Powerful 2D Soft Morphing Actuator Propels Giant Manta Ray Robot

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1. Introduction

Soft actuators provide novel solutions to many challenging applications due to their unique characteristics such as softness, motion modality, miniaturization, self-healing, and variable stiffness. As the most studied topic in the field of soft robotics, soft actuators have been developed using various mechanisms and have evolved with a multiplicity of capabilities. For example, soft fluidic actuators (SFAs) achieve relatively high force and intricate morphing from 1D to 3D structures with entirely soft bodies; Dielectric elastomer actuators, with high energy density, are engineered into miniature soft artificial muscles capable of high-frequency actuation. Shape memory alloys are utilized as low-profile soft actuators for rotary joints with high torques. Their unique features indeed push the boundary of the capabilities of the robots.

However, there are still many challenges to overcome, such as energy efficiency, untether-ability, and entire softness. One of the major research challenges for soft actuators is to simultaneously produce high force (e.g., >100 N) and complex motion (e.g., surface morphing). Recent research has reported interesting morphing capabilities with many different materials and mechanisms, such as gel actuators, electric active polymers, and shape memory alloys. However, they all lack substantial force.

The SRPFs are able to propel the manta ray robot to a decent swimming speed with biomimetic fin motions. As a new member of the soft actuator family, SRPs exhibit strong capabilities through this manta ray robot, and they can potentially become unique tools for many engineers and researchers to tackle challenging applications requiring high force and surface morphing.

Soft actuator is the main technology that drives the development of soft robotics as it defines the capabilities of soft machines. One of the key challenges in soft actuator research is to simultaneously produce complex morphing (e.g., surface morphing) and high force. Therefore, a soft robotic pad (SRP) was developed as a new soft actuator that can potentially tackle this challenge. This article demonstrates the highly flexible customization process of the SRP regarding fabrication, morphing design, and force scaling for a challenging application: a giant manta ray robot with the Mobuliform swimming mode. Soft robotic pectoral fins (SRPFs) are customized using the SRP technology for the robot. Detailed characterization results show that the SRPFs can generate almost 100 N force or 25 Nm torque with a dual curving motion to mimic the manta ray fin kinematics. The SRPFs are able to propel the manta ray robot to a decent swimming speed with biomimetic fin motions. As a new member of the soft actuator family, SRPs exhibit strong capabilities through this manta ray robot, and they can potentially become unique tools for many engineers and researchers to tackle challenging applications requiring high force and surface morphing.
output or scalability. Meanwhile, high forces of soft robots are mostly generated by SFAs.\[19–21] Recently, two new fluidic actuation systems are developed to achieve complex morphing.\[22,23]\n
In the first system, patterned layer constraints are attached to the surfaces of the elastomer layer and then allow the complex 2D to 3D morphing.\[23,24]\n
In the second one, a soft elastomer disc is developed with customized channel patterns to achieve intricate surface morphing.\[23]\n
However, they are also limited in force output as the soft morphing body cannot withstand fluidic pressure higher than 50 kPa.

The main reason for the force limitation is the lack of reinforcement in the soft material to withstand higher fluidic pressures. Unlike the fiber reinforcement in the tubular SFA, which is simple and uniform, the construction of reinforcement in a larger 2D or 3D structure remains a challenge. Therefore, a soft robotic pad (SRP) is developed to tackle this challenge.\[24,25]\n
SRP, shaped into a flat elastomer body, is a 2D soft actuator with a single large chamber inside. A large matrix of fiber reinforcements with optimized patterns is embedded into the top and bottom elastomer layers so that the SRPs, depending on the motion types, can tolerate fluidic pressures up to 400 kPa.\[26]\n
By varying the pattern of the surface constraint layers, the SRPs can achieve different surface morphing with strong force outputs.

