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A bio-robotic remora disc with attachment and detachment capabilities for reversible underwater hitchhiking

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***Abstract*—Remoras employ their adhesive discs to rapidly attach to and detach from a wide range of marine surfaces. By analyzing high-speed images of remoras' (*Echeneis naucrates*) hitchhiking behavior, we describe the fish's detachment mechanism as a lip curling up to break the seal between the disc and substrate. By mimicking the kinematic and morphological properties of the biological disc, we fabricated a multi-material biomimetic disc (whose stiffness spans four orders of magnitude) that is capable of both attachment and detachment. Detachment is realized by a flexible cable-driven mechanism that curls the anterior region of the silicone soft lip, allows leakage under the disc, and equalizes the internal pressure to the external pressure. The disc lamellae with attached carbon fiber spinules can be rotated by hydraulic soft actuators whose internal pressure is precisely tuned to the ambient underwater pressure. During attachment, increasing the rotational angle of the lamellae and the preload of the disc significantly enhanced the adhesive forces. We found that curling up the soft lip and folding down the lamellae rapidly reduced the pulling force of the disc by a factor of 254 compared to that under the attached state, which lead to detachment. Based on these mechanisms, underwater maneuvers involving repeated attachment and detachment were demonstrated with an integrated ROV unit that had a self-contained actuation and control system for the disc. This study lays a foundation for the development of fully untethered robotic systems for underwater hitchhiking in real-world marine environments.**

***Keywords*—Attachment and detachment, soft robotics, underwater adhesion.**

I. INTRODUCTION

The natural world is home to a diverse array of animals that have evolved a variety of efficient adhesion mechanisms for static and dynamic attachment [1]. Examples include geckos [2]-[4], tree frogs [5][6], octopuses [7], fishes [8]-[10], and mussels [11]. As an extraordinary example of the underwater bio-adhesion system, remoras can achieve rapid and reversible attachment and detachment on various marine surfaces with a dorsal adhesive disc [12]-[15]. This behavior is commonly referred to as "hitchhiking," and it reduces swimming energy expenditure and provides survival advantages (predator avoidance, mating, etc.) [16][17]. The remora disc is composed of thousands of rigid spinules embedded in lamellae that are surrounded by a soft lip capable of curling up and down with the use of surrounding muscles [18][19].

In order to understand the biomechanics of remora hitchhiking, we previously developed a biomimetic disc prototype that could attach to surfaces with different roughness [20]. The mechanism of remora attachment has previously been investigated [21]-[23]. The detachment mechanism of the live remora, however, is still not well understood. Developing a biomimetic remora disc with a detachment mechanism would allow for a more detailed study of the remora's adhesion force and dynamic performance during detachment, and give the prototype both attachment and detachment capabilities in underwater environments. To our knowledge, no previous study has described the design and manufacture of a composite underwater biomimetic disc with both of these properties.

In this paper, we describe the detachment mechanism of the remora disc according to kinematic observations of live remoras. We adopted multiple techniques (such as multi-material 3D printing [24][25], laser cutting [26], and multi-step molding and casting [27]) to fabricate a biomimetic remora disc prototype that had both attachment and detachment capabilities. Specifically, a biomimetic curling mechanism was used to achieve detachment. A hydraulic actuation system, which is suitable for underwater operation, was developed to actuate the lamellae and curling mechanism. Furthermore, we measured the mechanical properties of the soft lip, adhesive performance (inner-chamber pressure, pull-off force, and backward frictional force), and adhesive properties (surface adhesion, forward frictional force, and detachment time) during the disc prototype's detachment. Finally, we demonstrated the performance of the disc prototype by executing multiple transitions from attachment to detachment through a remotely operated vehicle (ROV) with self-contained hydraulic actuation and control system for the adhesive disc, and by executing pick-and-place movements by gripping planar objects in air. This work will improve our understanding of biological adhesion mechanisms and underwater biomimetic devices.

