Cartilage Increases Swimming Efficiency of Underwater Robots

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Abstract

Underwater robots are useful for exploring valuable resources and marine life. Traditional underwater robots use screw propellers, which may be harmful to marine life. In contrast, robots that incorporate the swimming principles, morphologies, and softness of aquatic animals are expected to be more adaptable to the surrounding environment. Rajiform is one of the swimming forms observed in nature, which swims by generating the traveling waves on flat large pectoral fins. From an anatomical point of view, Rajiform fins consist of cartilages encapsulated in soft tissue, thereby realizing anisotropic stiffness. We hypothesized that such anisotropy is responsible for the generation of traveling waves that enable a highly efficient swimming. We validate our hypothesis through the development of a stingray robot made of silicone-based cartilages and soft tissue. For comparison, we fabricate a robot without cartilages, as well as the one combining soft tissue and cartilage materials. The fabricated robots are tested to clarify their stiffness and swimming performance. The results show that inclusion of cartilages in the robot fins increases the swimming efficiency. It is suggested that arrangement and distribution of soft and hard areas inside the body structure is a key factor to realize high-performance soft underwater robots.

Introduction

The ocean contains valuable resources such as mineral resources and marine life [1, 2]. To explore them, underwater robots are useful as many areas in the ocean are inaccessible to humans. Traditional underwater robots use screw propellers [3–5], which may be harmful to marine life due to noise and accidental entrapment [6, 7]. In contrast, robots that incorporate the swimming principles, morphologies, and softness of aquatic animals are expected to be more adaptable to the surrounding environment. Hence, various types of soft biomimetic underwater robots have been developed [8–38]. There are robots that mimic the propulsion mechanisms of aquatic animals [8–30], as well as the machine has also robots with high mechanical performance [31–38]. Aquatic animals, specifically fishes have a wide variety of swimming forms. For example, swimming of Batoidea, a kind of stingrays is based on Rajiform [39–41]. This type of swimming is based on generation of traveling waves on flat, large pectoral fins. The plane morphology of Rajiform swimmer is expected to be suitable for moving around the seafloor, which would enable efficient exploration of rare earths and marine life.

Stingray is the one of the Rajiform swimmers whose swimming behavior is shown in Fig. 1 in the form of sequential photos. The structural waves of the fins travel from the front to the back, generating thrust force in the forward direction. This suggests that the fins of stingrays are compliant in the swimming direction and relatively rigid in the perpendicular direction in order to transmit the momentum of traveling waves. From an anatomical point of view, the skeleton of stingrays is consisted of cartilages, an elastic tissue. As can be seen in Fig. 2, cartilages are radially distributed across the fins, resulting in anisotropic nature of their stiffness. We hypothesize that this stiffness anisotropy enhances the generation of the traveling waves and assures efficient swimming.

In this study, we validate our hypothesis through development of stingray robots with embedded cartilages. To the best of our knowledge, no study on the incorporation of cartilages has been reported, even though numerous stingray-like robots have been developed [42–51]. Our robots consist of silicone elastomers with the different Young's modulus that represent soft tissue and cartilages. Hence, we investigate first time the effect of cartilage inclusion on the anisotropic stiffness in a soft structure by performing a tensile test. Next, we fabricate stingray robots using the materials characterized in the tensile test. Next, we conduct compression test of the robots to confirm the overall stiffness of the body. Then, we show experimentally that stiffness anisotropy of the fins realized by the cartilages can increase the swimming efficiency even though the overall stiffness of the robots remains the same.

Results

Tensile test. Specimens were fabricated and the tensile test was performed to investigate the effect of cartilage inclusion on anisotropic stiffness. Specimens of two types of silicone elastomers were tested: Ecoflex 00–20 (Smooth-On) and Sylgard 184 (Dow Corning). The former was a compliant elastomer (tensile strength ~ 1.1 MPa) used as the soft tissue. The latter was a rigid elastomer (tensile strength ~ 6.7 MPa) and used as the cartilage. Based on these materials, four types of specimens were prepared as shown in Fig. 3(a): A) specimen with soft tissue and vertically (i.e., tensile direction) arranged cartilages, B) specimen with soft tissue and horizontally arranged cartilages, C) specimen consisting of soft tissue only, and D) specimen consisting of a randomly arranged cartilage materials in the soft tissue. In the specimen Type-D, the amount and mass ratio of the materials are the same as those in the

