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Parametric Study of an Underwater Finned Propulsor Inspired by Bluespotted Ray

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Abstract

The performance of bluespotted rays was emulated in the design of a bioinspired underwater propulsor in the present work. First, the movement of a live bluespotted ray was captured for the swimming mode and useful information to the biomimetic mechanism design. By virtue of the modular and reconfigurable design concept, an undulatory fin propulsion prototype was developed. With a proper experimental set-up, orthogonal experiments were conducted to investigate the effect of various fin design parameters on the propulsion speed, thrust, and power of the fish robot. The controllable fin parameters include frequency, amplitude, wavelength, fin shape, and undulatory mode. The significance of these parameters was also determined by using the variance analysis. The results demonstrate that the designed propulsor, imitating bluespotted rays with large expanded undulatory fins, is able to propel itself by changing various kinematic parameters.

Keywords: biomimetic underwater propulsor, bluespotted ray, undulatory fin, fish robot, parametric study

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1 Introduction

In recent years, engineers, scientists, and designers are increasingly turning towards nature as an important source of inspiration to foster innovation^[1]. Among these, fish provide one of the best inspiration examples for the design of efficient underwater vehicles^[2]. The evolution and natural selection over millions of years showed that fish and other aquatic animals are efficient swimmers. Fish have remarkable manoeuvrability, trajectory following capability and stability, even in currents and surges, leaving little noticeable wake behind^[3,4]. It is hoped that submersible robots that swim like fish might be superior in some applications to submersibles utilizing propellers^[5,6]. Ultimately, the objective of biomimetics underwater robotics is to emulate the performance of fishes for useful applications^[7] by taking advantage of biological inspiration.

On the other hand, the study and research for general aquatic locomotion, ocean exploration, environmental protection, data gathering, military reconnaissance and decoys, video exploration, searching and rescue devices and remote maintenance operations have

been quite active in recent years. However, the high cost of performing such operations with ship-based platforms prevents researchers from probing the oceans extensively^[8]. By applying robotic technologies, one of notable contributions was made by the team in Massachusetts Institute of Technology (MIT) led by Triantafyllou^[6], who developed the ‘Robotuna’. Subsequently, a number of research works addressed the issues of fish propulsion, especially in the context of the challenges of autonomous fish-like vehicles^[9]. Ultimately, the fish-like robots are expected to provide noiseless propulsion, be more manoeuvrable, and high efficiency of energy consumption^[10].

Fish swimming modes can be divided into Body and/or Caudal Fin (BCF) locomotion and Median and/or Paired Fin (MPF) locomotion, based on the body structures or fin segments that contribute mostly in generating propulsion^[11]. About 85% of fish species use BCF undulations for propulsion^[12,13]. The BCF propulsion can further be categorized into five different modes of swimming: anguilliform, sub-carangiform, carangiform, thunniform, and ostraciiform^[14,15]. Among these, the fish presents undulatory motion with a propagating wave

formation through its body^[16]. The rest of the fish families use MPF modes as their routine propulsive means, or for maneuvering and stabilization^[12].

The emulation of the MPF locomotion seems to be more attractive for both unmanned and manned vessels. The main body of the MPF locomotion mode is isolated from fin vibrations, which can be used for various practical applications^[17]. The MPF propulsion can be performed in either of the two different modes and the combination: undulatory and oscillatory fin motions. One of the subcategories of this locomotion is ‘rajiform’, which covers stingrays and skates^[15]. Stingrays and skates have large triangular pectoral fins that extend over the entire length of their body. The thrust is produced by large-amplitude undulations of pectoral fins propagating from the anterior part to the fin apex and tapering towards the posterior^[15].

In recent years, several teams have developed the robotics prototype resembling real fish with MPF modes. Fig. 1 illustrates some relevant robotic fishes developed and tested^[2,18–33]. The biomimetic undulating fin mechanisms were developed by using various actuators, such as motors^[5,9,25,34], parallel bellows actuator^[18], SMA^[35,36], and IPMC^[22,37].

