Artif Life Robotics (2015) 20:237–243
DOI 10.1007/s10015-015-0216-y

ORIGINAL ARTICLE

# Design and control of a ray-mimicking soft robot based on morphological features for adaptive deformation

**Kenji Urai[1] · Risa Sawada[2] · Natsuki Hiasa[3] · Masashi Yokota[2] · Fabio DallaLibera[1]**

Received: 2 April 2015 / Accepted: 29 May 2015 / Published online: 11 July 2015


**Abstract** Underwater tasks are diversified and articulated. The environment in which they must be accomplished is often unconstrained and unpredictable. Operating AUVs assuring safety of the robot and of its surrounding is therefore very difficult. On the other hand, many fishes are able to easily move in the same environments. A crucial factor for this capability is their body, which consists primarily of elastic and soft structures that enable both complex movement and adaptation to the environment. Among the most efficient swimmers we find rays, which show abilities like high speed turning and omnidirectional swimming. In this paper we propose an underwater soft robot based on the morphological features of rays. We mimic both their radially skeletal structure with independent actuators for each bone and the compliance of their fins. This flexibility of the structure provides an adaptive deformation that allows our robot to swim smoothly and safely.

**Keywords** Underwater robot · Soft robotics · Biomimetics · Morphological computation · Batoid fishes

This work was presented in part at the 20th International Symposium on Artificial Life and Robotics, Beppu, Oita, January 21-23, 2015.

✉ Kenji Urai
urai.kenji@is.sys.es.osaka-u.ac.jp

Fabio DallaLibera
Fabio.dl@is.sys.es.osaka-u.ac.jp

1 Department of Systems Innovation, Graduate School of Engineering Science, Osaka University, Toyonaka, Japan

2 Graduate School of Frontier Biosciences, Osaka University, Suita, Japan

3 Graduate School of Information Science and Technology, Osaka University, Suita, Japan

## 1 Introduction

Recently, many researchers are focusing on the development of new tools for underwater tasks. Underwater tasks are very diversified. They include, for instance, ecological observation, seabed resource exploration and environmental conservation. To achieve these tasks, many types of underwater robots have been studied and developed [1]. However, it is difficult to realize underwater robots which have sufficient maneuverability, necessary for performing various behaviors, and which are safe at the same time. These robots need to move in an environment where there could be many unpredictable obstacles, like rocks, corals, other fishes, etc. Assuring safety both for the robot and for its environment is still an open problem.

Bio-inspired robots are gathering attention as a next generation type of underwater robots that can satisfy these needs [2, 3]. Many fishes are composed primarily of elastic and soft structures which allow them to perform complex movements, as well as to adapt to their environment [4]. In particular, rays are known for having great maneuverability among fishes [5]. They are very efficient swimmers, they can turn around at high speed and they are able to swim freely in any direction.

Analysis of biological locomotion suggests that during their movement rays can keep high propulsive force and maneuverability by adaptively and flexibly controlling their large pectoral fin [6]. Furthermore, morphological features of rays, such as their elasticity, shape and musculoskeletal structure, contribute to their flexible swimming motion by skillfully regulating the stiffness of their pectoral fins [2]. Some underwater robots with a ray-like propulsion mechanism have been studied and developed [7–9]. However, these robots cannot realize the wide variety of swimming