types A and B. Every specimen had the dimensions of 70 mm (width) × 70 mm (length) × 3 mm (thickness). The results of the tensile test are shown in Fig. 3(b). The details of this experiment are explained in the Method section. The Young's modulus values of each specimen obtained from the experimental data are summarized in Fig. 3(c). The data showed that type-A specimen has the largest modulus among the samples (0.22 MPa). Type-B and Type-C exhibited similar modulus: 0.05 MPa and 0.03 MPa, respectively, whereas Type-D showed the modest rigidity with the Young's modulus of 0.13 MPa. The difference in Young's modulus in the specimens was clearly correlated with the presence of the cartilages. This result also suggests that the anisotropy of stiffness is called by the alignment of cartilages.

Fabrication of the robots. We developed three types of stingray robots based on the same set of materials used in the previous section. The first was with cartilages (Type-A indicates the stiffness that transmits the power. Type-B indicates the softness that generates the traveling wave.), the second was without cartilages (type-C), and the third comprised a mixture of soft tissue and cartilage materials (type-D). In the last one, the amount and ratio of the materials were the same as in the first one. The cartilages were designed by the analogy with the actual skeleton of a stingray that has radially distributed cartilages. Figure 4(a), (b) illustrates the structure of the robot having a circular shape with a diameter of 160 mm and a fin thickness of 3 mm. The cartilages were 1 mm thick and 6 mm width. The robots were made of the three main parts: the cartilages, the body (soft tissue), and the servomotors (FS 0403, FEETECH). The servomotors were powered externally through electrical wires. The servomotors were coated with a silicone bond (BathbondQ, KONISHI) to ensure water resistance. The use of waterproof servomotors can also be considered. However, they were not used in this study because of the robot size limitation. A pressure-tube consist of rubber and very light and bond coat plug joint were used to prevent short circuits. For the fabrication of robot body and cartilages, the molds were used to solidify the liquid materials. The molds were made of an acrylic resin, and consisted of multiple parts. A CNC router (MDX-540S-AP, Roland) and a laser cutting machine (Speedy 360, trotec) were used to produce the molds. Figure 5 summarizes the fabrication process of the robot based on the molding. The cartilage parts were fabricated by injecting Sylgard 184 into the mold, and then solidified in an oven at 80°C for 1 h. Bubbles inside the silicone were removed using a vacuum chamber. For fabrication of the robot body, Ecoflex 00–20 was injected into the mold to fix the servomotors, cartilages, and other parts. After the silicone was completely solidified, the robot was removed from the mold. The fabricated robots are demonstrated in Fig. 4(c)-(e).

Compression test. We performed compression test of the robots to examine their overall stiffness (see the Method section for the details of the experiment). Figure 6 shows that the stiffness of the robot with cartilages (type-A) is similar to that in the robot made of the mixture of soft tissue and cartilage materials (type-D). Therefore, by comparing the performance of these two robots it is possible to distinguish the effect of cartilage inclusion on the swimming efficiency disregarding the overall stiffness. In addition, the type-C robot with the much lower stiffness made only of soft tissue material (type-C) illustrates the effect of overall stiffness on the swimming efficiency.

Swimming test. We conducted swimming test of the developed robots in the experimental environment shown in Fig. 7(a) where the robot is immersed in a water tank filled with tap water. Figure 7(b) depicts a sequence of swimming movements of the robot with cartilages. Following the expectations, traveling waves were generated along the fins that push the robot forward. We measured the swimming speed and electric power consumption for each type of the robots while varying the frequency of the driving voltage from 0 to 9 Hz (7.5 V). At every tested frequency, the measurements were performed 10 times and the average value was reported. Figure 8(a) plots the measured swimming speed of the robot with cartilages. A peak speed of 13.1 mm/s appeared at a frequency of 4 Hz at a. The peak electric power consumption was 3.48 W. The presence of peak in the swimming speed suggests that there is a resonance vibration of the structure which enhances the amplitude of traveling waves. Regarding the robot without cartilage (i.e., made of the soft tissue only), the swimming speed was lower compared with the other robots as can be seen in Fig. 8(b). This may be due to the high compliance of the fin structure where the water pressure reduces the transmission efficiency of the traveling waves. As for the robot made of the mixture (Fig. 8(c), it exhibited a trend similar to that of the robot with cartilage. A peak speed of 11.2 mm/s was observed at a frequency of 4 Hz. The peak electric power consumption was 3.73 W.