Fig. 1 Swimming modes of fishes using MPF propulsion (diagrams of prototypes are taken from Refs. [2,18–33]).

The present paper is organized as follows. Section 2 reviews the biological fish^[38] and presents the design of undulating fin mechanisms for biomimetics propulsion. Section 3 describes the experimental set-up for the parametric study. In section 4, a statistical analysis for the significance effect of various parameters on the propulsion performance of the fish robot is conducted and discussed. The parameters include the frequency, amplitude, wavelength, fin shape, and the undulatory models. Finally, the work is concluded with some remarks.

2 Biological observation and bioinspired mechanisms design

2.1 Biological fish

The understanding of morphology and locomotion modes of the bluespotted ray (*Taeniura lymma*) is useful for the fin mechanism design in the present work. The bluespotted ray (*Taeniura lymma*) is one of the species of stingray in the family *Dasyatidae* (Fig. 2)^[39–42].

Fig. 2 *Taeniura lymma*^[43].

Fig. 3 shows a gross dissection of the musculature and an X-ray of *Taeniura lymma* to illustrate the structure of the different layers of muscle and skeleton in the pectoral fins^[38]. In *Taeniura lymma*, the fin radials extend out from the basal radials to the fin margin and are segmented along their length. The radials are the longest in the middle portion of the fin and become progressively shorter moving anteriorly and posteriorly (Fig. 3a). The dissection of the pectoral fin musculature of *Taeniura lymma* reveals the working principle of muscle. In general, the dorsal (abductor) muscle is used to elevate the fin and the ventral (adductor) muscle is used to depress the fin. As shown in Fig. 3c, they are composed of superficial and deep layers. Each of them is surrounded by sheaths. The superficial layer mainly consists of red muscle, which is contributed to the periodic motion of pectoral fins. The deep layer mainly consists

of white muscle, which was often used for the transient motion^[44]. By alternately lengthening or shortening dorsal muscle and ventral muscle, *Taeniura lymma* is able to move the fin ray upward/downward, thus produces a traveling wave.

As mentioned, for rajiform modes (for example, stingrays), the swimming is by undulations of their large elongated and highly flexible pectorals. The stingray swims forward by producing a traveling wave along the fin, from front to back. This is to generate thrust while keeping its laterally compressed body mostly rigid. It can move backward with similar agility by reversing the direction of waveform propagation on its finned propulsor.

Fig. 3 Dissection of the musculature and an X-ray of *Taeniura lymma*. (a) Dorsal view of a cleared and stained skeleton of *Potamotrygon motoro*, a species closely related to *Taeniura lymma*. MT, metapterygium; PR, propterygium; R, radials; V, vertebrae; (b) dorsal view dissection of pectoral abductor muscles in *Taeniura lymma*; (c) schematic drawing of a pectoral fin cross section (at arrow) showing superficial and deep muscles, fin radials and the basal radial. (photos extracted and modified from Ref. [38]).

2.2 System design

The above-mentioned morphology, locomotion and physiology observations of bluespotted rays were applied to the present work in terms of the movement patterns of bioinspired finned mechanisms. For simplicity, several assumptions are made: firstly, the thickness of pectoral fins is neglected; secondly, the pectoral

fin locomotion is described in sinusoidal waveform; finally, the baseline of fin ray is simplified to a straight line. The spatial form of the swimming performance can be achieved by changing the length of fin ray.

The designed robotics bluespotted ray comprises three modules: pectoral fin module, electronics housing module, and center-of-gravity adjustment module. Fig. 4 shows the part drawings of bluespotted ray. The fin ray components include axle sleeve, axle, steering-gear base, steering-gear, and steering-gear support (Fig. 4b). The housing is used to install battery, control electronics and center-of-gravity adjustment module (Figs. 4c and 4d). The micro-controller based (Altera Max II, CPLD) built-in system controls the fin motions. Backed up with optical sensors are used for environment exploration. This stand-alone system is the first step to achieve a full autonomy of the robotics prototype.

