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Chiton radula feeding demonstrated by a fundamental zipper pulling mechanism

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1 Introduction and Research Purpose

To achieve automated off-terrain environmental sampling, a robotic system must be able to collect materials from surfaces of irregular roughness and unknown topology. This ability is essential for the survival of biological organisms by feeding, and has been achieved countless times in evolution. Molluscs in particular have the ability to forage on surfaces of varied topology. Here, we focus on extracting the basic principle of the feeding mechanism of *Cryptochiton stelleri*, a marine mollusc also known as the gumboot chiton. Chitons are a class of marine molluscs comprising over 940 species, among which *C. stelleri* is the biggest, reaching over 35 cm and 2 kg **[1]**.

Their fleshy girdle covers an articulated hard shell, and their muscular foot allows both attachment and locomotion (**Fig. 1**). Inside their mouth is the radula, a belt-like structure with two rows of teeth that enables them to scrape algae off of rough surfaces. The teeth of *C. stelleri* are one of the hardest natural teeth known, reinforced with magnetite and santabarbaraite **[2]**. Their feeding activity contributes to rock erosion and the formation of mushroom-shaped islands **[3]**.

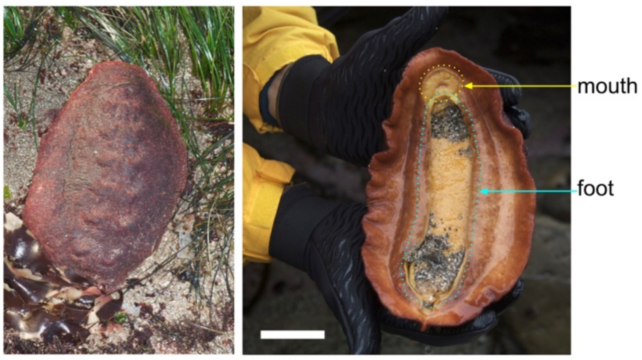

Figure 1: Dorsal and ventral view of a gumboot chiton. Scale bar: approximately 8 cm. Photo by Jerry Kirkhart.

In this research, we aim to achieve the following, and this paper focuses on demonstrating (1). The movement of chiton radula is explained in more detail in Section 2.1.

(1) Demonstrating the basic mechanism of the chiton radula movement and its biological significance for feeding from an engineering viewpoint;

(2) Achieving inwards rolling motion of the teeth with an optimal angle of attack to enable scraping;

(3) Addition of a surrounding soft half-torus structure to achieve upwards collection of the material;

(4) Application of the artificial chiton mouth to outdoor sampling of environmental samples;

(5) Realization of an autonomous robotic sampler that can sample rough surfaces in outdoor environments.

2 Conceptual Design and Prototyping

2.1 Description of Radula's Natural Movement

The movement of the radula can be decomposed into the following steps (**Fig. 2**). First, two rows of inwards-oriented teeth are set to the target surface. Second, the target surface is scraped as the teeth close up in a zipper. Finally, the mouth rolls up inwards and the mouth closes. These three steps are repeated endlessly during feeding. In other words, the chiton radula enables not only the scraping of hard substrates but also the collection of feeding material by upwards rotary motion with the teeth closing up like a zipper. Dissection of chitons previously showed that the motion of the radula is achieved by a biological muscle inside the body of the chiton **[4]**.

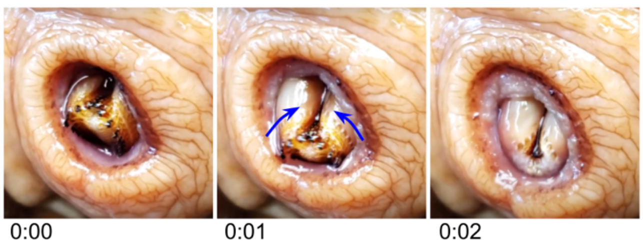

Figure 2: *C. stelleri* radula movement (unit: seconds). Video by Sam Larson (https://www.youtube.com/watch?v=07jKMYBSQ2s).

2.2 Engineering Principle of Radula's Mechanism

In this paper, we demonstrate both why and how the chiton is able to achieve the zipper-like function by transforming a simple pulling motion into a rotary zipper motion, from an engineering standpoint.

2.2.1 Biological advantage of rotary configuration

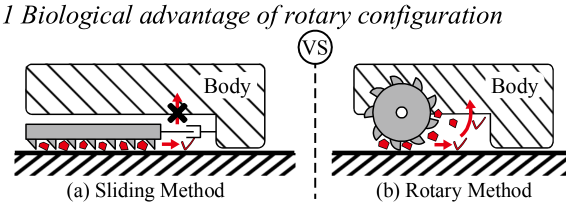

Figure 3: Comparison of sliding and rotary configuration. Upward red arrows indicate the flow of collected material.

As shown in **Fig. 3**, assuming a flat surface, a sliding motion using a flat scraper is expected to scrape more food. However, upwards collection is difficult. In comparison, a rotary motion is a much more favorable configuration to enable the upwards collecting of the food into the body of the chiton. Furthermore, it also compatible with a wider variety of surface topologies, as the contact point surface is minimized (**Fig. 4**).

