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A bionic adhesive disc for torrent immune locomotion inspired by the Guizhou Gastromyzontidae*

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***Abstract* - The Guizhou Gastromyzontidae showed extraordinary normal adhesion and anisotropic friction on wet and slippery surfaces in the torrential stream. In this study, the surface microstructures of adhesive disc of the Guizhou Gastromyzontidae were characterized firstly by using the Scanning Electron Microscopy (SEM). It had been found that the fin rays of the fish were composed of the hexagonal pad-like unculi, setae arrays and micro-pores. Then, inspired by the surface structures of the adhesive disc of Guizhou Gastromyzontidae, the artificial adhesive discs with surface microstructures were designed and fabricated by using the 3D printing and molding technology. The regular disc with no surface microstructures was also fabricated for comparison study. The adhesion properties of two different disc samples were investigated in water condition on substrates with various roughnesses. The results show that the bionic adhesive discs with composite microstructures have good adhesion properties in water condition. The proposed adhesive disc could have potential applications for underwater robotics.**

Index Terms* - *Guizhou Gastromyzontidae,adhesion, microstructure, bionic

I. INTRODUCTION

Many animals have excellent adhesion ability in nature and they can provide solutions to achieve highly adaptive and easily released synthetic adhesives. For examples, geckos [1], tree frogs [2] [3] and some insects were found to have toe pads with reversible, reusable and self-cleaning properties. They can live in a variety of environment even in wet surface conditions [4]. Inspired by these creatures, researchers have developed various adhesive materials for different applications.

In addition to the above terrestrial and amphibian animals, there are many aquatic fishes that also have excellent adhesion capacity. Octopus has overcast hairy suckers on its tentacles that enable itself quickly attach on the coral [5]. Climbing goby fishes can easily adhere to rocks using their oral sucker [6]. The Northern clingfish can sustain 80–230 times of its body weight when it sucks on the rocks. The adhesion force of clingfish has been found mainly from its adhesive disc, especially the edge of the disc, the submillimeter level of Unculi and micro-scale setae structures play an important role in the adhesion [7]. The similar structure was also found in the feet of abalone [8]. In addition to providing capillary and van der Waals forces for underwater attachment, the micrometer-scaled structures of the abalone's pedal feet enable themselves compliance to various roughness surfaces for an effective sealing the interface [9]. Recently, one species (Guizhou Gastromyzontidae) of hill stream fishes [10] [11], a freshwater fish, has been found to possess superior sticking and climbing abilities in wet conditions [13]. The surface microstructure of disc plays an important role in friction enhancement for fast motion [13]. In order to further understand the wet adhesion of the Guizhou Gastromyzontidae' disc, in this study, we firstly characterized the micro and nanostructures of the Guizhou Gastromyzontidae' disc by using the scanning electron microscopy (SEM). Followed by observing the micro and nanoscale structural features of the Guizhou Gastromyzontidae' disc, a bionic disc with synthetic setae arrays were fabricated on silicone rubber. The adhesion force of the microstructured discs were measured by using an adhesion testing equipment. Effects of micro setae arrays on adhesion were investigated experimentally.

II. THE BIOLOGICAL ADHESIVE DISC

The Gastromyzontidaes used in the experiments were caught in the rocky torrential streams of Sanjiang, Guangxi Province. The fishes were kept in a $50\text{cm} \times 30\text{cm} \times 70\text{cm}$ transparent aquarium that was equipped with an air pump thermostat (25 ± 1℃) and a filtration system. Fish foods were supplied three times per week. Fresh water was replaced every two weeks. Only healthy Gastromyzontidae individuals were used in experiments, and all of the samples were raised for more than one week before the experiments. The experiments were handled in accordance with the Regulations for the Administration of Affairs Concerning Experimental Animals issued by the Institutional Animal Care and Use Committee of Jiangsu.

A. Observation of the macroscale disc structure.

The Gastromyzontidaes with a weight of about 2.92g - 3.65g and a total length of about 82mm - 97mm were used in the experiments. Fig. 1(a) shows a Gastromyzontidae that is

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sticking on the ventral wall of an aquarium. It has a flat streamlined body, a pair of protruding eyes at the top of the head and many black spots in the back. The Gastromyzontidae demonstrates superior sticking ability on the surface underwater by using its adhesive disc system. As shown in figure 1(b), two interconnected translucent discs on the ventral side of the fish were observed. At the outer edges of the discs, there are a pair of pelvic fins and a pair of pectoral fins inclined to the rear of the body. Although the fish usually sticks to the wall or bottom of the aquarium quietly, it also can quickly move its body by twisting two pairs of discs and contracting two pairs of fins, which indicates that the anisotropic shear force exists in the adhesive disc system. Via animal experiments, it was found that the shear friction toward the tail was greater than that toward the head because of the two pairs of directionally expandable fins. This anisotropic feature enable the fishes to withstand rapids easily [13].