Table 1 lists the design parameters of the robotics bluespotted ray. The biomimetics propulsor has a similar movement pattern as that with bluespotted ray, including the adjustable range of propulsion frequency, amplitude, wavelength, etc. This is to ensure the similarity of the basic motion function.

The undulatory fin of the biological rays consists of the rays in changing span and stiffness with a flexible membrane connecting them together. With this in mind, we developed a modular robotic fin that enables us to test different materials for the rays and flexible membrane.

Fig. 4 Detailed drawings of fish robot fin assembly relation. 1 lid; 2 center of gravity adjustment mechanism; 3 oscillating module; 4 baseboard; 5,12 housing; 6 fin ray; 7,15 axle sleeve; 8 axle; 9 steering-gear base; 10 steering-gear support; 11 steering-gear; 13 wire connection plate; 14 sealing gasket; 16 connector; 17,21 support; 18 balance masses; 19 guide stem; 20 trapezoid screw.

Table 1 Parameters of robotics propulsor versus biological ray

Parameter	Robotic propulsor	Bluespotted ray ^[38,45]
Total length, L_b (mm)	710	710
Total width, W_b (mm)	640	640
Total height, H_b (mm)	42	42
Weight of the entire robot, W_g (kg)	4.7	—
Number of fin rays, N	8	>200
Fin ray length, L_r (mm)	No. 1=182, No. 2=208, No. 3=213, No. 4=206, No. 5=189, No. 6=167, No. 7=135, No. 8=87.	10–220
Fin ray width, W_r (mm)	10	0.3–1.0
Fin ray height, H_r (mm)	3	0.3–1.0
Fin ray space, ζ (mm)	64.5 (Equal distance)	<2.0 (Non-equidistance)
Fin ray modulus of elasticity, H_r (GPa)	72	0.1–3.4
Fin ray obliquity, θ_r (°)	90	–100–85
Surface width, W_f (mm)	462.5	710
Membrane modulus of elasticity, E_f (MPa)	2.7	0.14
Frequency, f (Hz)	≤ 3	≤ 3
Amplitude, A (°)	≤ 60	≤ 45
Wavelength, λ (mm)	>475	355–890
Actuator	motor	muscle

As illustrated in Fig. 5, each fin ray is directly connected to its corresponding motor. The advantage of this direct-connection mode is that the amplitude, frequency and phase of each fin ray can be independently controlled. Each motor drives a radial insert, which is mounted at an angle 90° from the centreline of fin ray. The motors drive the radial inserts up/down to generate waves that propagate along the circumference of the body. The control electronics provides a Pulse Width Modulated (PWM) signal to control the amplitude and frequency of each motor. The fin is assembled from eight identical actuator modules, each of which has a steering-gear (Model S9402, FUTABA Corp.) A STR-36 series micro-power module is used as the wireless data transceiver in short-ranges. The undulating gait generation for the finned fish robots is similar to the concept suggested by Bai *et al.*^[46].

Compared with the large number of fin rays in the biological undulating fin, the number of fin rays in the mechanical fin is rather limited to avoid the control complexity. The number of fin rays must ensure that the phase difference between two adjacent rays does not

exceed $\pi/2$. According to Shannon's sampling theorem, the number of fin rays N should satisfy the following expression:

$$N > 4 \frac{L}{\lambda} + 1 = 4n + 1, \quad (1)$$

where $L_b = 710$ mm is the total fin length and $\lambda = 475$ mm is the wavelength, as noted in Table 1, and n is the wave numbers in the undulating fin. In the present study, we selected eight fin rays (i.e. a maximum of 1.75 waves.)

Fig. 5 Mechanism of the developed biomimetic pectoral fin module.