However, the potentials of the SRPs are not fully revealed. Therefore, this work aims to demonstrate the strong motion and force performance, customizability, and scalability of the SRP via a challenging application: a life-sized manta ray robot. The manta ray enjoys a reputation for its highly maneuverable and also graceful swimming capabilities. It swims using its largely expanded pectoral fins primarily in an oscillatory (Mobuliform) mode, analogous to the flight of birds.\[27–30]\n
Such oscillating motions shed a series of vortices into the wake, impart momentum and impulse to the fluid environment and eventually propel the body forward.\[31]\n
One key kinematics of the manta ray fins is that their fins form two curves in both the span- and chord-wise directions.\[29,31,32]\n
Such complex fin morphing has not been actively achieved in the existing manta ray robots\[33–45]\n
but can be potentially managed by the SRP. In contrast, the existing manta ray robots are usually small. It is challenging to build a giant manta ray robot with powerful fins at a low profile.

In this article, we demonstrate the customization process and the strong force and motion capabilities of the SRP in the application of a giant manta ray robot. First, a soft robotic pectoral fin (SRPF) is engineered to reproduce the fin morphing exhibited in the manta ray during normal flapping. With the optimization of the fiber matrix pattern, the SRPF is able to withstand high fluidic pressure and generate around 100 N force or 25 Nm torque. With patterned constraint layers, the SRPF is programmed to bend in both span- and chord-wise directions. After the fin characterization, a giant manta ray robotic swimmer is then constructed with 1.93 m in span length and 50 kg in weight. The SRPFs are strong enough to flap in water and propel the robot at speeds up to 28.5 cm s\(^{-1}\) (0.41 BL s\(^{-1}\)), which is close to the swimming speed of manta rays at their foraging or relaxed state (\(\approx 33\) cm s\(^{-1}\)).\[36–48]\n
With the SRPF morphing modality, the fin undulations in both span- and chord-wise directions are captured as the bio-mimicry of the manta ray swimming. SRP, capable of surface morphing and exerting strong forces, can be used in many other applications such as underwater robots, wearable devices, morphing artworks, and safety cushioning systems. With the detailed customization process shown in the manta ray robot application, this work can interest, instruct, and inspire more researchers and engineers to tailor their own SRPs for specific applications where complex morphing and high force are required.

2. SRPF

The SRPF design and fabrication are elaborated in this section along with the fiber pattern optimization for reinforcement of the fin.

2.1. Design

The SRPF is comprised of one active fin, one passive fin, and one peripheral appendage as shown in Figure 1. The SRPF design includes the consideration of stiffness distribution, shape generation, and torque output, which are explained as follows.

The stiffness of the fin is tuned by hydraulic actuation, the inherent stiffness of the chosen material, and fin dimension. Oscillatory swimming like manta rays requires sweeping motions of the fins with large amplitudes, which requires the bending of the fin to be concentrated proximally and great stiffening in regions next to the bending section to overcome the drag force from the water.\[29,49]\n
Therefore, hydraulic pressurization is used in the fluid chamber to generate the bending motion in the medial bending region and stiffen almost the entire active fin, which is marked as stiffness region I (Figure 1A). Notably, by virtue of the single through-all chamber, the stiffness in the active fin can be largely consistent, which eliminates the yielding and buckling issues. As the stiffness gradient decreases radially, stiffness region II is the edge area of the active fin in the span-wise direction and the passive fin in the chord-wise direction. Both the active fin and the passive fin are made of silicone rubber (DragonSkin 0010, Smooth-On, Inc.—150 kPa at 100% strain) and cotton fabric (Elastic modulus—around 400 MPa) on the surface (Figure 1B,C), therefore, stiffness region II is still relatively stiff. It is reported that animals often propel themselves through a fluid by employing flexible appendages that generate lift and thrust forces while producing highly 3D wakes.\[31,50,51]\n
Therefore, the peripheral appendage is added onto the fin as stiffness region III, which is made of a softer silicone (EcoFlex 0030, Smooth-On, Inc.—70 kPa at 100% strain) and the same cotton fabric on the surface (Figure 1C).