II. MATERIALS AND METHODS

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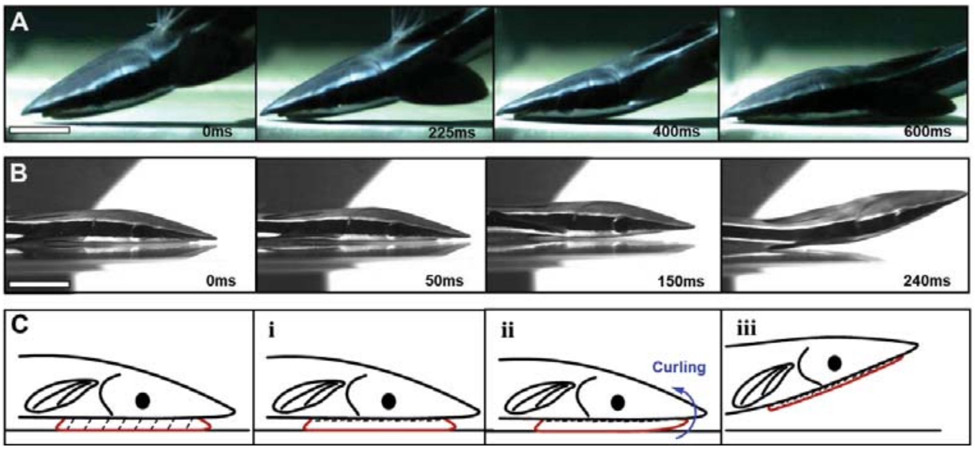

Fig. 1. Attachment and detachment of a live remora. Side view, high-speed images of a remora's attachment (A) and detachment (B) on a smooth glass surface. Scale bars 2 cm. (C) Schematics of the remora's detachment process. i) the disc lamellae fold down (towards the head); ii) the fleshy disc lip curls upward away from the surface from the anterior disc section to the posterior; iii) the remora subsequently detaches from the surface.

A. Attachment and Detachment of Live Remoras

Three live remoras (*Echeneis naucrates*) were used to investigate disc attachment and detachment in a water tank(length, width, and height: 60 cm, 30 cm, 33 cm). Two synchronized high-speed cameras (bottom and side views) were used to record attachment and detachment behaviors of the remoras at a sampling rate of 500 Hz (FASTCAM Mini UX100, Photron Ltd., Tokyo, Japan). Figs. 1A and 1B show the four high-speed images of a remora's attachment (movie Part 1) and detachment motion (movie Part 2: side view; movie Part 3: bottom view) on a smooth glass surface at different times. We used three live remoras to measure the detachment kinematics (10 times for each fish, with a total of 30 videos). A schematic of the remora's detachment process is provided in Fig. 1C.

B. Design and Fabrication of the Biomimetic Remora Disc

We measured the elastic modulus of five fleshy biological lip samples (x, y, and z directions) acquired from the posterior of disc (10 mm long, 6 mm wide, and 2 mm thick) via a Dynamic Mechanical Analysis (DMA, Q800, TA Instruments New Castle, DE, USA). We also tested three types of silicone elastomeric materials (Mold Star 30, Ecoflex 00-50, Dragonskin 20, Smooth-On Inc., PA, USA) that are commonly used for soft robotics.

Based on the hierarchical structures of the remora's adhesive disc imaged by multiple microscopy techniques [20], we designed and fabricated the biomimetic remora disc. We utilized multi-material 3D printing technology to fabricate the lamellae and actuation mechanisms (Fig. 2A). Note that the soft lip was fabricated using silicone rubber (Young's modulus of 517 kPa) according to a mold/cast method described in Fig. 2B. The molds were 3D printed using epoxy, and the silicone rubber used for the soft lip was Mold Star 30 (Young's modulus of 517 kPa). As illustrated in Fig. 2C, four hydraulic actuators were utilized for actuating the disc lamellae. The linear relationship between the hydraulic pressure and lamellae pitch angle (θ) was analyzed in Fig. 2D to prepare for subsequent experiments. In summary, the biomimetic disc prototype was 127 mm long and 72 mm wide, with a mass of 180 g.