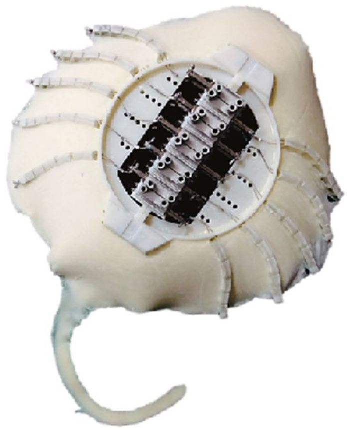


Fig. 1 Developed underwater soft robot

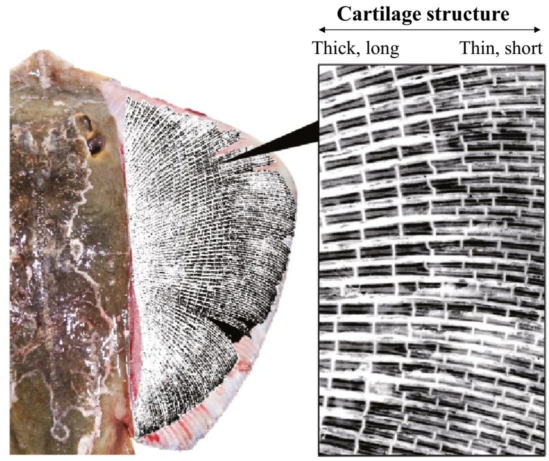



Fig. 2 Skeletal structure of ray

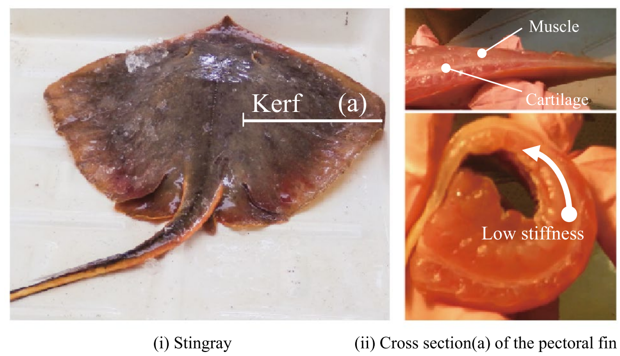



Fig. 3 Stiffness of the pectoral fin

locomotion types that rays are capable of, such as swimming in any directions freely and turning around at high speed.

In our previous work, we developed a prototype of a ray-inspired robot based on our observation that various motions seen in rays seem to be realized by a radially skeletal structure and independent actuators for each bone [10]. The robot shown ray-like flexible mobility that allowed swimming forward, backward, turning right and left by a simple feed-forward control framework. However, being too stiff the motion of the robot was still different from the one of real rays. Furthermore, the safety of the robot and its environment were not completely guaranteed.

In this paper, we present an underwater soft robot based on the morphological features of rays (Fig. 1). Biomimetic shape is coupled with compliance of fins obtained by utilizing soft material. Thanks to this flexibility of the soft material, adaptive deformation, i.e. flexible response against external forces, is possible. This, in turn, enables smooth and safe swimming motions. Together with safety, we expected that the inherent compliance of soft material makes the robot highly adaptable to a wide range of tasks and environments. The mechanism we propose is expected to be a new underwater propulsion mechanism for underwater robots that are both intrinsically safe and highly maneuverable.

## 2 Morphological features of ray

Rays belong to the group of batoid fishes. Stingrays (Dasyatis akajei) were analyzed in this study. Morphological features contributing to the high athletic performance of stingray were identified by dissection and observation of the musculoskeletal structure.

### 2.1 Musculoskeletal structure of ray

The musculoskeletal structure of stingray, investigated by dissection, is shown in Figs. 2 and 3. It can be seen that disk-shaped pectoral fins have a radial skeleton whose cartilage blanches at the chip, and that fins are covered with the planate muscle. This radially shaped musculoskeletal structure contributes to flexible and articulated motion of the pectoral fins by the control of many parts of the planate muscle with a high number of degrees of freedom. Additionally, it was observed that the fins are highly compliant for upward foldings, while they present relative stiffness when they are folded downwards. This property was maintained in our robot prototype, as shown in Fig. 4.

### 2.2 Compliance of the pectoral fin

From the two observations reported above, we developed a prototype of a ray-inspired robot. There are many previous works in the development of bio-inspired robot; rays are no exception. Recently, many bio-inspired underwater robots with ray-inspired mechanism have been developed.