3 Experimental setup and parameters

3.1 Experimental setup on undulatory fin

The experimental setup to test a pectoral fin consists of a transparency tempered glass water tank (with a working area dimension of $4.5 \text{ m} \times 2 \text{ m} \times 1.8 \text{ m}$), a high-speed camera system, a precision linear rail, transducers, a base with an indication of grid and reference grid coordinates ($1 \text{ cm} \times 1 \text{ cm}$). The high-speed camera system (Model SpeedCAM), which was lighted by two 1 kW tungsten lamps with the camera hanging over the tank, recorded images at a shutter speed of $1/250 \text{ s}$ with maximum resolution ratio of $512 \text{ pixels} \times 512 \text{ pixels}$. Video recordings were played back for digitization. Data were taken when the robotic fin was swimming in the middle of the tank to minimize wall effects^[47]. The schematic layout of the experimental apparatus and methods is shown in Fig. 6.

To measure the thrust force, the fin mechanism was mounted on the precision linear rail and attached to a force transducer (Fig. 6). All tests on the robotic fin shown in Fig. 6 were conducted in still water.

Fig. 6 Experimental apparatus and methods (a) schematic diagram; (b) tank; (c) transducer; (d) precision linear rail.

3.2 Multiway analysis of variance (M-ANOVA)

A statistical method, ANOVA, is applied to find the significance of controllable parameters of the fin propulsion^[48]. Five fin parameters (or factors) are the variables considered in the experiments: undulatory frequency of fin (f), amplitude (A), wavelength (λ), fin shape (S), and undulatory pattern (P). A set of experiments was conducted to evaluate the effect of these parameters on the force, velocity, power consumption and efficiency of the ray-like underwater fin propulsor.

The levels of the five parameters selected are given in Table 2. The levels depend on the prototype capability, transducer limitation and the range of practical application. There would be a total of 1024 runs of experiment, if we consider all ranges of controllable parameters and levels in Table 2. To provide the necessary data for a meaningful analysis to achieve the experimental objectives while keeping the number of runs manageable, we adopt Taguchi's orthogonal scheme^[48]. An orthogonal array selector can assist in determining how many trials are necessary and the factor levels for each parameter in each trial as well^[49]. Accordingly, the head of orthogonal scheme form is listed in Table 3. The interactions between fin shape and undulatory patterns are considered here (see Ref. [49] for a detailed discussion on the interactions among kinematic parameters). In our experiment, a $L_{32}(4^9)$ orthogonal array is selected with a

total of 32 experiments conducted. The four fin shapes are depicted in Table 4.

The significance levels of individual variation were tested by using the multiway analysis of variance (M-ANOVA), which is an important method in exploratory and confirmatory data analysis. The experimental data were analyzed to determine the significance of controllable parameters.

Table 2 Levels of the input parameters

Factors	Levels			
	1	2	3	4
f	$f_1(1.11)$	$f_2(1.25)$	$f_3(1.43)$	$f_4(1.67)$
A	$A_1(60)$	$A_2(80)$	$A_3(100)$	$A_4(120)$
λ	$\lambda_1(258)$	$\lambda_2(322.5)$	$\lambda_3(387)$	$\lambda_4(451.5)$
S	S_1 (Rectangle)	S_2 (Right triangle)	S_3 (Left triangle)	S_4 (Trapezoid)
P	P_1	P_2	P_3	P_4

Notes: P_1 : constant amplitude envelop; P_2 : amplitude envelop gradually decrease from anterior to posterior; P_3 : amplitude envelop gradually increase from anterior to apex and decrease to posterior; P_4 : amplitude envelop gradually increase from anterior to posterior.