The cable-driven curling mechanism used to achieve disc detachment consisted of a 3D-printed curling section, a slider mechanism, and a miniature hydraulic cylinder, as shown in Fig. 2F. The curling section, an auxiliary structure of the soft lip, was independently printed using a multi-material 3D printer (Objet500 Connex3, Stratasys Ltd., MN, USA) with TangoPlus FLX930 (flexible) and VeroWhitePlus RGD835 (rigid) materials, then glued to the soft lip (Fig. 2E). The slider mechanism, including two supports and one slider, was fixed to the extendable end of a hydraulic cylinder (CJPB10-10, SMC Corp., Tokyo, Japan). One end of a braided steel cable was fixed to the slider and the other end was fixed to the curling section. The hydraulic cylinder was fixed on one support and actuated to pull the cable and make the soft lip curl up.

C. Hydraulic Actuation System and ROV Platform

A micro hydraulic system that could provide a maximum pressure of 230 kPa, was designed to control the curling mechanism and the lamellae rotation. In contrast to a traditional pneumatic system, a hydraulic system can directly use the surrounding water as the actuation medium. Additionally, a hydraulic system also avoids the instability effect of changing buoyancy produced by gas in an underwater environment. As a result, it can be effectively integrated into an ROV system to solve problems encountered with a pneumatic system, such as having an extended pipeline and actuation delay. The ROV platform is propelled by three DC motors, two of which are used to realize forward, reverse and rotation motions, and the remaining one to achieve up and down in the water.

D. Attachment and Detachment of the Biomimetic Disc

Tests of adhesive performance were conducted in a water tank. To fully immerse the disc in water, the distance between the substrate surface and the water surface was set to 20 cm. The smooth and rough substrates (surface roughness of Ra = 0 μm and Ra = 200 μm, respectively) used in the tests were

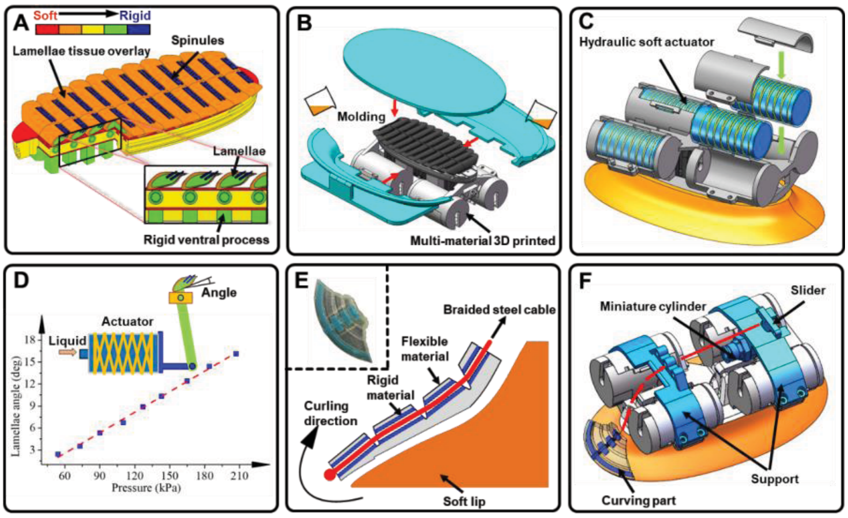

Fig. 2. Design and fabrication of the biomimetic remora disc prototype. (A) CAD model of the main disc and the lamellae mechanisms. Different colors correspond to different stiffness (from $10^4 \sim 10^{11}$ Pa). DPSS laser machined artificial spinules (blue) are the most rigid part of the disc (Young's Modulus: $\sim 2\times 10^{11}$ Pa). The main disc structure was printed with a multi-material 3D printer (Objet Connex500 C3). (B) The silicone elastomeric soft lip was fabricated and bonded to the lamellae mechanism through multi-step mold and cast approach. (C) Hydraulic soft actuators for actuating the disc lamellae. (D) The lamellae pitch angle (θ) increases linearly as a function of hydraulic pressure. (E) Cross-sectional schematic of the detachment mechanism. The internal channels (blue) and covering layer (translucent) were simultaneously printed with rigid and flexible materials, respectively. (F) Disc detachment is realized by the cable-driven curling mechanism that includes the 3D-printed curling section, the miniature hydraulic cylinder, and the slider mechanism. The pulling force for detachment is exerted from the pressure in the miniature hydraulic cylinder.

obtained by molding the female die with the epoxy resin material (EpoxAcast 650, Smooth-On Inc., PA, USA).