Discussion

Following the similar overall stiffness of the robots with cartilages and that made of the mixture, the result validates our hypothesis that the cartilages increase the swimming efficiency of underwater robots based on Rajiform swimming. The peak speed and electric power for the tested robots are summarized in Fig. 8(d), and the specific numbers at each peaks are indicated at Table 1. The result also suggests that anisotropic arrangement of soft and hard domains, as represented by soft tissue and cartilages in the robot, are

important structural parameter that may define the swimming behavior, as well as increase swimming efficiency. In the case of Rajiform swimming, radially arranged cartilages hold softness in the swimming direction to generate traveling waves, and hardness in the perpendicular direction to transmit the mechanical power efficiently. Future work will focus on investigation of the effect of anisotropic stiffness in different soft robotic platforms, and establishing the ways to design such robots with optimized geometry and modulus of materials to control the stiffness. Nevertheless, we believe that demonstrated arrangement and distribution of soft and hard domains in the structure can be a promising approach to designing high-performance underwater soft robots.

Table 1
Summary of peak speed and electric power for the tested robots

	With Cartilages	Without Cartilages (only soft tissue)	Without Cartilages (mixture of cartilage and soft tissue materials)
Maximum Speed [mm/s]	13.1	7.7	11.2
Electrical Power [W] (at the peak speed)	3.48	3.64	3.73

Methods

Table 2 shows the properties of the materials used. Both of the silicone elastomers employed are two-component liquid mixtures. Specific weights of both materials are slightly greater than that in water. Sylgard 184 is harder than Ecoflex 00–20 because of its higher tensile strength and hardness (Shore A) values. The silicone elastomers were prepared as the follows. Ecoflex 00–20 was a two-component liquid mixture fabricated in a 1:1 weight ratio as recommended by the producer. Sylgard 184 was mixed with the main agent and the curing agent by the same procedure at a weight ratio of 10:1. Sylgard 184 possesses a low viscosity and has a tendency to penetrate into small crevices. After mixing the materials until their whitening by incorporation of air bubbles, the silicone elastomers were placed in a vacuum vessel at a negative gage pressure of 0.1 MPa to remove the air bubbles. The mold was taken out of the container and the soft material was cured on a horizontal surface. Bubbles removal is a necessary procedure because they can cause breaking of silicone elastomers after hardening. A thin layer of mold lubricant (Shin-Etsu Silicone, KS702-1) was applied to the mold to facilitate removal of the soft material after the curing. The curing can be accelerated by heating; however, in this study the robots were cured at room temperature (around 25 °C) to avoid deformation owing to residual stress.

Table 2
Details of body tissue and cartilage

	Body tissue	Cartilage
Material	Ecoflex 00–20	Sylgard 184
Tensile strength	1.1MPa	6.7MPa
stiffness (Shore A)	0–20	43
Specific weight	1.4	1.03

Figure 9 represents a diagram of the system configuration used in this study. The servomotors are controlled by an Arduino Uno microcontroller. A microcontroller was supplied with 7.5 V, 0.8 A electric power. The electric power supply to the Arduino and to a ESP_Power Monitor, an electric power measurement device, was provided separately. Electric power supplied to the servos can be measured more accurately by using the ESP_Power Monitor only. A Grove_4-Digit Display and a Grove_Button are included into the system to check and change the frequency of the servomotors. A Grove Base Shield can be used by mounting it on an Arduino. However, because of the need to separate the electric power supply as mentioned earlier, we removed the electric power sharing pins. With this system, outputs such as movement angle and frequency can be adjusted individually for each of the four servomotors. The buttons allow the user to change the frequency of the servomotors. The display shows the frequency of the servos. In the microcomputer program, the robot was set to automatically stop in 10 s after it started moving; therefore, the robots swam for the same amount of time in all experiments. The phase of the input is shifted $\pi/4$ between the front two and the rear two servos, so that

the fins can generate a traveling wave. Power consumption was measured using the Power Monitor based on a INA 219 board and recorded at a period of 1 ms.