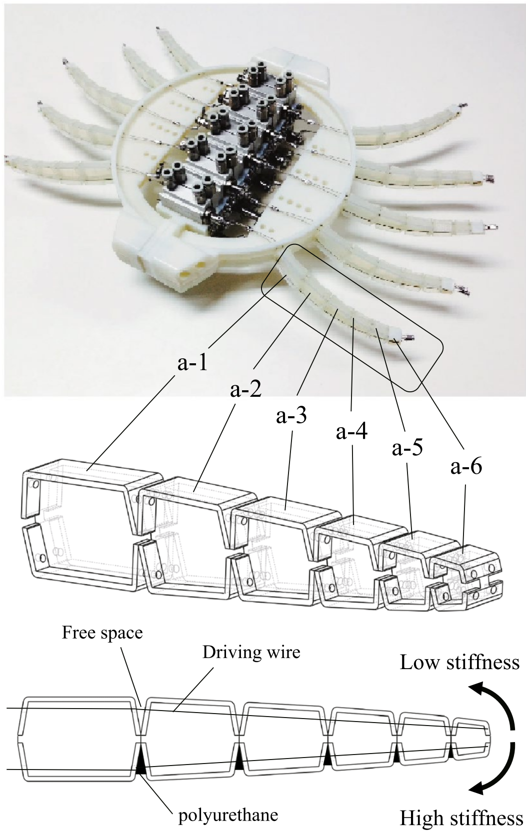



**Fig. 4** Bone structure of pectoral fin

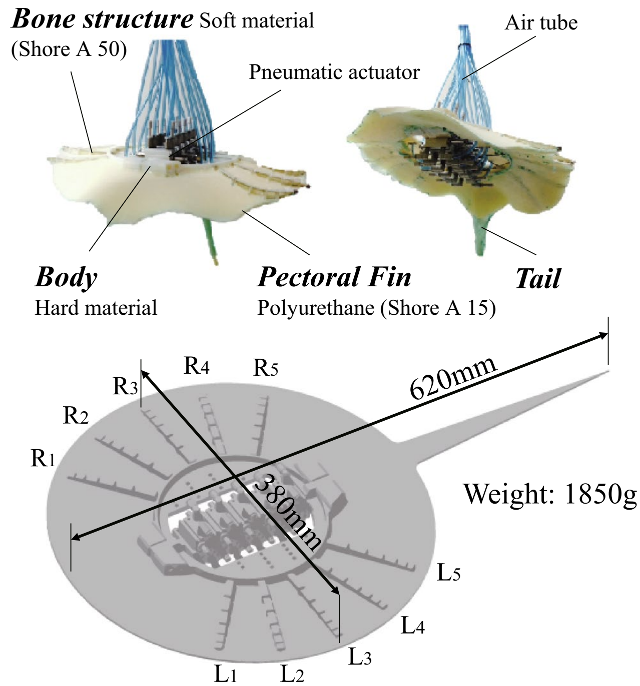



**Fig. 5** Specifications of the ray-mimicking robot

However, previous works differed from real rays in terms of configuration of the actuation mechanism: the skeleton was set in parallel, or actuator and locomotion patterns were limited and not redundant [7, 8, 11].

In this research, we develop an original bio-inspired underwater robot which is more closely based on the morphological features of real stingrays. In particular, we mimic the flexibility of real stingrays by constructing our robot entirely with soft materials. This kind of robots is getting more and more attention in the robotics field [12–14]. Advantages were proven in terms of safety, adaptability to external conditions and increases in the swimming efficiency due to the reduced resistance to the water flow offered by flexible robot bodies [15].

## 3 Ray-mimicking soft robot

In this section, the structure[1] and control system of our prototype underwater soft robot are described (Fig. 5). This robot is driven by pneumatic linear actuators and designed for the realization of flexible behaviors similar to the ones of stingrays.

### 3.1 Ray-mimicking pectoral fin

Fishes can create great propulsion forces due to their passive properties and interaction with the surrounding fluid [16]. Inspired by that, we developed a ray-mimicking soft prototype robot that explores the potential of a passive dynamic mechanism.

According to our biological observation, the following two facts are important morphological features: (1) The presence of a radially cartilage skeletal structure. (2) The compliance of the pectoral fin. The first function is realized simply by placing bones radially. The second is realized by using soft materials for the robot construction. We use a pneumatic linear actuator that powers the fin through a tendon-driven mechanism. More specifically, bones are driven by controlling the amount of compressed air supplied from a valve unit. The actuator has inherent flexibility thanks to the air driving it. The fin consists of a skeletal structures (10 bones) attached to a polyurethane fin. Therefore, it is expected to realize a smooth movement with soft response.

The design of our prototype robot is the transfer of functionality from rays to a underwater robot with respect to efficient mobility. We argue for the case of morphological computation, i.e. achieving efficiency (flexible locomotion)

[1] The tail is currently unactuated and unused. Future experiments will evaluate its possible usage for helping fast movements similar to the ones of real rays.