To investigate the adhesive property of the biomimetic disc, we first studied the pull-off force corresponding to different preloads on smooth and rough surfaces using a material testing system (MTS model e44, MTS Corp., EdenPrairie, MN, USA). In the initial stage of each experiment, an accurate preload (0-25 N with a 5 N interval) was applied for 5 s, after which the disc was pulled upward at a speed of 5 mm/s.

The backward frictional force of the disc prototype at lamellae pitch angles of 0°, 8°, and 16° under variable 5 s preloads (0-25 N with a 5 N interval) on smooth and rough surfaces was also measured.

The effect of lamellae pitch angle on detachment performance (forward frictional force and pull-off force) on a smooth underwater substrate was also investigated. Before each test, a 20 N preload was applied to the disc and removed after 5 s. The hydraulic system drove soft actuators to control the lamellae pitch angle (0°-16°) and to curl the soft lip. The robotic arm was then set to pull the disc forward and upward at a constant speed of 3 mm/s to measure the maximum static friction and pull-off force, respectively.

Curling performance under different preloads was also explored by measuring detachment time (T). Detachment time is defined as the period between the start of the inner-chamber pressure change to full detachment (0 kPa). A change in inner-chamber pressure indicates the attachment and detachment of the disc. The prototype was placed on a smooth underwater surface with a pressure sensor in the center of the biomimetic disc. Then, a certain preload (0-20 N with a 5 N interval) was applied. After 5 s, the preload was removed and the biomimetic disc was actuated to detach with a certain pressure (200 kPa).

III. Results

A. Attachment and Detachment of Live Remoras

The attachment and detachment mechanisms of live remoras were observed with two synchronized high-speed cameras. As shown in Fig. 1A, the remora's soft lip forms a seal with the substrate, and the lamellae inside the suction disc actively erect up and fold down to modify the adhesion force. For detachment, the anterior lip curls up to break the seal between the disc and the substrate (Fig. 1B). A schematic of the detachment mechanism is provided in Fig. 1C to further illustrate the interplay between the remora's soft disc lip, lamellae, and body. The detachment process can be summarized in three steps: i) the disc lamellae fold down; ii) the disc lip curls upward from the anterior disc section towards the posterior; iii) the remora fully detaches from the surface.

B. Mechanical Properties of the Biological and Biomimetic Soft Lip

We found that the soft lip of the live remora disc was anisotropic. From DMA tests, stress-strain curves of fresh lip tissue (x, y, and z directions) and three kinds of silicone elastomeric materials (Mold Star 30, Ecoflex 00-50, and Dragonskin 20) were obtained (Fig. 3A). The stress-strain curves were used to calculate the elasticity modulus. As shown in Fig. 3B, the elasticity moduli of lip tissue in the x, y, and z directions were 365, 878, and 495 kPa, respectively, and the elasticity moduli of frequently-used soft materials were 517, 83, and 273 kPa, respectively. The results show that biological lip tissue is anisotropic, with similar elasticity moduli in the x and z directions, and a large modulus in the y direction. The reason for this difference is that there are different tissue structures in the lip, which may be related to curling control. For the biomimetic disc lip, we chose Mold Star 30 since its elastic modulus was closest to that of the remora's disc lip.