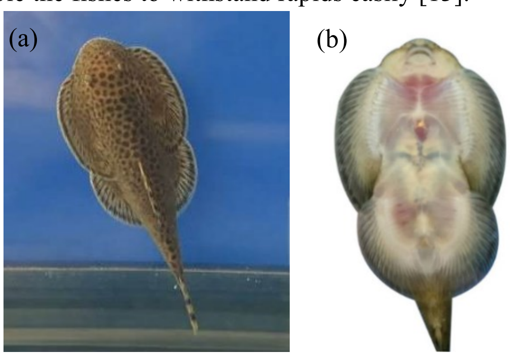


Fig.1 (a) A Gastromyzontidae (about 80mm in length) sticking on the vertical wall of an aquarium; (b) The ventral view of the Gastromyzontidae showing the macroscale disc structure.

A. Characterization of composite microstructures

The SEM was used to study surface microstructures of Gastromyzontidaes' adhesive discs. For the SEM sample preparation, a healthy fish was euthanized via submersion in a concentration of 0.5g/L MS 222 for 15 minutes. Then it was finalized in 2.5% glutaraldehyde solution for 24 hours and rinsed three times (15 min per rinse) in 0.1 M phosphate buffer (PH, 7.2). After that, the sample was dehydrated through an alcohol series (70%, 80%, 90%, 95% and 100%, 24 h in each). Finally, the sample was dried, glued on aluminum holders and coated with a layer of gold. The sample was viewed on a JSM-6360LA SEM at an operating voltage of 15KV.

Fig. 2 shows the SEM pictures of Gastromyzontidae's adhesive disc surface. Fig. 2(a) shows the epithelial cell surface in the middle area of the disc. It can be seen that some micro-bulges are sparsely distributed on the relatively flat epithelial cell surface. In Fig. 2(b), three types of surface microstructures from the left to the right are observed on the pelvic fin ray. In the left area, densely packed micro-pores with a diameter of about 2um are observed on the epithelial cell surface. In the middle area, micro-ridges are observed on the fins. The magnified image in the middle corrugated area shows polygonal epithelial cells with micro-ridge networks (about 10um in width). Similar structural features are observed on a tree frog's toe pads in its different development stages [2] [3]. In the right area, micro-pillars with irregular small dimples at the tips are observed on the epithelial cell surface. Fig. 2(d) shows densely packed setae arrays (about 0.1um in diameter) covering on the surface of one polygonal epithelial cell in the middle area (Fig. 2(b)). The micro-ridge networks and setae arrays may function to enhance the shear resistance of the adhesive discs by mechanical locking with microscale asperities of the substrate surface. The similar fibrils have also been observed in the abalone's adhesive disc system, in which the fibrils have been shown to play a key role in generating van der Waals and capillary forces [9]. When the fish adheres on wet conditions, the micro-pillars on the epithelial cell surface (Fig. 2(b)) facilitate the production of stable micro bubbles to help sealing of the adhesive disc [13].

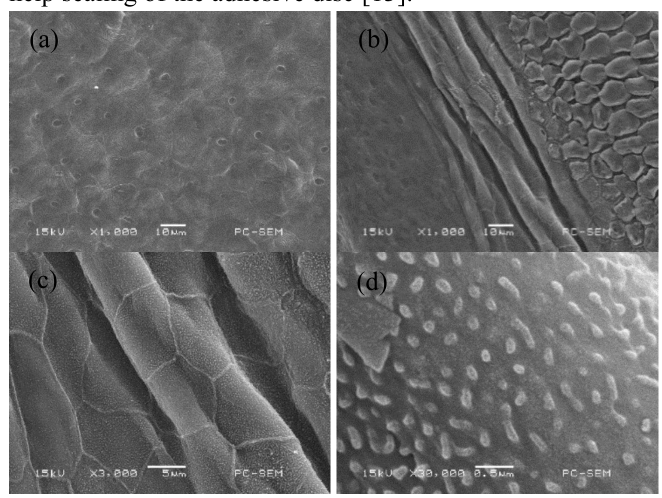


Fig.2. Scanning electron micrographs of the Gastromyzontidae's disc system: (a) the epithelial cell surface in the middle area of the disc. (b) Different epithelial cell surfaces on the pelvic fin ray. (c) The magnified polygonal epithelial cells in the middle corrugated area in figure 2(b). (d) Setae arrays covering on the surface of polygonal epithelial cells in figure 2(c).