Table 3 Head of orthogonal scheme form design

Head of form	S	P	$S \times P$	f			A		λ
Row number	1	2	3	4	5	6	7	8	9

Table 4 Four morphologies of fins

Fin shape
Name	Rectangle (S_1)	Right triangle (S_2)	Left triangle (S_3)	Trapezoid (S_4)

4 Experimental results

4.1 Velocity

The propulsion velocity of robotic fin can be evaluated by dividing the locomotion distance Δs over a time interval Δt :

$$v = k \frac{\Delta s}{\Delta t}, \quad (2)$$

where k is the scale factor. In our experiment, the fin propulsion velocity ranges from $0.035 \text{ m} \cdot \text{s}^{-1}$ to $0.457 \text{ m} \cdot \text{s}^{-1}$, the highest velocity appears at the 13 th experiment condition (namely, frequency = 1.67 Hz , amplitude = 120 mm , wavelength = 258 mm , trapezoid fin shape, and a constant amplitude envelop undulatory pattern).

Fig. 7a shows the influence levels of the input parameters on an average propulsion velocity. It is noted from Fig. 7a that the propulsion velocity increases with

the increase in undulatory frequency and amplitude. However, the propulsion velocity decreases with a further increase in frequency after 1.43 Hz (a turning-point of frequency), the phenomenon of which was observed in other electromechanical robotic fish^[1,50]. Furthermore, the propulsion velocity also increases with the increase in wavelength, which is in the same trend with the ecological observation and simulation results^[36]. The results indicate that the optimal combination of kinematic parameters to produce the maximum propulsion velocity in the present test is $f_3(1.43)A_4(120)\lambda_4(451.5)$.

The data collected from the 32 test runs were used as the data input to the statistical tools (Statistical Package for the Social Sciences, SPSS).

Fig. 7 Influence of levels of the input parameters on (a) average propulsion velocity; (b) average propulsion force; (c) average propulsion power consumption; (d) average propulsion efficiency.

As shown in Table 5, the influence of the factors on the propulsion velocity can be ranked as: fin shape (S) > amplitude (A) > frequency (f) > wavelength (λ) > undulatory pattern (P) > interactions between fin shape and undulatory pattern ($S \times P$).

Table 5 Analysis of variance of propulsion velocity (Dependent variable: velocity)

Source	Type III Sum of Squares	Degree of freedom (df)	Mean Square	F	sig.
Corrected model	0.306 ^a	18	0.017	4.596	
Intercept	1.529	1	1.529	413.302	
S	0.235	3	0.078	21.196	***
P	0.012	3	0.004	1.038	*
$S \times P$	0.008	3	0.003	0.686	
f	0.019	3	0.006	1.744	*
A	0.019	3	0.006	1.745	*
λ	0.013	3	0.004	1.170	*
Error (null)	0.006	13	0.002		
Total	1.895	32			
Corrected total	0.354	31			

a: R Squared = 0.864 (Adjusted R Squared = 0.676).

***: sig. < 0.01; **: sig. < 0.05; *: sig. < 0.1.

sig.: significant probability of F distribution.

4.2 Force

The propulsion force of robotic fin is measured by a force transducer (Fig. 6). In our experiment, the robotic fin propulsion force ranges from 0.74 N to 9.20 N, in which the maximum force appears at the 4 th experiment condition (frequency = 1.67 Hz, amplitude = 120 mm, wavelength = 451.5 mm, rectangle fin shape, and amplitude envelop gradually increase from anterior to posterior). On the other hand, the minimum force appears at the 22 th experiment condition (frequency = 1.11 Hz, amplitude = 80 mm, wavelength = 258 mm, right triangle fin shape, and amplitude envelop gradually decrease from anterior to posterior). The results indicate that the optimal combination of kinematic parameters to produce the maximum propulsion force is $f_4(1.67)A_4(120)\lambda_3(387)$.

As shown in Fig. 7b, the output thrust increases as the frequency and the amplitude increase. On the other hand, the thrust increases with the increases of undulatory wavelength to a peak.