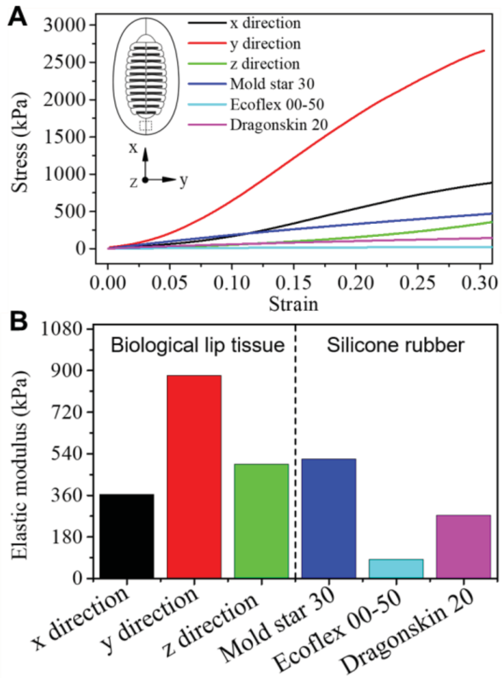

Fig. 3. The mechanical properties of the biological and biomimetic soft lip. (A) Stress-strain curves of fresh remora lip tissue (x, y, and z directions) and several silicone elastomeric materials (Mold star 30, Ecoflex 00-50, Dragonskin 20, Smooth-On Inc., PA, USA). (Inset) Schematic of remora disc with the position of fleshy lip sample and x, y, and z axes indicated. (B) Elastic modulus (gradient of stress-strain curves) of the fleshy lip and the silicone elastomeric materials.

C. Adhesive Performance of the Biomimetic Remora Disc

We investigated the effects of preload on the pull-off force of the disc on surfaces of different roughness. As depicted in Fig. 4A, whether on a rough or smooth surface, the pull-off force first increased quickly and then slowly with increasing preloads. The inset of Fig. 4A illustrates the pull-off force of the biomimetic disc (on the smooth substrate with a 10 N initial preload) as a function of time and the maximum value located at the apex of the curve. To generate a seal between the disc and substrate, the preload discharged some of the inner-chamber water during attachment. The pull-off motion, which increased pull-off force at a constant velocity, gradually increased the differential pressure between the disc chamber and external environment. When the seal was broken, causing disc attachment to fail, the pull-off force dropped sharply to zero. Additionally, given the same preload, the pull-off force produced on the smooth surface was two to three times higher than that on the rough surface. The force ranged from a minimum of 42.0±1.8 N on the rough surface to a maximum of 311.8±0.95 N on the smooth surface, showing a difference of approximately 7.4 times. The reason for this discrepancy is that an uneven surface will weaken the seal between the disc prototype and substrate during pull-off. Fig. 4A also shows that the disc prototype with a soft lip composed of Mold Star 30 and adhered to a smooth underwater surface with a 2 N preload, can produce a pull-off force of 137 N.

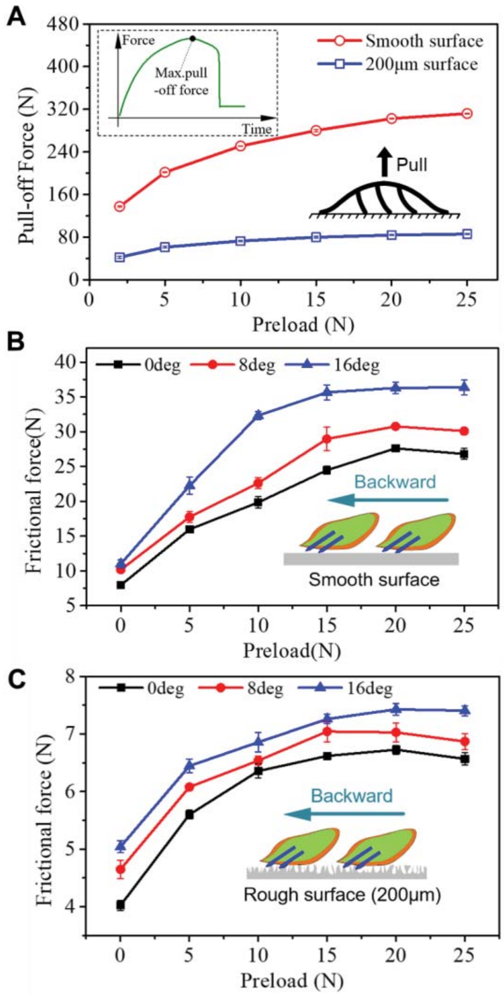

Fig. 4. The adhesive performance of the biomimetic remora disc. (A) The maximum pull-off force of the biomimetic disc prototype for different preloads on a smooth surface (surface roughness R_a = 0 μm) and a rough surface (R_a = 200 μm). (Inset) Vertically directed pull-off force time series (smooth surface, preload 10 N) and location of maximum pull-off force. Backward frictional force of the disc prototype at 0°, 8°, and 16° lamellae pitch angles under variable preloads on a (B) smooth surface and (C) rough surface (R_a = 200 μm). 5 replicate trials were performed for each experimental scenario. Error bars indicate the standard deviations.