III. BIO-INSPIRED ADHESIVE DISCS

A. . Design and fabrication

The Guizhou Gastromyzontidaes perform superior attachment and climbing ability in underwater conditions (Fig. 1). This feature is closely related to the micro- and nanoscale structures on the disc surface, such as micro-ridge networks (Fig. 2(c)), dense nanopillar arrays (Fig. 2(d)). Inspired by these surface structures, a hybrid adhesive disc with micropillar arrays was designed.

As shown in Fig. 3(a), we developed a computer-aided design (CAD) model of the bionic disc prototype. The disc prototype has a diameter of 60mm, with a mass of 21g. Fig. 3(b) shows the mold used to fabricate the bionic disc prototype, which was fabricated by Selective Laser Sintering (SLS) technology with Polycarbonate material. To facilitate the clamping of the disc, a black holder fabricated by 3D printing technology was glued on the back of the disc (Fig.3 (a)). The main body of the disc was made by soft silicone rubber material (Vyta Flex30, Smooth-On, Inc, PA, USA). In order to verify the influence of the setae arrays, Synthetic Gecko Tape (Gecko® Nanoplast®, Klettband, GER) with a pore diameter of 40um was purchased. Figs 4(a) and 4(b) show the scanning electron micrographs of the film with setae arrays. Then synthetic gecko tape was combined to the ventral side of the disc as shown in the grey annular area with width of 10mm. To make the tape to align with the disc tightly, we mold it together without any glue. The bionic adhesive disc prototype with micropillar arrays is showed in Fig. 3(c). In addition, the regular adhesive disc prototype without micropillar arrays was also fabricated as a control sample, as shown in Fig. 3(d).

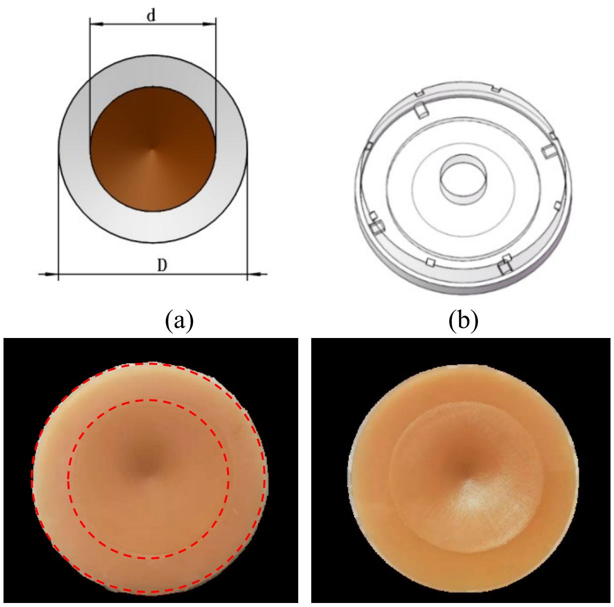
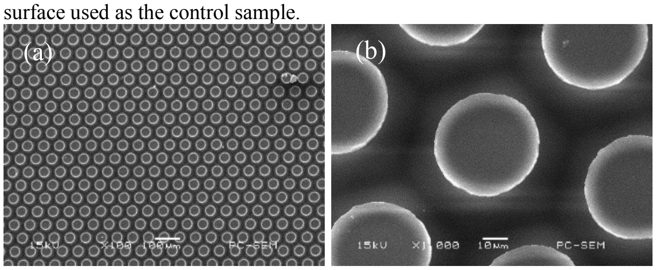


Fig.3 Design and fabrication of bio-inspired adhesive discs: (a) the CAD model showing the structure and geometry of the bionic disc; (b) the corresponding mold used to fabricate bionic discs; (c) the adhesive disc prototype with the microstructured surface. synthetic gecko tape was combined between in the red dotted lines; (d) the regular adhesive disc prototype without the microstructured surface used as the control sample.



(a) (b)

Fig. 4 (a) Scanning electron micrographs of the Synthetic gecko tape showing the microstructured surface; (b) Higher magnification image of the tape showing the micropillars.

B. Adhesion measurements

a. Methods

In order to evaluate the adhesion capability of biomimetic discs, a universal testing machine (E44.104, MTS, USA) was utilized in the tensile mode to measure the pull-off force. Fig 5(a) shows the picture of the testing machine and the magnified clamp on the bottom right. In order to facilitate the clamp to hold the sucker, we also made a black support glued to the back surface of the disc. The data acquisition frequency was set as 20Hz. Before the tensile test, a preload of 10N was applied on the disc to ensure that the disc was fully attached to the substrate, and then the disc was slowly pulled upward at a fixed speed of 50mm/min until the disc was completely detached from the substrate. Fig.2 (b) shows the typical force curve, in which point A represents the preload, and point B represents the pull-off force that is defined as the maximum tensile force during the whole detachment period (segment ABC in Fig. 5(b)). The pull-off force of discs was tested on the sandblasted substrates with underwater condition. In order to reduce measurement errors, more than 10 tests were conducted for the same testing condition and the results were averaged.