The shape generation and torque output are realized through active fin design. The active fin is a combination of two symmetrical fin SPRs, which are comprised of a silicone body with a flat chamber, vertical fiber arrays for thickness constraint, pattern fabric, and non-pattern fabric on the top and bottom surface, respectively, for morphing programming (Figure 1B).\[52]\n
To generate the two curves in span- and chord-wise directions, a simple and effective pattern is formulated on the surface fabric for the fin bending motion: a striped right trapezoid. The fabric stripes allow span-wise extension and prevent chord-wise elongation of the top surface, resulting in a span-wise bending during pressurization. Meanwhile, the trapezoid shape allows more bending in the leading edge than the rear edge of the active fin, and the difference in the amount of bending forms a chord-wise curve.
The bending shape of the active fin is verified in Section 3.3. To generate large torque, a huge cross-section area of the fluid chamber is usually needed. For the fin SRPs, the required large chamber cross-section area is distributed into a long thin rectangle so that the total thickness of the fin can be maintained in a low profile. In our design with a maximum chamber cross-section area of $24 \times 230$ mm$^2$, the fin can generate around $11$ Nm at $100$ kPa which is enough for the SRPF of this size to flap at a frequency of $0.5$ Hz with $120^\circ$ angular amplitude according to the initial simulation.

### 2.2. Fabrication

The entire SRPF is assembled from one active fin, one passive fin, and one peripheral appendage, which are fabricated separately. Figure 2 illustrates the main steps of the active fin fabrication. Assembled from carbon-fiber (CF) rods and 3D-printed rod holders, 100 winding frames of varying lengths and heights are prepared to form the tapering polygon body of the active fin. The winding process is accomplished by a customized winding machine with a winding width and pitch of $2.5$ and $2$ mm, respectively (Figure 2A). With the mold assembled from laser-cut acrylic sheets, the patterned fabric is attached to the mold (Figure 2B), which is then filled with freshly mixed silicone (Figure 2C). Then the winding frames are quickly and carefully placed into the mold (Figure 2D). After one curing session, a symmetrical mold is prepared with non-patterned fabric and fresh silicone in place (Figure 2E). The partially formed fin SRP demolded from the first mold is then flipped and pressed into the second mold (Figure 2F). After another curing session, the partially formed fin SRP is demolded followed by the removal of rod holders and CF rods, leaving no hard material in the fin SRP (Figure 2G).

The channels left by the CF rod removal are filled with fresh silicone using a customized syringe pump (Figure 2H). The aforementioned steps are repeated to make the symmetrical fin SRP, and then the two fin SRPs to be bonded together (Figure 2I). The last three steps are the sealing of the three open edges using fresh silicone (Figure 2J–L). They are processed in a metal frame with acrylic panels preventing the fin SRP from collapsing. Eight tubes are attached in their predetermined positions before the last edge sealing. After demolding, the active fin is complete with some minor trimming. The SRP fabrication at this scale requires meticulous design and operation in the processes. Meanwhile, the production of the active fin exhibits the flexibility and scalability of the SRP fabrication, which will facilitate future SRP applications. Also, for the detailed fabrication process of the active fin along with the passive fin and the peripheral appendage, please refer to Supporting Information Section II and Figure S1–S3, Supporting Information.

With all fin parts ready, the entire robotic fin is then assembled together (Figure S4 and S5, Supporting Information). After
assembly, each fin weighs 9 kg when empty and 12 kg when filled with water. The aspect ratio, given by \( b^2/S \), where \( b \) is the fin span length and \( S \) is the fin area, is 2.66, which meets the standard for Mobuliform rays (\( >2.6 \)).[48]

2.3. Fiber Pattern Optimization

The development of the SRP came with one major issue—premature failure, meaning that the SRPs sometimes break down at low pressures in different fashions.[24] The failures are closely correlated to the fiber pattern parameters: the winding width and pitch. Therefore, an optimization method was proposed, which effectively improved the strength of the SRPs.[26] Depending on the dimension and needed deformation of the SRP, the optimized fiber winding width and pitch are different and the resultant maximum applicable pressures vary. For the case of the active fin, the bending region of the fin SRP is built into an irregular shape, but it can be simplified into a rectangular flat pad for optimization. Detailed dimensions along with other parameters are given in Supporting Information Section II and Table S1, Supporting Information. To better understand the geometry and the optimization, please refer to the detailed optimization.[26] The optimization outputs three winding width and pitch pairs (2-1.6, 2.5-2, and 3-2.4, unit—mm) with similar maximum applicable pressures at 437 kPa. The pair of 2.5-2 is chosen for the fabrication.