We also observed that the preload and lamellae pitch motion could significantly affect the backward frictional force of the disc prototype (Figs. 4B and 4C). As the preload increased, the backward frictional force on the smooth and rough substrates both increased, and then remained stable or even decreased with lamellae pitch angles of 0°, 8°, and 16°. Furthermore, at a given preload, the frictional force increased with higher lamellae pitch angles. At the same given preload force and pitch angle, the frictional force values of the prototype were significantly larger on the smooth surface than on the rough surface.

D. Detachment Performance of the Biomimetic Disc

We found that live remoras always detach from a surface by first curling the portion of the disc anterior. We conducted a series of experiments to explore the detachment performance (pull-off force, forward frictional force, and detachment time) of the biomimetic disc with a similarly anterior-first lip curl detachment mechanism.

The force-time history of the bio-robotic disc prototype (underwater, soft lip in curling state, smooth surface) in a pull-off test is illustrated in Fig. 5A (inset panel) at a lamellae pitch angle of 8°. The maximum force (F_{max}) was the instantaneous force when the suction disc suddenly detached from the substrate. The average residual weight (F_{re}) is the total weight of the prototype and other residual water weight on it. We defined the difference between F_{max} and F_{re} as the pull-off force, with the results illustrated in Fig. 5A. It can be noted that when lamellae pitch angles were 4°, 8°, 12°, and 16°, the pull-off force significantly increased by 12.6%, 29.4%, 65.5%, and 166.4% compared to that at 0°, respectively. The result reveals that as the lamellae pitch up, the force required to pull the prototype off the substrate increases. There is also an interfacial force between the disc and the contact surface, which meant that the prototype generated a certain pull-off force even while detaching (with the lip curling). The interfacial force increases with an increasing contact area between the prototype and the substrate as the lamellae pitches up, which causes a larger pull-off force.

The maximum static force over a range of different lamellae pitch angles was obtained as indicated in Fig. 5B. The inset of Fig. 5B shows the forward frictional force of the disc prototype (underwater, curling state, smooth surface) at an 8° lamellae pitch angle versus time during a representative trial. The forward frictional force increased from 2.68 N to 2.98 N (11.2%) when the lamellae were raised from 0° to 16°. Similar to the result of the pull-off force test above, this result indicates that as the lamellae pitch up the force needed to pull the prototype forward increases.

The detachment time of the disc prototype, which characterized whether the curling mechanism was working efficiently, was investigated with different preloads (5, 10, 15, and 20 N). Because of the changing pressure differential between the disc chamber and ambient environment, the preload can increase the pressure on the disc prototype to resist curling up the soft lip, which increased detachment time. The test results show that the detachment time increased under different preloads from 5 N to 20 N (Fig. 5C). Although the detachment time significantly increased when the preload was20 N (5.9 times longer than with a 5 N preload), the disc was still able to detach completely. With a lower preload force, the disc's detachment time was less than 0.8s.

E. Underwater Hitchhiking and Pick-and-Place

To verify the attachment and detachment performance of the biomimetic remora disc, we mounted the disc and hydraulic system to an underwater ROV. We demonstrated the robot's performance by executing repeated transitions from stable attachments to detachment in a tank (length, width, and height: 1.2 m, 0.8 m, and 1 m). The bio-inspired remora disc was mounted on the ROV through a connection device that involved four springs and four soft silicone hydraulic elastomer actuators, and the hydraulic system was integrated to the ROV to control the curling mechanism and the lamellae rotation (Fig. 6A).