The result of the analysis of variance on propulsion force is listed in Table 6. The result shows that the kinematic parameters as well as fin shape have a certain effect on the propulsion force, whereas the interactions between fin shape and undulatory pattern or the undulatory pattern are found to have no significant effect on the propulsion force. According to their influence upon the propulsion force, the factors can be ranked as:

amplitude (A) > frequency (f) > wavelength (λ) > fin shape (S) > undulatory pattern (P) > interactions between fin shape and undulatory pattern ($S \times P$).

Table 6 Analysis of variance of propulsion force (Dependent variable: force)

Source	Type III Sum of Squares	Degree of freedom (df)	Mean Square	F	Sig.
Corrected model	0.734 ^a	18	0.041	1.530	
Intercept	4.514	1	4.514	169.271	
S	0.128	3	0.043	1.604	*
P	0.059	3	0.020	0.741	
$S \times P$	0.010	3	0.003	0.128	
f	0.186	3	0.062	2.325	*
A	0.195	3	0.065	2.439	*
λ	0.155	3	0.052	1.941	*
Error (null)	0.147	13	0.017		
Total	5.395	32			
Corrected total	1.081	31			

a: R Squared = 0.679 (Adjusted R Squared = 0.235).

***: $sig.$ < 0.01; **: $sig.$ < 0.05; *: $sig.$ < 0.1.

4.3 Power consumption

The power needed for the fish swimming mainly consists of three parts: firstly, the storage mechanical energy of inertia, gravity, and elastic deformation of organizations; secondly, the lost mechanical energy of elastic deformation of organizations and joints friction; thirdly, the work fishes done to their surrounding fluid^[51]. The propulsion power of robot fin is calculated by multiplying electric current by voltage as

$$P = UI. \quad (3)$$

In the experiment, the consumed power ranges from 4.395 W to 7.599 W. The minimum consumed power takes place at the 14 th experiment condition (viz. frequency = 1.43 Hz, amplitude = 100 mm, wavelength = 322.5 mm, trapezoid fin shape, and amplitude envelop gradually decrease from anterior to posterior). On the other hand, the maximum consumed power appears at the 24 th experiment condition (viz. frequency = 1.43 Hz, amplitude = 120 mm, wavelength = 387 mm, right triangle fin shape, and amplitude envelop gradually increase from anterior to posterior). The results indicate

that the optimal combination of kinematic parameters to consume the minimal power is $f_3(1.43)A_4(120)\lambda_1(258)$.

It can be seen from Fig. 7c that the averaged propulsion power increases with the increase of undulatory wavelength before it reaches the peak. The result of the analysis of variance on consumed power is listed in Table 7. It shows that the wavelength has a significant effect on the power consumption ($sig.$ < 0.01), the undulatory pattern are found to have a certain effect on it ($sig.$ < 0.1), whereas others have no significant effect on its power consumption ($sig.$ > 0.1). According to their influence upon the average propulsion power, the factors can be ranked as: wavelength (λ) > undulatory pattern (P) > amplitude (A) > fin shape (S) > interactions between fin shape and undulatory pattern ($S \times P$) > frequency (f).

Table 7 Analysis of variance of consumed powers (Dependent variable: power)

Source	Type III Sum of Squares	Degree of freedom(df)	Mean Square	F	Sig.
Corrected model	23.226 ^a	18	1.290	3.136	
Intercept	1164.726	1	1164.7	2830.	
S	1.832	3	0.611	1.484	
P	6.364	3	2.121	5.155	*
$S \times P$	1.197	3	0.399	0.970	
f	0.706	3	0.235	0.572	
A	1.915	3	0.638	1.551	
λ	11.211	3	3.737	9.082	***
Error (null)	5.349	13	0.411		
Total	1193.301	32			
Corrected total	28.575	31			

a: R Squared = 0.813 (Adjusted R Squared = 0.554).