3. The Characterization of SRPF

To understand the mechanical performance of the fin, detailed characterizations are conducted including the measurement of block force and torque, the frequency–amplitude relation, and the fin shape reconstruction.

3.1. Block Force and Torque

Figure 3A gives the block force and torque profile of the fin and shows the fin can generate about 25 Nm at most and 23 Nm on average at 200 kPa. The results from the three fins are similar. At 100 kPa, the torque generation is 9 Nm, slightly lower than the estimated 11 Nm, which is because the cross-section area of the fluid chamber at the rotation axis (Figure S6, Supporting Information) is smaller than the \( 24 \times 230 \text{ mm}^2 \) profile at the
medial end. Another observable feature is the nonlinearity in the force and torque curves which is probably caused by the expansion in the chamber cross-section with the pressure increase (Figure S6, Supporting Information).

### 3.2. Bending Amplitude

The amplitude tests are conducted both in air and in water with flapping periods from one to eight seconds as shown in Figure S7, Supporting Information, and the results are given in Figure 3B in the form of angular and tip displacements with shaded areas indicating the standard deviations. Powered by four gear pumps (24V-ZC-760, Lin An Zhongchuang Electronics, Inc. Max pressure—450 kPa; Max flow rate—5.6 L min⁻¹) working at full tilt, the fins require three seconds to achieve a proper displacement in a cycle, meaning that the fins can reach the same amplitude of manta rays at their slow flapping mode (less than 0.5 Hz) for foraging and relaxed cruising. In general, the fins achieve around 57° angular amplitude in water at 4 s period and 85° at 6 s period. Interestingly, the underwater amplitudes are slightly higher than the in-air results in most of the tested periods. This feature shows that the pumps make almost no compromise in flow rate even with the additional resistance from the water. In contrast, unlike the in-air tests in which the inner flow system is filled with water without any air, some air is inevitably trapped in the fin chambers, tubes, and pumps when setting up the in-air tests. The compressibility of the air slows down the fin response upon pressurization. Another noticeable feature is that the in-air amplitude at 2 s period is higher than 3 s period, which is probably because the natural resonance frequency of the fin is close to 0.5 Hz. Overall, the SRPFs driven by four pumps are able to sweep in water and also deliver momentum to the water (Video S1, Supporting Information).

### 3.3. Bending Modality

The characterization of the bending modality for the fin is implemented using a motion tracking system (Vicon Motion System) to track the coordinates of the markers attached to different positions of the fin during actuation (Figure S8, Supporting Information). The needed information is then extracted and calculated from the coordinate data. The goal of the bending characterization is to verify that the fin can generate two curves in both the span- and chord-wise directions. We extract the coordinates of the points that are attached along the two directions and fit them into two curves. The measured bending angles of the two curves at different pressures are given in Figure 3C. The span-wise bending, representing the fin flapping, is the primary bending with 60° at 100 kPa and 95° at 150 kPa. The chord-wise bending is around one-quarter of the span-wise bending at 150 kPa. Analytical modeling is established in Supporting Information Section IV with the illustration of Figure S10, Supporting Information, which gives predictions in both the primary and secondary bending angles with adequate accuracy. Aside from the bending of the two curves, the fin shapes are also reconstructed using the coordinates of the
markers and are visualized in Figure 3D and Video S2, Supporting Information. Especially from the top views, a clear out-of-plane bending can be seen, which verifies the existence of the chord-wise curve. Moreover, the comparison between the reconstructed fin with the actual fin in both views and at the same pressure points in Figure S9, Supporting Information, demonstrates that the actual shapes are accurately sculpted by shape reconstruction.

The performance of the fin, in general, is adequate in terms of force and torque output and shape generation. Although the flapping speed is not at the most desirable rate used by manta rays in their fast swimming mode, the SRPF still has the potential to generate thrust to propel the robot.

4. Manta Ray Robot

In this section, the design of the manta ray robot is elaborated followed by the swimming tests.