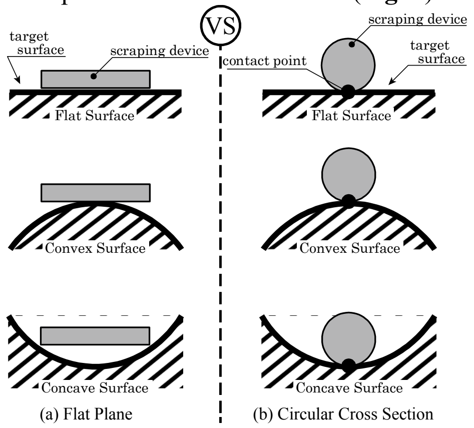

Figure 4: Relationship between the configuration shape (left: sliding; right: rotary) and the contact point surface.

2.2.2. How to achieve rotary zipper motion by linear pulling?

To demonstrate the principle of the rotary zipper mechanism from an engineering standpoint, we set a lateral pulling motion and complementary spring as shown in **Fig. 5**.

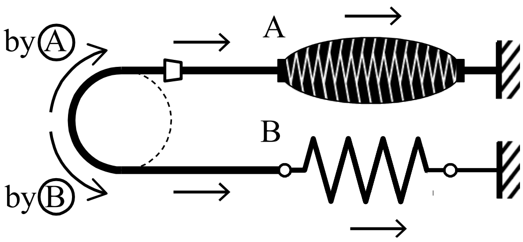

Figure 5: Combination of artificial muscle (A) and spring (B) to convert linear motion into rotary motion.

3 Results

3.1 Prototype Building

The prototype comprises a Main Mechanism Unit, in which the chiton's radula is represented by a zipper with a slider body, and an Actuation Unit, in which the chiton's muscle is represented by a pneumatic artificial muscle (**Fig. 6**). There are two versions of the prototype: one in which the slider body has full compliance, meaning that it can rotate by any angle θ depending on pulling force and during the returning motion, and one with a fixed-angle slider body (**Fig. 7**).

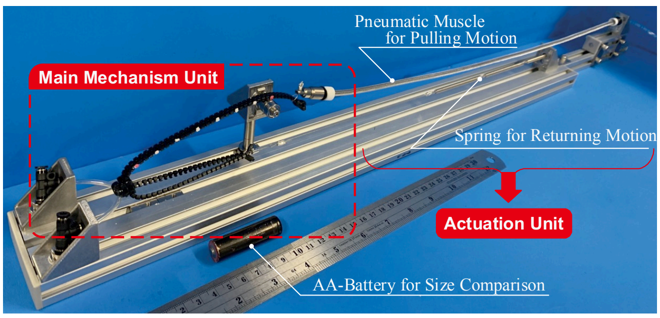

Figure 6: General description of prototype model.

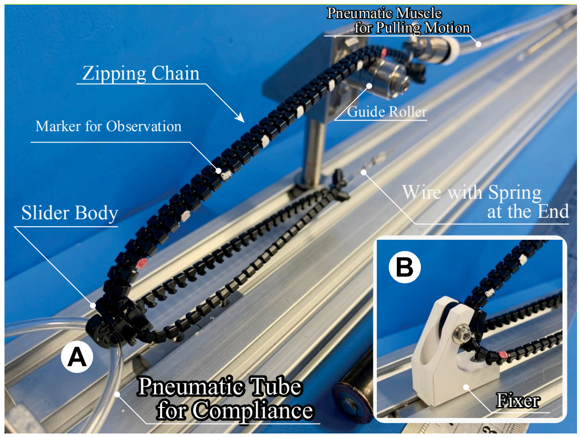

Figure 7: Detailed description of prototype model with (A) a compliant slider body and (B) a fixed-angle slider body.

3.2 Analysis of Physical Displacement

A movie was shot at 6 frames/second and the acceleration in mm/frame of a fixed point on the zipper was estimated based on the distance traveled between consecutive frames (**Fig. 8**). The results show that compliance at the slider body is essential to realize both the pulling and returning motion in a reproducible manner. A video summary of this is available: https://youtu.be/vzwBtIQZow0

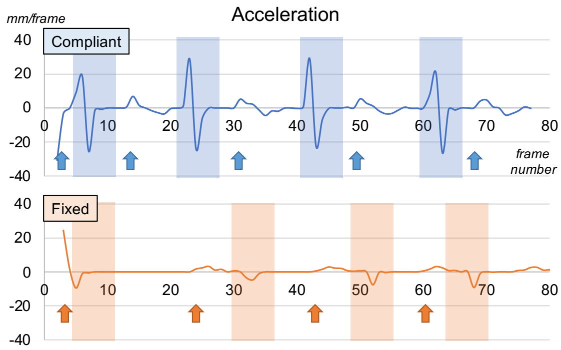

Figure 8: Acceleration (mm/frame) of a fixed point on the zipper. The arrows indicate the starting point of pulling, and the shaded areas represent the returning motion.

4. Conclusions & Future Work

Although the device presented here is still far from achieving the full range of movement of the natural radula, this work successfully demonstrates that (1) a simple pulling motion is sufficient to drive the rotary zipping motion observed in the chiton, and that (2) compliance at the slider body position is essential to allow reversible motion reproducibly. In our next work, we would like to achieve the zipper-like motion without a slider body, and the passive inwards motion of the teeth to enable sample collection.

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