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Bio-Inspired Protective Skin Mechanism with an Exhaustive Arrangement of Tiny Rigid Bodies

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1 Introduction

In recent years, bag-type grippers have been developed with gripper mechanisms capable of grasping objects of various shapes. A flexible bag filled with powder or fluid is constructed to conform to the shape of the object being gripped. Many conventional bag-type gripper mechanisms are made of elastic rubber material or cloth, which causes the gripper surface to tear when gripping a sharp object, resulting in leakage of the internal powder or fluid, which results in an inability to grasp the object.

Therefore, we constructed a cut-resistant cover for a soft robot made of blade-proof fabric and realized a flexible gripper with high cut resistance while maintaining its flexibility (Fig. 1, left).

However, although the blade-proof fabric shows high protective performance against cutting, thin needles can penetrate between the fibers of the blade-proof fabric, resulting in low puncture resistance. In view of this problem, this study focused on the scales of living organisms and devised the basic principle of a soft robot protective outer skin "scaly mechanism" with improved puncture resistance by overlapping and encompassing the arrangement of hard plates. We also conducted basic characteristic experiments using a prototype based on the devised principle (Fig. 3) and confirmed the effectiveness of the protective function reported here.


(a) Shellfish https://onl.bz/FffWj6Y
(b) Fish https://onl.bz/tn3JGRy
(c) Reptiles https://onl.bz/y4jw34U
(d) Pangolin https://onl.bz/SvjnLW2

Figure 1: Soft gripper mechanism with cut resistance and Examples of organisms with scales on their body surfaces

2 Scale Mechanism

2.1 Biological exemplar:

We focused on the scales of living organisms as a method of protecting soft robots such as bag-type grippers from sharp objects while maintaining their flexibility. Scales are small, protective pieces of animal skin. They protect the animal's body from attacks and changes in its external environment(as shown in Fig. 1 right). Although each individual scale is more rigid than the skin it protects, the individual scales are small in relation to the body, and their flexible connections with neighboring scales do not inhibit the flexible movement of the animal's body [1], [2]. The aim was to realize a soft robotic protective hull with both flexibility and high rigidity by comprehensively arranging small rigid pieces similar to the scale of a living organism.

2.2 Engineering research focusing on scales

Conventional engineering research focusing on the scales of living organisms has been conducted, for example, on peristaltic actuators with a skin having anisotropic friction that imitates the scales of snakes to increase the efficiency of movement [3], variable stiffness elements with spiral-type structures inspired by the shape and helical arrangement of fish scales [4], and methods for producing a scale-patterned appearance [6]. Research has also been conducted on this topic.

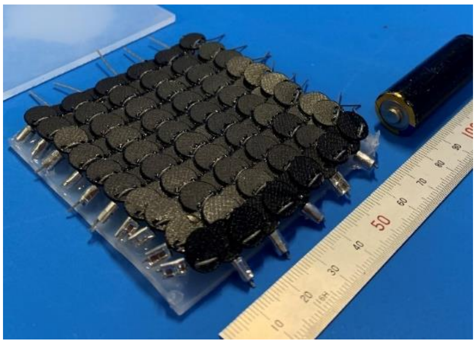
Figure 2: The Prototype of the robotic scaled mechanism

Examples of research focusing on the protective function of biological scales include the protective system of overlapping rigid plates on a flexible sheet developed by Martin et al. [7], who confirmed that the overlapping structure of biological scales has excellent puncture resistance and flexibility in resisting bending deformation. However, the protection system by Martin et al. attached small pieces of scale by gluing them onto a flexible sheet, leaving issues to be resolved regarding the elasticity required for a soft robot protective skin, which does not inhibit robot movement, and descaling resistance, which prevents the pieces from coming off, even if they come into contact with the external environment.

2.3 Verification of the protective function using an actual machine for principle verification

To achieve high elasticity and descaling resistance, the small pieces were arranged by connecting them with wire-like beads instead of gluing them together to construct a scaly epidermis.

3 Experiments on Basic Properties

3.1 Basic deformation performance

A prototype of the scaled mechanism is shown in Figure 2. Focusing on the circular scale shape of fish, small pieces of scales are circular. Small pieces were arranged horizontally and vertically and a single wire was used to connect them to form a row, which was then connected laterally to form a surface. Each small piece was circular, 10 mm in diameter and 0.75 mm thick, and was produced by laser cutting polypropylene sheets. The small pieces were divided into two rows, one at the front and one at the back and a row of small pieces was made by overlapping the through holes at the top and bottom, passing a wire through them and applying an elastic force to the small pieces that caused the bent wire to straighten back.

3.2 Experiments to verify elasticity

To verify the elasticity of the direct-stitched scaly mechanism, a row of direct-stitched scaly skins was subjected to a tensile test, as shown in Fig. 5(right). Polypropylene and silicone rubber sheets of the same size were measured in the same manner for comparison, and five tests were performed on one type of specimen. An Instron 3343 tensile-testing machine (Instron) was used.