4.1. Robot Design

The rhomboidal robot design is based on the profile of a real manta ray from the top view as shown in Figure 4A, and the final prototype is given in Figure 4B, in which a CNC machined diamond-shaped polyethylene body frame serves as the natural girdle in the manta ray skeleton (44, 45) with all the electronics installed inside and the two fins emanating from two sides. The waterproof seal is achieved by the body frame sandwiched in between two acrylic sheets (8 mm) of the same profile with custom-made seal rings tightened by screws (Figure S11A, Supporting Information). As for fin actuation, eight gear pumps are utilized to actuate two fins (four each). The fins and gear pumps are connected via eight bulkhead fittings installed through the body frame (Figure S11B–D, Supporting Information), and, for each bulkhead fitting, two seal rings are attached and tightened inside and outside the body frame to ensure water-tightness. In addition, the fins are fixed in the sheet-metal sleeve at the proximal side and bolted onto the frame wall. In this way, the fins can be securely fused to the body with maximum flapping performance. For detailed robot assembly and component specifications, please refer to Supporting Information Section V. Statistically, the robot weighs 48.6 kg after full assembly, and has a 1.93 m span and a 0.85 m body length (body aspect ratio—2.27). Since the head is only for aesthetic purposes, the effective body length is 0.7 m from the front side of the body frame to the rear tip of the fin.

Figure 4. Design of manta ray robot and the final prototype. A) Top view of the robot design as compared to a real manta ray. B) The final prototype and its constitution.
4.2. Robot Swimming Performance

With full assembly (Figure S11, Supporting Information), the robot is placed in water for swimming tests and the SRPFs successfully propel the robot with decent performance. The underwater experiments include swimming speed tests and thrust tests at 2, 3, and 4 s flapping periods. The maximum speed achieved is 28.5 cm s\(^{-1}\) at 4 s period, corresponding to 0.41 BL s\(^{-1}\), which is comparable to the speed of manta rays during foraging (≈33 cm s\(^{-1}\)).\(^{[30,46–48]}\) 3 and 2 s periods yield relatively slow speeds at 14.93 cm s\(^{-1}\) (0.213 BL s\(^{-1}\)) and 9.21 cm s\(^{-1}\) (0.132 BL s\(^{-1}\)), respectively. One critical parameter in describing the efficient propulsion of oscillating fins is the Strouhal number, which is given by \(St = f \cdot A / U\), where \(f\) is the fin flapping frequency, \(A\) is the peak-to-peak trailing edge amplitude of motion at the midspan, and \(U\) is the free-stream velocity or the swimming speed.\(^{[31,52]}\) With the frequencies and measured swimming speeds, the Strouhal number is calculated as 1.12, 0.64, and 0.32 at 2, 3, and 4 s periods, respectively. (Supporting Information Section VI). With the increase in the flapping period, the robot speeds up, indicating improvements in the fin performance which are also confirmed by the Strouhal number approaching and entering the most optimum range (0.2-0.4) where most swimming and flying species cruise.\(^{[52,53]}\) As for thrust production, the robot yields time-averaged 5.02, 7.2, and 9.53 N at 2, 3, and 4 s periods, respectively. The swimming power of the robot can be roughly estimated according to the production of the speed and the thrust, which are 0.463, 1.075, and 2.72 W, respectively. With the powers delivered to water (8.86, 11.52, and 12.95 W) obtained, the propulsive (Froude) efficiencies are then calculated. In 4 s period, the robot achieves a 21% propulsive efficiency which is decent, whereas 2 and 3 s periods yield low numbers at 5.22% and 9.33%, respectively. For all the numbers related to the robot swimming performance, please refer to Table S2, Supporting Information.