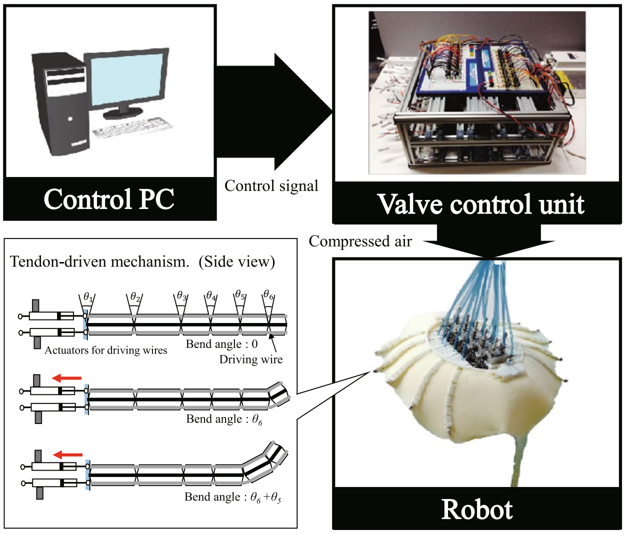



**Fig. 6** Open-loop control framework

and high mobility by duplicating rays' physical body structure. In this way, a possibly large part of the ray locomotion ability is outsourced to the embodiment, i.e. achieved by the interaction of the ray body parts and the water flow. This approach makes us focus on the material properties of a compliant pectoral fin propulsion mechanism.

### 3.2 Control system

Figure 5 shows the underwater soft robot we developed and its specifications. The robot has 10 bones placed radially, each of which is controlled independently by a pneumatic linear actuator (CUJB10-20D, SMC). Pneumatic actuators are often preferred over fluid due to their compressibility and to their environmentally benign nature.

Only tractive force of the actuators is used, therefore two actuators are required for driving each bone structure. Since the robot does not have any kind of electrical components, waterproof mechanisms are not required. To make the robot work power source, air compressor, control system and valves can be placed above water. The only connection required between this system and the robot are air tubes exiting from the valves.

Figure 6 shows the control system of our developed robot. This system consists of the control PC, the valve control unit and the robot. The robot system is operated simply by an open-loop control framework. More specifically, the robot is operated by control signals that regulate the amount of compressed air supplied to the pneumatic actuators. Control signals are sent to the valves control circuit through a DIO board (NI USB-6509, national instruments). By opening and and closing the valves, the pneumatic actuators can be operated. Valves can only be in two states, opened or closed. However, each actuator can take an intermediate state by controlling the opening time of its valve through PWM control.

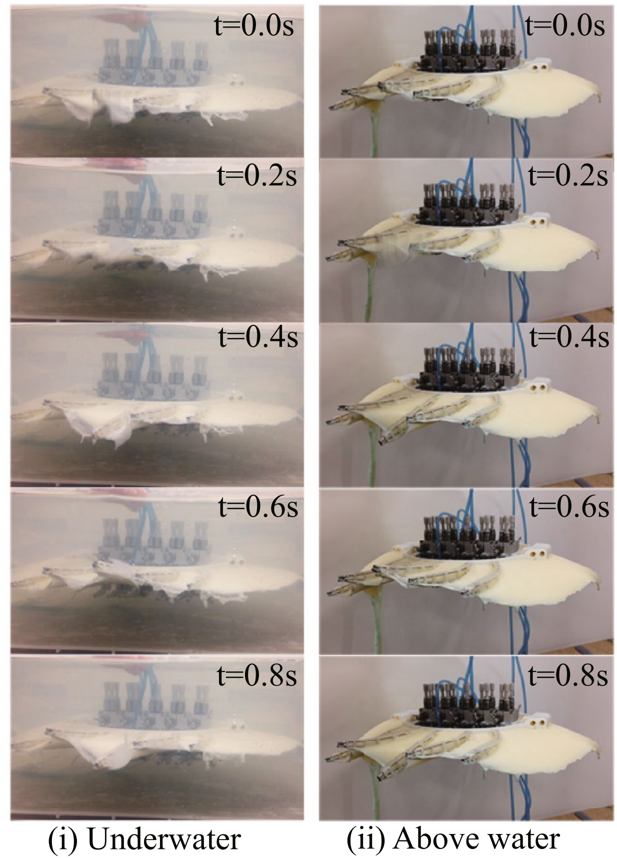



**Fig. 7** Difference of behavior between underwater and above water

## 4 Adaptive deformation of our prototype robot

We demonstrated the effectiveness of the proposed mechanism by conducting two experiments. The experimental setup consists of a water tank for the robot to swim and the control system shown in Fig. 6.