The results of the tensile tests are shown in Fig. 5(left). Fig. 5(left) shows that under an applied load of 5 N, the polypropylene sheet elongated by approximately 1 mm, whereas a row of straight-stitched scaly skin elongated by approximately 30 mm. Thus, the straight-stitched scaly skin has high elasticity, which is not observed in simple polypropylene sheets. Fig. 5 also shows that the silicone rubber sheet does not converge in elongation below 40 mm, whereas the direct-stitched scaly skin 1-row tends to converge at approximately 40 mm elongation because the wire sewing the small pieces in a row is 120 mm long and the ends are fixed. This was thought to be due to the convergence of the elongation of the scaly epidermis as it approached the length limit of the wire.

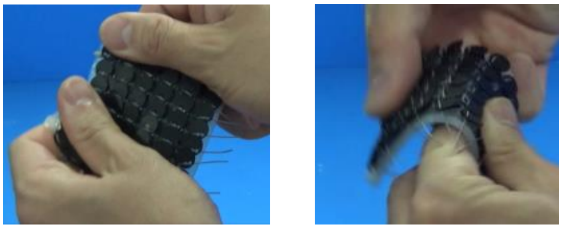
(a) Shear deformation (b) Bending deformation

Figure 3: Flexibility test of the prototype model

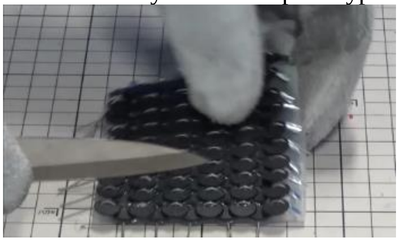
Figure 4: Cut resistance test (please watch the movie at the following site, thank you.
https://www.youtube.com/watch?v=K1oylnUtRiU)

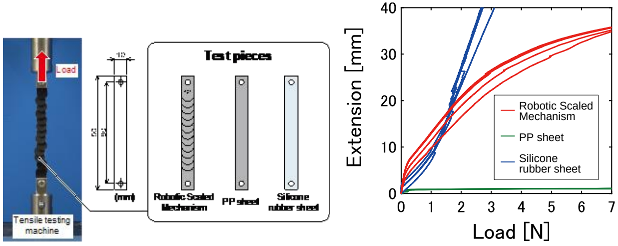

Figure 5: Elasticity test

3.3 Non-clogging properties

With blade-proof fabrics, thorns can get between fibers when they come into contact with sharp objects, which can impede the movement of the soft robot to be protected, or even damage the robot. However, in a scaly mechanism, such clogging problems do not occur if a configuration in which neighboring small pieces overlap without gaps, such as fish scales, can be achieved.

3.4 Light transparency

If the scaly skin protecting the soft robot is transparent, its outer state can be monitored using visual sensors and cameras mounted inside the robot. In addition, by attaching markers to small pieces, a function for visualizing the degree of force and deformation of a soft robot can be expected. This is a characteristic specific to the scaly mechanism because the blade-proof fabric cannot be made transparent.

An actual machine for checking the principle of the scaling mechanism in Fig. 3 was manufactured using transparent polypropylene sheets, and experiments were conducted to verify the light transmission. The experimental setup is shown in Fig. 6. A flashlight (Panasonic BF-BG20) was shone through a 30 mm diameter hole in a wall in a dark place to let light into the dark place. A scaly mechanism made of small pieces of transparent material was attached to the wall, and light transmission was measured using an illuminometer. For comparison, the same measurements were performed using a scaly mechanism composed of small black pieces, as shown in Fig. 2. The experimental results are presented in Fig.7. Fig.7 shows that the light transmitted through the transparent version was stronger than that transmitted through the black version.

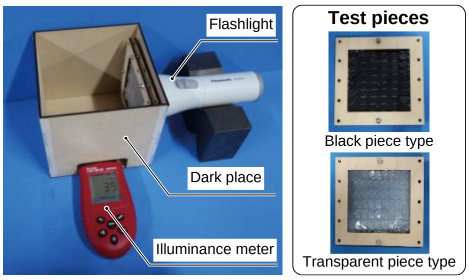

Figure 6: Light transmission test

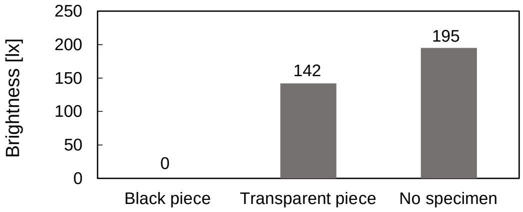

Figure 7: Result of the light transmission test

4 Conclusion

Focusing on the scales of living organisms, the basic principle of the "scaly mechanism," a soft robot protective outer skin with both flexibility and high rigidity, was devised. Basic characteristic experiments were conducted using a prototype machine based on the devised principle, and the effectiveness of the protection offeredwas confirmed. We also developed a prototype of a straight-stitching-type scaling mechanism and confirmed through verification experiments that it had high elasticity and descaling resistance.

In the future, a sewing method that considers the elasticity of the wire will be investigated to solve the problem of curvature of the entire scaly epidermis owing to the elasticity of the wire, as described in Section 3.2.

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