Cartilage Increases Swimming Efficiency of Underwater Robots

Masaki Yurugi
Meijo University

Toshiaki Nagai
University of Electro-Communications

Jun Shintake
University of Electro-Communications

Yusuke Ikemoto (ikemoto@meijo-u.ac.jp)
Meijo University

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

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 π/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 kg·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.

References

1. Takaya, Y. et al. The tremendous potential of deep-sea mud as a source of rare-earth elements. *Rep.* 8, 5763 (2018).
2. Suzuki, K. Ishibashi, J. Kato, Y. Nozaki, T. Preface: Front edge of submarine mineral resources research in Japan. *J.* 49, 575-577 (2015).
3. Jaulin, L. A nonlinear set membership approach for the localization and map building of underwater robots. *IEEE Robot.* 25, 88-98 (2009).
4. Wynn, B. R. et al. Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience. *Geol.* 352, 451-468 (2014).
5. Kunz, C. et al. Deep sea underwater robotic exploration in the ice-covered arctic ocean with AUVs. *IEEE/RSJ International Conference on Intelligent Robots and Systems*, September 22-26, Acropolis Convention Center, Nice, France (2008).
6. Holles, S. D. Simpson, S. N. Radford, A. Berter, L. Lecchini, D. Boat noise disrupts orientation behavior in a coral reef fish. *Ecol. Prog. Ser.* 485, 295–300 (2013).
7. Amoser, S. E. Wysocki, L. Ladich, F. Noise emission during the first powerboat race in an Alpine lake and potential impact on fish communities. *Acoust. Soc. Am.* 116, 3789 (2004).
8. Marut, K. Stewart, C. Michael, T. Villanueva. Priya, S. A jellyfish-inspired jet propulsion robot actuated by an iris mechanism. *Smart Struct.* 22, 094021 (2013).
9. Ko, Y. et al. A jellyfish-like swimming mini-robot actuated by an electromagnetic actuation system. *Smart Struct.* 21, 057001 (2012).
10. Godaba, H. Li, J. Wang, Y. Zhu, J. A soft jellyfish robot driven by a dielectric elastomer actuator. *IEEE Robot. Autom. Lett.* 1, 624-631 (2016).
11. Barbar, A. et al. Design and development of bio-inspired underwater jellyfish like robot using Ionic Polymer Metal Composite (IPMC) Actuators. *Proceedings of SPIE - The International Society for Optical Engineering* 7976, 797624 (2011).
12. Joshi, A. Kulkami, A. Tadesse, Y. FludoJelly: Experimental study on jellyfish-like soft robot enabled by Soft Pneumatic Composite (SPC). *Robotics* 8, 56 (2019).
13. Christianson, C. et al. Jellyfish-inspired soft robot driven by fluid electrode dielectric organic robotic actuators. *Robot. AI* 6, 126 (2019).

14. Ren, Ziyu. Hu, W. Dong, X. Sitti, M. Multi-functional soft-bodied jellyfish-like swimming. *Commun.* 10, 2703 (2019).

15. Frame, J. Lopez, N. Curet, O. Engeberg, E. Thrust force characterization of free-swimming soft robotic jellyfish. *Biomim.* 13, 064001 (2018).

16. Cheng, T. et al. Untethered soft robotic jellyfish. *Smart Mater. Struct.* 28, 015019 (2019).

17. Shintake, J. Shea, H. Floreano, D. Biomimetic underwater robots based on dielectric elastomer actuators. *IEEE/RSJ International Conference on Intelligent Robots and Systems* (2016).

https://infoscience.epfl.ch/record/222727/files/Jun_SHINTAKE_IROS_underwater_robots_V7.pdf

18. Wang, W. Liu, J. Xie, G. Wen, L. Zhang, J. A bio-inspired electrocommunication system for small underwater robots. *Biomim.* 12, 036002 (2017).

19. Marchese, D. A. Onal, D.C. Rus, D. Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators. *Soft Robot.* 1, 75-87 (2014).

20. Neveln, D.I. et al. REVIEW Biomimetic and bio-inspired robotics in electric fish research. *Exp. Biol.* 216, 2501-2514 (2013).

21. Katzschmann, R. K. et al. Exploration of underwater life with an acoustically controlled soft robotic fish. *Robot.* 3, 16 (2018).

22. Marras, S. Porfiri, M. Fish and robots swimming together: attraction towards the robot demands biomimetic locomotion. *R. Soc. Interface* 9, 1856-1868 (2012).