Besides the aforementioned statistics of the swimming performance, the robot movements and fin modalities in water are also analyzed in Figure 5. Figure 5A–C each gives five subsets evenly distributed along the cycle with one-quarter cycle interval and the first subsets are located right at the beginning of each cycle. D,E) The front and side view of fin modality using 3 s flapping period. The four subsets are evenly distributed along the cycle with one-quarter cycle interval and the first subsets are located right at the beginning of the cycle. The wave region between the two black dotted lines in the wave diagrams represents the fin wave state.
positions of the robot in their respective cycles of 2, 3, and 4 s flapping periods. The position analysis given in Figure 5A.i, B.i,C.i shows that the second and fourth quarters of the cycle achieve greater distance than the first and third quarters. This is because, in the odd quarters, the power of the pumps is also used for stretching the silicone of the fins, resulting in a slower fin flapping. In the even quarters, the energy stored in the silicone during the odd quarters is released in the following quarter cycles and, combined with the pump power, produces a faster fin motion and more thrust. During the tests, the robot floats in water with 10% of the body above the water level, the gravitational force reduces the fin amplitude above the transverse plane of the robot body. The reduced peak-to-peak amplitude is one of the key factors that restrain the swimming speed. The sequential subsets of Figure 5D give the front view of the fin at the points corresponding to Figure 5B.i–B.iv, and clearly show the propagation of a wave from the proximal side towards the distal tip of the fin in one cycle. In contrast, another wave is propagating simultaneously in the downstream direction as shown in the side views of the fin from the diagrams of Figure 5E which corresponds to Figure 5D. The chord-wise wave is not as pronounced as the span-wise wave, which is mostly because the chord-wise curve created by the active fin is not substantial according to Figure 3C. Continuous motion in Video S3, Supporting Information, displays the undulatory modality of the fins during robot swimming. In general, the fins installed on the robot are able to produce wavy motions in span- and chord-wise directions, which resembles manta rays in their slow swimming mode.

5. Discussion

Building this manta ray robot demands careful engineering in many aspects. Most of the efforts are focused on the SRPF, which is an integration of multiple design considerations including fin SRP optimization, fin stiffness distribution, power, shape generation, and final fabrication scheme. Being able to fabricate and activate the fin motion that meets most of the specific and rigorous requirements exhibits the customizability and scalability of the SRP as the first shape and surface morphing technology that can generate huge force and torque for practical applications. By propelling this manta ray robot of 1.93 m in wingspan and 48 kg in weight, the SRPF demonstrates strong power as an artificial muscle with a unique low profile. The SRPF motion design also results in a close similarity in the fin undulations between the robot and real manta rays.

The strength of the SRP can be used in many other applications that require surface morphing and strong force. The manta ray application demonstrates the detailed customization procedure, which is summarized as follows to facilitate future SPR applications: 1) The first step is to finalize the shape and dimension of the SRP including the length and width. 2) The thickness of the SRP shall be decided by the amount of force and torque needed for the application. 3) The next step is to design the SRP motion and formulate the fabric layer patterns. 4) With the motion design, the maximum deformation of the material in the length and width direction can be calculated as the input along with the SRP dimensions for the fiber pattern optimization. 5) The fabrication can be planned by preparing the fiber winding templates, which can be complicated depending on the shape of the SRP. For irregular shapes, the rod holders and the CF rods are all different. The molds can be produced via either 3D printing or assembly from acrylic sheets. Please refer to Supporting Information Section I.i for other supporting components that may be needed for the fabrication, depending on the size of the SRP. 6) With all the components ready, the final SRP can be produced via the standard fabrication processes.

6. Conclusion

In this article, the customization procedure of the SRP is demonstrated in detail via the manta ray robot application. From the fabrication of the SRPF, it can be seen that the SRP technology is scalable and customizable to incorporate other considerations such as the initial SRP shape, motion modality, and torque output. The SRPF characterization shows that the fin SRP can generate forces and torques up to 100 N or 25 Nm, respectively. Meanwhile, the dual-curve in span- and chord-wise is achieved through the patterned constraining layers, which contributes to the bio-mimicry of the manta ray fin kinematics. With full assembly, the SRPF successfully propels the robot in water with a maximum swimming speed of 28.5 cm s\(^{-1}\) and the fin flapping in water forms undulations in both the span- and chord-wise directions as the bio-mimicry of the manta ray swimming.

Given the strong customizability and scalability of the SRP as a 2D actuator capable of high force and complex morphing, it will find more applications in different fields. Apart from the manta ray, SRPs can be customized to mimic the body motions of other marine species with flat muscles, such as marine flatworms and other batoids. The low profile allows the SRP to be incorporated into wearable devices for motion assistance (e.g., wrist, elbow, neck, or heart sleeve), massage, and impact buffer. SRP can also be made into safety cushions with unique surface shapes to fit into the complicated structures of the task sites. The programmable morphing capability of the SRP can be valued in morphing artworks to showcase unconventional surfaces that are impossible for existing actuators. With the strong capability of the SRP and the detailed customization procedure demonstrated in the manta ray robot application, the SRP can become unique solutions to more applications in which high force and complex morphing are required.