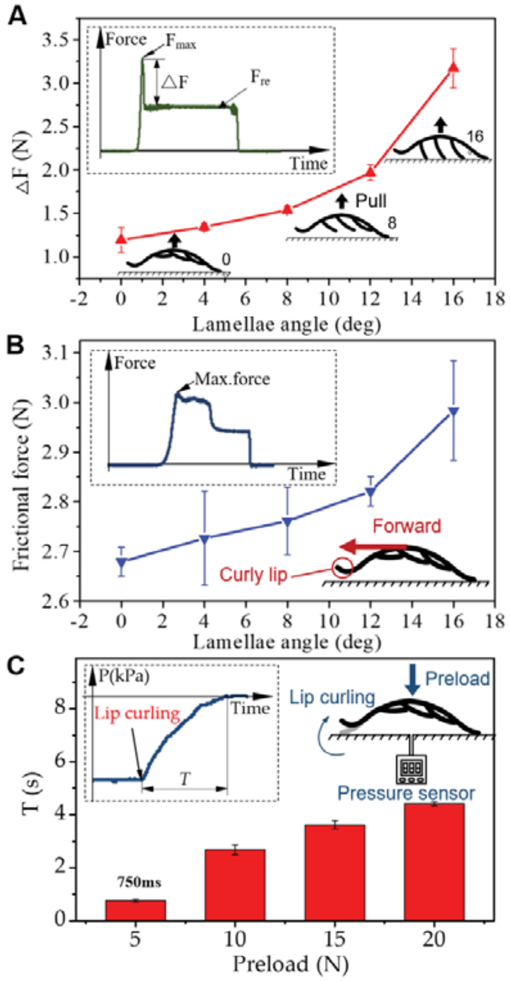

Fig. 5. Performance of the biomimetic remora disc prototype during detachment (underwater, soft lip in curling state, smooth surface). (A) Surface adhesion ΔF (F_{max}-F_{re}, with the soft lip curling up) increased with the lamellae pitch angles (θ = 0°, 4°, 8°, 12°, 16°). Inset panel: vertically directed pull-off force as a function of time (underwater, soft lip in curling state, smooth surface), maximum pull-off force (F_{max}), and average remaining weight (F_{re}). (B) Maximum forward frictional force increased with the lamellae pitch angles (θ = 0°, 4°, 8°, 12°, 16°). (Inset) Frictional force (θ = 8°) as a function of time. (C) Detachment time of the disc prototype under different preloads (smooth surface, underwater). Detachment time (T) represents the period from the start of the lip curl to full detachment. Inset panels indicate the change in inner-chamber pressure of the disc as a function of time. The pressure sensor was located at the center of the disc. 5 replicate trials were performed for each experimental scenario. Error bars indicate the standard deviations.

Fig. 6B shows two successive attachment and detachment maneuvers of the ROV on a smooth surface. The attachment and detachment of the integrated vehicle can be summarized in four steps: (i) the ROV navigated from the bottom of the tank to an overhanging smooth surface in water. Once the