23. Jiang, Y. Ma, Z. Zhang, D. Flow field perception based on the fish lateral line system. *Biomim.* 14, 041001 (2019).

24. Xie, O. Zhu, Q. Shen, L. Ren, K. Kinematic study on a self-propelled bionic underwater robot with undulation and jet propulsion modes. *Robotica* 36, 1613-1626 (2018).

25. Shen, Z. et al. A biomimetic underwater soft robot inspired by cephalopod mollusc. *IEEE Robot. Autom. Lett.* 2, 2217-2223 (2017).

26. Renda, F. et al. A unified multi-soft-body dynamic model for underwater soft robots. *J. Robot. Res.* 37, 648-666 (2010).

27. Wehner, M. et al. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Nature* 536, 451-455 (2016).

28. Calist, M. et al. An octopus-bioinspired solution to movement and manipulation for soft robots. *Biomim.* 6, 035002 (2011).

29. Sfakiotakis, M. Lane, D. M. Bruce, J. Davies, C. Review of fish swimming modes for aquatic locomotion. *IEEE J. Ocean. Eng.* 24, 237-252 (1999).
40. Rosenberger, L. J., Westneat, M. W. Functional morphology of undulatory pectoral fin locomotion in the stingray *Taeniura Lumma* (CHONDRICHTHYES: DASYATIDAE). *Exp. Biol.* **202**, 3523–3539 (1999).

41. Blevins, E. L., Lauder, G. V. Rajiform locomotion: three-dimensional kinematics of the pectoral fin surface during swimming in the freshwater stingray *Potamotrygon orbignyi*. *Exp. Biol.* **215**, 3231-3241 (2015).

42. Li, G. et al. A bio-inspired swimming robot for marine aquaculture applications: from concept-design to simulation. *OCEANS Conference*, Shanghai, 1-6 (2016), doi: 10.1109/OCEANSAP.2016.7485691.

43. Punning, A., Anton, M., Kruusmaa, M., Aabloo, A. A biologically inspired ray-like underwater robot with electroactive polymer pectoral fins. (2014) https://static.aminer.org/pdf/PDF/000/354/863/an_experimental_undulating_fin_device_using_the_parallel_bellows_actuator.pdf

44. Alvarado, P. V., Chin, S., Larson, W., Mazumdar, A., Youcef-Toumi, K. A soft body under-actuated approach to multi degree of freedom biomimetic robots: A stingray example. *3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, Tokyo, pp. 473-478, doi: 10.1109/BIOROB.2010.5627803 (2010).

45. Moored, K. W., Fish, F. E., Kemp, T. H., Bart-Smith, H. Batoid Fishes: Inspiration for the next generation of underwater robots. *Technol. Soc.* **45**, 99-109 (2011).

46. Zhou, C., Low, K. H. Design and locomotion control of a biomimetic underwater vehicle with fin propulsion. *IEEE/ASME Trans. Mechatron.* **17**, 25-35, (2012), doi: 10.1109/TMECH.2011.2175004.

47. Li, T. et al. Fast-moving soft electronic fish. *Adv.* **3**, e1602045 (2017).

48. Zhang, Y., He, J., Low, K. H. Parametric study of an underwater finned propulsor inspired by bluespotted ray. *Bionic Eng.* **9**, 166-176 (2012).

49. Cloitre, A., Aresen, B., Partikalakis, N. M., Youcef-Toumi, K., Alvarado, P. V. Y. Propulsive performance of an underwater soft biomimetic batoid robot. The Twenty-fourth International Ocean and Polar Engineering Conference, 15-20 June, Busan, Korea (2014)

50. Shin, S. R. et al. Electrically driven microengineered bioinspired soft robots. *Mater.* **30**, 1704189 (2018).

51. Urai, K., Sawada, R., Hiasa, N., Yokota, M., DallaLibera, F. Design and control of a ray-mimicking soft robot based on morphological features for adaptive deformation. *Life Robot.* **20**, 237–243 (2015).

52. Huskey, S. The Skeleton Revealed: An illustrated tour of the vertebrates. 142-43, 230-31, 268-69, 344-45 (Johns Hopkins University Press, 2017).

53. Shintake, J., Cacucciolo, V., Floreano, D., Shea, H. Soft robotic grippers. *Mater.* **30**, 170735 (2018).

54. Hughes, J. et al. Soft manipulators and grippers: A review. *Robot. AI* **3**, 69 (2016).