive system and anisotropic shear force of Guizhou Gastromyzontidae. *Sci. Rep.* **1**, 1–10. (doi:10.1038/srep37221)
6. Budney LA, Hall BK. 2010 Comparative morphology and osteology of pelvic fin-derived midline suckers in lumpfishes, snailfishes and gobies. *J. Appl. Ichthyol.* **26**, 167–175. (doi:10.1111/j.1439-0426.2010.01398.x)
7. Arita GS. 1962 A comparative study of the structure and function of the adhesive apparatus of the Cyclopteridae and Gobiesocidae. Masters thesis, University of British Columbia.
8. Green DM, Barber DL. 1988 The ventral adhesive disc of the clingfish *Gobiesox maeandricus*: integumental structure and adhesive mechnisms. *Can. J. Zool.* **66**, 1610–1619. (doi:10.1139/z88-235)
9. Ditsche P, Wainwright DK, Summers AP. 2014 Attachment to challenging substrates—fouling, roughness and limits of adhesion in the northern clingfish (*Gobiesox maeandricus*). *J. Exp. Biol.* **217**, 2548–2554. (doi:10.1242/jeb.100149)
10. Ditsche P, Michels J, Kovalev A, Koop J, Gorb S. 2014 More than just slippery: the impact of biofilm on the attachment of non-sessile freshwater mayfly larvae. *J. R. Soc. Interface* **11**, 20130989. (doi:10.1098/rsif.2013.0989)
11. Wainwright DK, Kleinteich T, Kleinteich A, Gorb SN, Summers AP. 2013 Stick tight: suction adhesion on irregular surfaces in the northern clingfish. *Biol. Lett.* **9**, 20130234. (doi:10.1098/rsbl.2013.0234)
12. Ditsche P, Hicks M, Truong L, Linkem C, Summers A. 2017 From smooth to rough, from water to air: the intertidal habitat of Northern clingfish (*Gobiesox maeandricus*). *Naturwissenschaften* **104**, 33. (doi:10.1007/s00114-017-1454-8)
13. Ditsche P, Summers AP. 2014 Aquatic versus terrestrial attachment: water makes a difference. *Beilstein J. Nanotechnol.* **5**, 2424–2439. (doi:10.3762/bjnano.5.252)
14. Scherge M, Gorb SN. 2001 *Biological micro- and nanotribology*. Berlin, Germany: Springer.
15. Donlan RM. 2002 Biofilms: microbial life on surfaces. *Emerg. Infect. Dis.* **8**, 881–890. (doi:10.3201/eid0809.020063)
16. Ditsche P, Ford W, Summers AP. 2016 The role of cup elasticity in suction attachment in Northern Clingfish. In *Society for Integrative and Comparative Biology Annual Meeting, 3–7 January, Portland, OR*. (www.sicb.org/meeting/2016/SICBOral.pdf).
17. Koch K, Schulte AJ, Fischer A, Gorb SN, Barthlott W. 2008 A fast, precise and low-cost replication

technique for nano- and high-aspect-ratio structures of biological and artificial surfaces. *Bioinspir. Biomim.* **3**, 046002. (http://iopscience.iop.org/1748-3190/3/4/046002)

18. Bowden FP, Tabor D. 1950 *The friction and lubrication of solids, band 1*. Oxford, UK: Clarendon Press.
19. Gorb SN. 2008 Biological attachment devices: exploring nature's diversity for biomimetics. *Phil. Trans. R. Soc. A* **366**, 1557–1574. (doi:10.1098/rsta.2007.2172)
20. Wang Y *et al.* 2017 A biorobotic adhesive disc for underwater hitchhiking inspired by the remora suckerfish. *Sci. Robotics* **2**, eann8072. (doi:10.1126/scirobotics.aan8072)
21. Beckert M, Flammang BE, Nadler JH. 2016 A model of interfacial permeability for soft seals in marine organism, suction-based adhesion. *Soft Mater. Biomater.* **1**, 2531–2543. (doi:10.1557/adv.2016.445)
22. Gorb SN. 2001 *Attachment devices of insect cuticle*, 1st edn. Dordrecht, The Netherlands: Kluwer Academic Publishers.
23. Autumn K. 2016 How gecko toes stick. *Amer. Sci.* **94**, 124–132. (doi:10.1511/2006.58.124)
24. Gorb S, Beutel R. 2001 Evolution of locomotory attachment pads of hexapods. *Naturwissenschaften* **88**, 530–534. (doi:10.1007/s00114-001-0274-y)
25. Hanna G, Barnes WJP. 1991 Adhesion and detachment of the toe pads of tree frogs. *J. Exp. Biol.* **155**, 103–125.
26. Drechsler P, Federle W. 2006 Biomechanics of smooth adhesive pads in insects: influence of tarsal secretion on attachment performance. *J. Comp. Physiol. A* **192**, 1213–1222. (doi:10.1007/s00359-006-0150-5)
27. Tramacere F, Kovalev A, Kleinteich T, Gorb SN, Mazzolai B. 2014 Structure and mechanical properties of *Octopus vulgaris* suckers. *J. R. Soc. Interface* **11**, 20130816. (doi:10.1098/rsif.2013.0816)
28. Beckert M, Flammang BE, Nadler JH. 2015 Remora attachment is enhanced by spinule friction. *J. Exp. Biol.* **218**, 3551–3558. (doi:10.1242/jeb.123893)
29. Smith AM. 1991 Negative pressure generated by octopus suckers: a study of the tensile strength of water in nature. *J. Exp. Biol.* **157**, 257–271.