7. Experimental Section

**SRPF Characterization:** Fin characterization is conducted on the combined active fin and passive fin for ease of experimentation. In all tests, the fins were fixed upright on a supporting frame assembled from standard 20 × 20 mm\(^2\) aluminum rods. Testing the fin without the peripheral appendage did not affect the results in the block force and fin shape characteristics. For the amplitude test, the results may be smaller with the peripheral appendage as it will incur more drag from the water, but the difference is estimated to be trivial due to the power of the pump and the incompressibility of the water inside the inner flow system.

In the block force and torque tests, the loadcell (measuring range: 0-500 N) was installed 25 cm away from the rotary axis of the fin as shown in Figure S6, Supporting Information. Signals from the loadcell and the pressure sensor (ISE30A, SMC, Inc.) were acquired simultaneously by a DAQ (USB6003, National Instruments Corp.) at a sampling rate of 100 Hz. Three fin samples were tested three times each.
Shape characterization experiments were conducted in free space. 24 markers were attached to the surface of the fin as illustrated in Figure S8, Supporting Information, and their positions were tracked by six cameras of the Vicon system at a 100 Hz sampling rate. The primary bending angle was measured upon the 7 markers along the leading edge, while the secondary bending was based on the 5 markers 22 cm away from the medial (left) edge in the chord-wise direction. For both the force and shape measurement, the fin was powered by one gear pump at a 50% duty cycle, which resulted in a pressure increase rate at around 10 kPa s^{-1}. The bending angle and fin shape reconstruction were processed in MATLAB.

For the amplitude tests (Figure S7, Supporting Information), the fins were actuated by four pumps at full tilt to generate as much flapping amplitude as possible in all tested frequencies. Video camera (Hero6, GoPro, Inc.) was fixed above the fin to record the motions at a 120 fps frame rate, and the videos were analyzed on a motion analysis software (Tracker, Open Source Physics). Three fins were tested and actuated for 10 flapping cycles at periods from 1 to 4 s. The corresponding results were the averaged measurements from the last three cycles of the three fins at each flapping period. For periods from 5 to 8 s, the fins were actuated for one cycle to protect the fin from over deformation which will lead to damage. From the measurements, there was no difference between the first and the following cycles, therefore, the results from the one-cycle tests are sufficient. In the underwater tests, the upper 1 cm of the leading edge remained above the water level so that the camera could capture the actual fin positions.

Robot Underwater Test: Swimming speeds were obtained from the amount of time used to finish a 5 m distance. Before the start of the time count, the robot was given 2 m to accelerate from still. Three flapping periods, 2, 3, and 4 s, were used and tested three times each. Due to the asymmetric flapping range, 4 s was chosen as the largest period to avoid the over deformation in the fin SRP on the top side.

Thrust tests were conducted with the rear of the robot attached to a lever setup as shown in Figure S12, Supporting Information. With the same moment arm length at two sides of the fulcrum, the upper side of the lever was in contact with a loadcell (measuring range: 0–200 N) and the lower side is submerged in water and connected to the robot. The robot and the lever are connected by a rubber band as a “force capacitor” to filter out the abrupt force readings. DAQ (USB6003, National Instruments Corp.) is used to acquire the loadcell signal at 100 Hz.

The efficiencies reported in this article are indirect estimations obtained from following the method. First, the characteristics of the eight pumps were measured including the pressure−current and the pressure−voltage relations. In the in-air and in-water fin flapping, the fins were fixed on the same frame used in the fin characterization. Two pressure sensors (ISE30A, SMC, Inc.) were connected to the two fluid chambers of each fin. The absolute difference between the pressure readings (DAQ USB6003, National Instruments Corp.) from the two sensors was used to find the current and voltage based on the pump characteristics measured previously. The powers of the in-air and in-water fin flapping were calculated accordingly. The power that was delivered to the water was estimated by calculating the differences between the power delivered to the pumps when the fin was flapping in air and when it was flapping in water and then the results were multiplied by the motor efficiency which was estimated at 75%. The swimming power was estimated by multiplying the swimming speed by the thrust.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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