First, we evaluated the difference in the fin movement between underwater and above water robot activation. Figure 7 shows the experimental results. It was confirmed that the structure of the robot prototype deforms depending on the medium in which it is immersed, either water or air, respectively. Observing Fig. 7, it can be observed that the fin shape, under the same input command, is completely different. For instance, at time $t = 0$ when the prototype is in water the fin between the bones forms U shaped arcs. Comparing the depth of the arcs with the actuators' dimension (in terms of number of pixels) in the image, the depth can be estimated to be of approximately 22 mm. When the

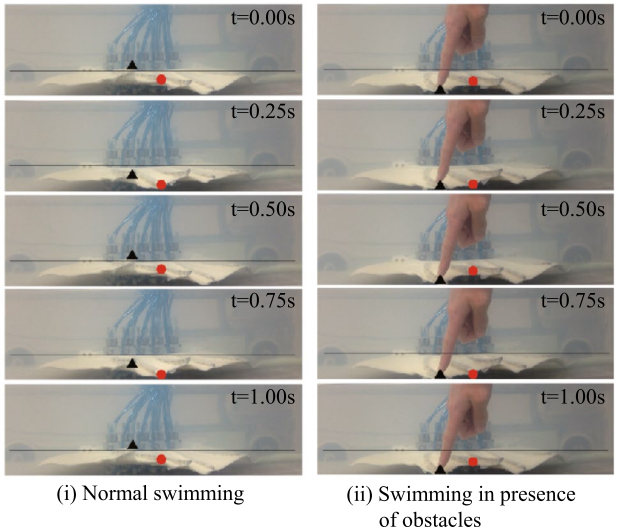



**Fig. 8** Adaptive deformation. For making the deformation clearer, two bones' extremities are highlighted by a *triangle* and a *circle*, respectively

robot is above water, with the exact same command, the fin placed between consecutive bones bends much less. A similar evaluation leads to approximately 9 mm. More in general, thanks to flexibility of the elastic fin and pneumatic actuators, adaptive deformation happens, and smooth swimming motion was generated when the robot was placed in water. The experiment was conducted by periodically driving bones $R_3$ and $L_3$ (Fig. 5) in phase. More in detail, as shown in Fig. 6, each bone is driven by two antagonist tendons, which are actuated at alternate times, each for half of the period, by the corresponding on-off valve. The control is open loop, so pressure or amplitude of the oscillation of the fins are not measured. The characteristics of the movement emerge by the interaction of the robot with the surrounding environment.

Second, we conducted an experiment to investigate the compliance to obstacles during underwater operation. Swimming behavior was obtained by driving all bones (Fig. 5, $R_1$ to $R_5$ and $L_1$ to $L_5$) at a constant frequency of 2Hz with phases opportunely set by trial and error to assure the robot locomotion in water. Also in this case, open loop control was employed, so pressure or amplitude of the oscillation of the fins were not defined.

Figure 8 presents the experimental results. Our prototype robot responds flexibly to external forces by changing its motion adaptively. This results confirms that our developed prototype robot is flexible enough to adapt to external forces, and at the same time it is able to continue its swimming behavior. This compliance to external forces suggests that the developed robot is suited for swimming in presence of complex environments like irregular seabed.