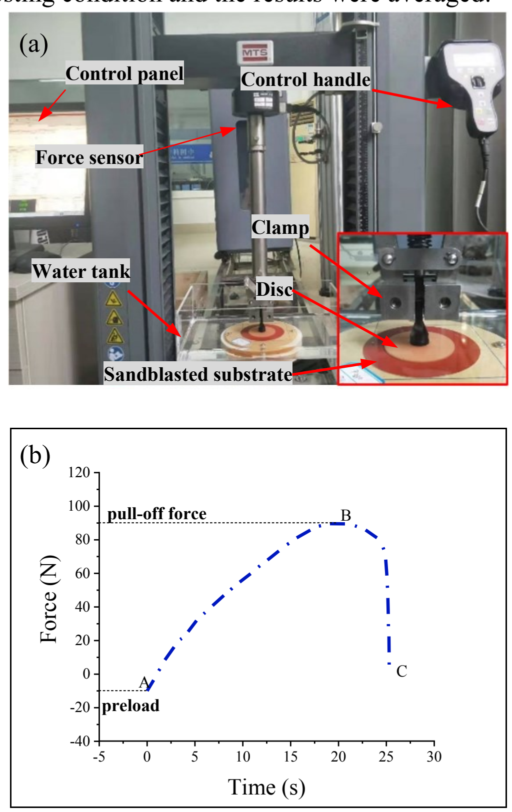


Fig.5 (a) The universal testing machine for pull-off force tests; (b) a typical force curve showing the pull-off force.

b. Results and discussion

In order to verify the influence of setae arrays on the pull-off force of the bionic disc, we fabricated bionic discs with setae arrays and regular samples without setae arrays respectively, and then evaluated their adhesion capabilities by conducting tensile tests. Sandblasted acrylic sheets were selected as substrates and the roughness were measured by Surface Profiler (Form Talysurf® CNC Series, Taylor Hobson, UK). Fig. 6 shows the results of samples were tested underwater with depth of 10mm. Orange bars represent regular disc, and green bars represent bionic disc. As shown in the figure, in the range of roughness (30.6-15.92 um), the maximum pull-off force of both types of discs decreases as the roughness increases, and the maximum pull-off force of the bionic disc is larger than that of regular disc, while in the range of roughness (9.76-4.19 um). The maximum pull-off force of the bionic disc is smaller than the regular disc. It can be found that the maximum pull-off force of the bionic suction disc is significantly larger than that of the regular suction disc on the substrates with a relative large roughness, while on the relative smooth substrates, the maximum pull-off force of the bionic disc and the regular disc is not much different.

The experimental results show that the bionic disc with microstructures has better performance on the relatively rough surface. These results also present another evidence to explain why the Gastromyzontidaes fish can stick to the rock and climb upstream.

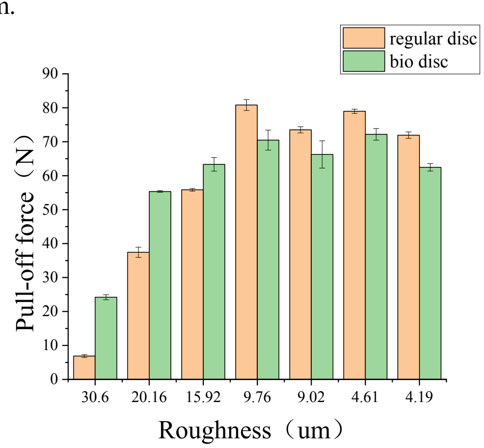


Fig .6 The comparison of pull-off force for the bionic and regular discs on a series of rough substrates in water condition.

IV. Conclusion

We studied the microscale structural features of the Guizhou Gastromyzontidae' disc, and observed several microstructures such as hexagonal unculi, setae arrays and micro-pores on the surface. It implicates that the surface microstructures of the fish's disc may play a key role in the water environment to make themselves in resisting flow currents.

Inspired by these surface structures, a bionic disc with synthetic setae arrays was fabricated by using silicone rubber. The pull-off forces on different level rough surfaces were investigated under water condition. The results indicated that the bionic disc with setae arrays had better attachment performance in water environments. The findings may offer possible solutions for the design of adhesion systems for the underwater robots.

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