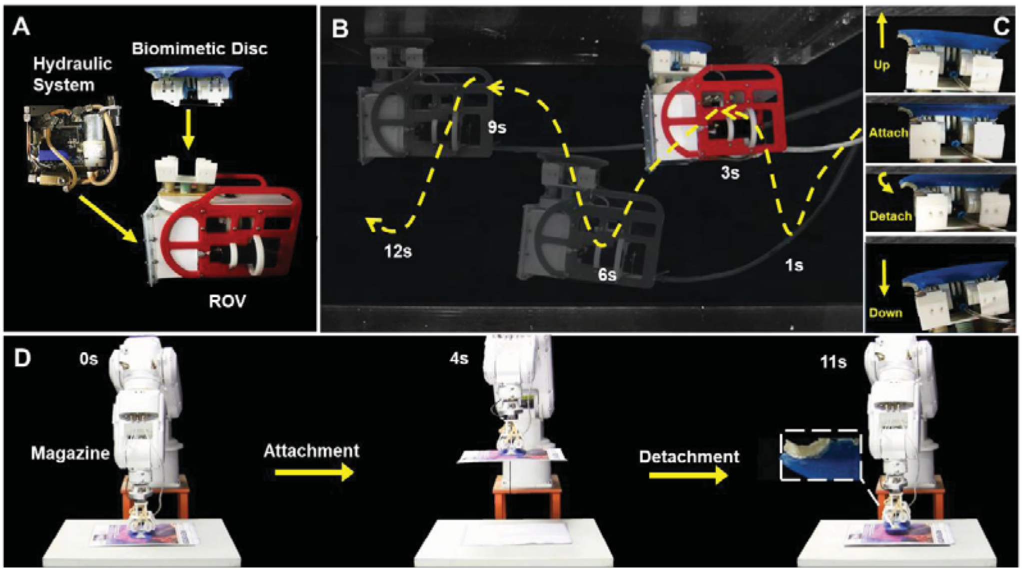

Fig. 6. Verification tests of the attachment and detachment performance of the biomimetic remora disc. (A) An integrated underwater vehicle. The biomimetic remora disc was mounted on the ROV through a connection device that included four springs and four soft silicone hydraulic elastomer actuators. A hydraulic system was connected to the front of the ROV to control the disc's curling mechanism and lamellae motion. (B) The integrated ROV can switch seamlessly between attachment and detachment. (B) shows two continuous attachment and detachment maneuvers on a smooth surface within 12 s. Scale bar 5 cm. (C) A complete attachment and detachment maneuver that shows the details of the disc's motion. Scale bar 3 cm. (D) Demonstration of gripping and releasing a magazine in air. Scale bar 10 cm.

biomimetic remora disc came in complete contact with the surface, four soft silicone elastomer actuators controlled by a hydraulic system provided a 20 N preload to enhance the contact between the surface and the disc. (ii) The ROV was propelled down, left, and right to confirm a successful attachment event. (iii) To initiate the detachment process, the disc's soft lip curled up with the cable-driven curling mechanism. (iv) Once the disc prototype detached from the surface without ROV's assistance, the vehicle was driven from the surface to the bottom of the tank to prepare for the next attachment maneuver (movie Part 4). The integrated ROV can demonstrate an attachment-detachment-attachment process within 6 s. Details of the biomimetic disc's complete attachment and detachment process are provided in Fig. 6C.

IV. Conclusion

In this study, we found that live remoras detach from substrates by curling up the anterior lip of their suction discs. We fabricated a multi-material biomimetic adhesive disc with both attachment and detachment capabilities based on the morphological and kinematic features of the remora disc. Detachment can be mediated by a curling mechanism assembled on the anterior disc lip with a small cable force (less than 2.6 N). Based on our experiments with the biomimetic robotic disc, our key results can be summarized as follows: (1) we found that the biomimetic remora disc can attach to surfaces of different roughness (0-200 μm) even with a very small preload (less than 2 N). Increasing the lamellae angle (θ) and the preload can significantly increase the pull-off force (260%) and the backward frictional force (470%). (2) With the lip curling mechanism, the disc prototype can achieve detachment under a wide range of preload force conditions (2-20 N, a wider force range than that of the live counterpart). The vertical pulling force of the disc can be rapidly (within 750 ms) reduced up to 253 times compared to that of the fully attached state. (3) With the disc lamellae folded down, the remaining interfacial force decreased 62% compared to that of the fully erected lamellae state. Based on the above results, we hypothesize that the live remora's curled lip and folded lamellae result in a significantly smaller vertical interfacial force and frictional force, thus enabling the animal to achieve rapid and effective detachment.

We demonstrated the hitchhiking behavior of an integrated underwater ROV through a continuous series of attachment and detachment maneuvers with the biomimetic disc. The control and actuation system are self-contained. It should be noted that both the attachment and detachment mechanisms of the disc were actuated by hydraulic soft actuators whose internal pressure can be tuned with respect to the ambient underwater pressure. We regard our study as a first step toward developing real-world untethered marine robots that are capable of hitchhiking and working at various ocean depths.

We also utilized the disc to demonstrate pick-and-place maneuvers in air with objects of different roughness and material properties. By installing the disc on a robotic arm, we showed that various planar objects, including a magazine (Fig. 6D), wooden plate, acrylic plate, and silicone pad (see Movie Part 5), can be reliably gripped and controllably released.

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