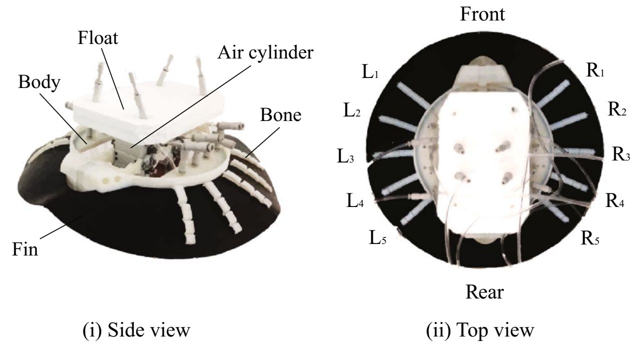



**Fig. 9** Experimental setup (Ray-mimicking robot: Type B)

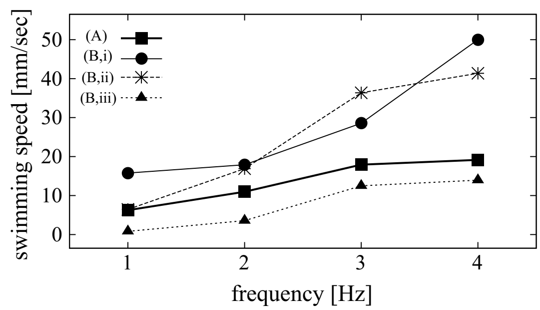



**Fig. 10** Relationship between the frequency of the fin and swimming speed. Hardness Shore A 45, 65 and 90 were tested for robot B. Data are reported as curves (B,i), (B,ii) and (B,iii), respectively. For reference, data of robot type A are also plotted as (**a**)

## 5 Effects of fin hardness on the swimming speed

To investigate the relationship between the hardness of the fin and swimming speed, we developed an additional prototype robot, shown in Fig. 9, in which the fin can be easily replaced. Swimming behavior was obtained by periodically driving the skeleton $L_4$ and $R_4$ bones (Fig. 9) in phase. In more detail, we investigated how the relationship between the frequency of the fin movement and the swimming speed changes for fins of different hardness. In this experiment, we used the first prototype (Fig. 5), hereafter named Type A, with fin of hardness Shore A 15, and the new prototype, called Type B, with three fins of different hardness: Shore A 45,65 and 90, respectively.

For each setting, we measured the average swimming speed over a period of ten seconds, and the number of flap motions required to perform 1 m. The amplitude of the fin movement reduces for frequencies higher than 4 Hz. In order to assure a constant amplitude among the experiments, the frequency of the movement was thus limited to a maximum 4 Hz, and frequencies of 1,2,3 and 4 Hz were used for the experiment.

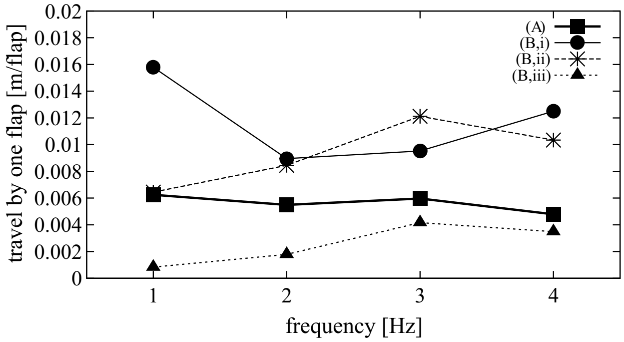
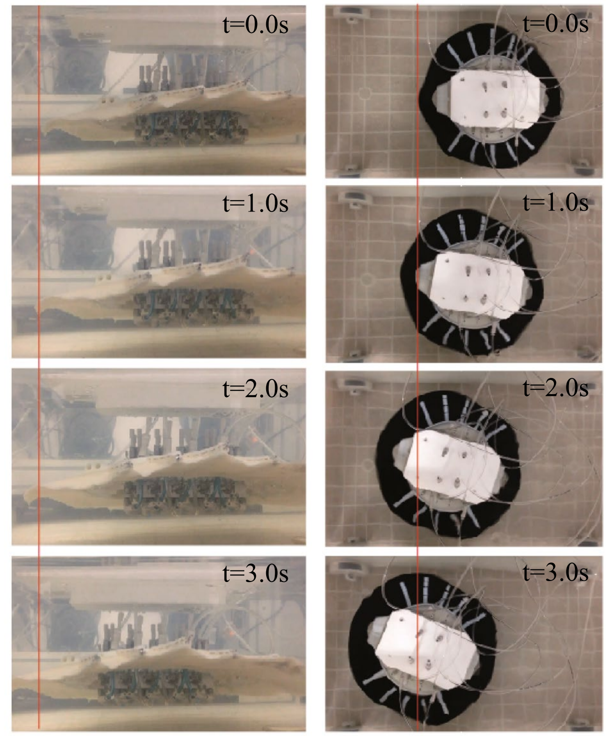



**Fig. 11** Relationship between the frequency of the fin and the distance traveled by one flap. Hardness Shore A 45, 65 and 90 were tested for robot B. Data are reported as curves (B,i), (B,ii) and (B,iii), respectively. For reference, data of robot type A are also plotted as (A)

Experimental results show that when the hardness of the fin is Shore A 45 and the frequency of the fin is 4 Hz, swimming speed is maximized (Fig. 10) and the distance traveled by one flap is maximized at 1 Hz with Shore A 45 (Fig. 11). Figure 12 shows the swimming behavior under the conditions that achieved maximum swimming speed. As the result, we found that the hardness of the fin strongly affect the swimming speed. Therefore, it is necessary to properly design the hardness of the fin based on the characteristics of the robot (e.g. size, shape, weight, etc).