In this study, compression tests were performed to investigate the stiffness of the robots. Tensile tests were performed to confirm the effect of cartilage. Figure 10 shows a test scene of tensile test. In the tensile test, the test pieces could not be directly fixed, so we fabricated a jig. The test pieces had the dimensions of $70 \times 70 \times 3 \text{ mm}^3$. The stress on the fins was estimated to be 0.013 MPa based on the torque of the servomotors used ($0.7 \text{ kg}\cdot\text{cm}$). Therefore, in this study, the stress was offset up to 50% of the strain and approximated to obtain the Young's modulus. Jigs were fabricated to fix the robots in the compression test (Fig. 11). Joints to the load cell were fabricated with a polylactide and the other parts were fabricated of acrylic. The test speed was 10 mm/min, and the test stroke was 10 mm away from the place of contact with the robot; however, it was offset by the test force in the graph.

Declarations

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Competing interests

The authors declare no competing interests.

Author contributions statement

All authors conceived and designed the experiments. MY and YI performed the hardware development. TN and JS performed tensile test. MY and TN analyzed the data. All authors wrote the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

Swimming of a stingray (pictures are taken by the authors). Traveling waves are passing from anterior to posterior along the pectoral fins.

Figure 2

Skeleton diagram of stingray (drawn with reference to [52]). Cartilages are radially distributed in the body providing anisotropic body stiffness.

Figure 3

Results of tensile test. (a) Photos of four types of specimens (Type-A, -B, -C, and -D) consisting of the same silicone elastomers. The composition and structure of Type-A and -B samples are the same, whereas the direction of cartilages is parallel and perpendicular to the strain direction. Type-C sample is without cartilages, whereas Type-D is a mixture of soft tissue and cartilage materials. (b) Stress-strain curves of the specimens. The solid lines are the measured data, and the corresponding dashed lines are linear approximations. (c) Young's modulus of each specimen obtained by the linear approximation of stress-strain curves.

Figure 4

Overview of a developed robot consisting of soft tissue (Ecoflex 00-20, Smooth-On), servomotors (FS 0403, FEETECH), and cartilages (Sylgard 184, Dow Corning): (a) top view of the robot structure; (b) side view of the robot structure; (c) robot with cartilages; (d) robot without cartilages (soft tissue only); (e) robot made of the mixture of cartilage and soft tissue materials.

Figure 5

Robot fabrication process based on molding. The mold is made of multiple acrylic parts: (a) Ecoflex 00-20 is put in a mold and cured in an oven; (b) servomotors are placed inside the mold; (c) cartilages made of Sylgard 184 are placed above the servomotors (cartilages are fabricated separately in another mold); (d) mold is filled with Ecoflex 00-20.

Figure 6

Result of compression test of the fabricated robots. Solid lines represent the measured data, and dashed lines are their linear approximation.

Figure 7

(a) Experimental setup to measure the swimming speed and power consumption of the robots; (b) sequence of swimming movements of a robot with cartilages. Traveling waves are generated by oscillating servomotors from the front to the back of the pectoral fin, thereby realizing swimming of the robot.

Figure 8

Measured swimming speed and electric power consumption as functions of the driving frequency for: (a) robot with cartilages, (b) robot without cartilages, and (c) robot made of a mixture of soft tissue and cartilage materials. (d) Swimming speed as a function of the electric power. The robot with cartilages exhibits the highest speed and the lowest power consumption indicating the effect of cartilage inclusion to increasing the swimming efficiency.

Figure 9

Power monitor and servomotor control diagram. The black line is the power supply electrical wires. The red line is connection for control the electrical wires. The dashed line depicts the controller components.

Figure 10

Tensile test equipment (MCT-2150).

Figure 11

Compression test for robots performed with an AGS-20NX.