(i) Type: A, Frequency: 4Hz, Hardness: Shore A 15

(ii) Type:B, Frequency: 4Hz, Hardness: Shore A 45

**Fig. 12** Swimming motion of the prototype robots

## 6 Conclusions

In this paper, we present a prototype of a ray-mimicking underwater soft robot based on our observation that various fish motions, such as the ones of rays, seem to be realized by utilizing soft materials. The developed robot was shown to be capable of ray-like flexible locomotion by a simple open-loop control framework. We show that its pectoral fin, entirely realized by elastic elements, enables a safe and adaptive deformation. More in general, this work illustrates the potential of utilizing passive body properties, especially in an unsteady and unpredictable environment. This prototype robot achieved flexible swimming behaviors. The proposed mechanism is expected to become a new underwater propulsion mechanism for underwater robots for which high safety is required. Furthermore, in this work we highlight that compliance of the fin can provide advantages in terms of propulsion force (and in turn traveling speed). Specifically, experiments showed that fins with a suitable compliance can bring speed improvements compared to harder fins.

In our future work, we will improve the design of our underwater robot by reconsidering morphological properties such as the robot's body shape and material, in order to obtain even better swimming performance. Additionally, we will conduct more practical tasks that require flexibility and safety, e.g. interactive observation of fishes in their environment.

**Acknowledgments** This research was supported by "Program for Leading Graduate Schools" of the Ministry of Education, Culture, Sports, Science and Technology, Japan.

## References

1. Chu SW, et al (2012). Review of biomimetic underwater robots using smart actuators. Int J Precis Eng Manuf
2. Moored, Keith W, et al (2011) Batoid fishes: inspiration for the next generation of underwater robots. Marine Technol Soc J
3. Ijspeert AJ (2014) Biorobotics: using robots to emulate and investigate agile locomotion. Science 346(6206):196–203
4. Webb PW (1994) The biology of fish swimming. In: Mechanics and physiology of animal swimming, p 4562
5. Comas OA (2014) Biomechanics in batoid fishes
6. Rosenberger LJ, Westneat MW (1999) Functional morphology of undulatory pectoral fin locomotion in the stingray Taeniura lymma (Chondrichthyes: Dasyatidae). J Exp Biol 202: 3523–3539
7. Low KH, Willy A (2006) Biomimetic motion planning of an undulating robotic fish fin. J Vib Control
8. Takagi K (2006) Development of a rajiform swimming robot using ionic polymer artificial muscles. In: Proceedings of the

IEEE/RSJ International Conference on Intelligent Robots and Systems
9. Ikeda M, et al (2014) A pectoral fin analysis for diving rajiform-type fish robots by fluid dynamics. Artificial Life and Robotics, pp 1–6
10. Urai K, et al (2014) Development of a ray-like robot as a next generation bio-inspired autonomous underwater vehicle. In: Aero Aqua Bio-mechanisms (ISABMEC), pp 171–175
11. Yang SB, Qiu J, Han XY (2009) Kinematics modeling and experiments of pectoral oscillation propulsion robotic fish. J Bion Eng 6(2):174–179
12. Galloway KC, et al (2013) Mechanically programmable bend radius for fiber-reinforced soft actuators. In: Advanced Robotics (ICAR), pp 1–6
13. Mosadegh B et al (2014) Pneumatic networks for soft robotics that actuate rapidly. Adv Funct Mater 24(15):2163–2170
14. Pfeifer R et al (2012) The challenges ahead for bio-inspired'soft'robotics. Communications of the ACM 55(11):76–87
15. Ziegler M, et al (2011) Varying body stiffness for aquatic locomotion. Robot Autom ICRA, pp 2705–2712
16. Fiazza C, et al (2010) Biomimetic mechanical design for soft-bodied underwater vehicles. In: IEEE OCEANS 2010, pp. 1–7