***: $sig.$ < 0.01; **: $sig.$ < 0.05; *: $sig.$ < 0.1.

4.4 Efficiency

The propulsion efficiency of robotic fin can be evaluated by

$$\eta = \frac{P_e}{P_t} \times 100\% = \frac{Tv}{UI} \times 100\%, \quad (4)$$

where η is propulsion efficiency, T is propulsion force, v is propulsion velocity, U is voltage, I is electric current, P_e is effective power, and P_t is the total power.

The propulsion efficiency ranges from 1.26 % to

29.44 %. The 14 th experiment condition shows the highest propulsion efficiency, (viz. frequency = 1.43 Hz, amplitude = 100 mm, wavelength = 322.5 mm, trapezoid fin shape, and amplitude envelop gradually decrease from anterior to posterior). On the other hand, the lowest propulsion efficiency appears at the 22 th experiment condition, (viz. frequency = 1.11 Hz, amplitude = 80 mm, wavelength = 258 mm, right triangle fin shape, and amplitude envelop gradually decrease from anterior to posterior). The results suggest that the optimal combination of kinematic parameters to produce the maximum propulsion efficiency is $f_4(1.67)A_4(120)\lambda_1(258)$.

It is noted from Fig. 7d that the propulsion efficiency increases with the increase in undulatory frequency and amplitude. In addition, the propulsion efficiency decreases with wavelength.

The result of the analysis of variance on propulsion efficiency is listed in Table 8. The result shows that the frequency has a certain effect on the propulsion efficiency ($sig. < 0.1$), while the fin shape ($sig. < 0.01$) and amplitude ($sig. < 0.05$) are found to have significant effect on the propulsion efficiency. However, the wavelength, undulatory patterns, or the interactions between fin shape and undulatory pattern have no significant effect. According to their influence upon the propulsion efficiency, the factors can be ranked as: fin shape (S) > amplitude (A) > frequency (f) > wavelength (λ) > interactions between fin shape and undulatory pattern ($S \times P$) > undulatory pattern (P).

Table 8 Analysis of variance of propulsion efficiency (Dependent variable: efficiency)

Source	Type III Sum of Squares	Degree of freedom (df)	Mean Square	<i>F</i>	<i>Sig.</i>
Corrected model	41.601 ^a	18	2.311	3.040	
Intercept	79.059	1	79.059	103.980	
<i>S</i>	22.475	3	7.492	9.853	***
<i>P</i>	0.295	3	0.098	0.129	
$S \times P$	0.367	3	0.122	0.161	
<i>f</i>	7.379	3	2.460	3.235	*
<i>A</i>	9.952	3	3.317	4.363	**
λ	1.133	3	0.378	0.497	
Error (null)	9.884	13	0.760		
Total	130.544	32			
Corrected total	51.485	31			

a: *R* Squared = 0.808 (Adjusted *R* Squared = 0.542).

***: $sig. < 0.01$; **: $sig. < 0.05$; *: $sig. < 0.1$.

4.5 Summary

The data collected from the 32 test runs was used as the data input to the statistical tools (Statistical Package for the Social Sciences, SPSS). Table 9 summarizes the influence level of the five factors on the robot fin propulsion velocity, propulsion force, propulsion power consumption, and propulsion efficiency.

From the statistical results, we may conclude that the fin shape, amplitude, frequency, wavelength and undulatory pattern have an effect on the propulsion performance of robotic undulatory fin with the exception of the interactions between fin shape and undulatory pattern.

Table 9 Statistical summary of orthogonal test results indicating the influence level of the factors

Target	Influence level of the factors	
	Significant	Non-significant
Propulsion velocity	$S > A > f > \lambda > P$	$S \times P$
Propulsion force	$A > f > \lambda > S$	$P > S \times P$
Propulsion power	$\lambda > P$	$A > S > S \times P > f$
Propulsion efficiency	$S > A > f$	$\lambda > S \times P > P$

5 Concluding remarks

In this paper, the parametric study on a robotic fin was conducted experimentally to determine the effect of various parameters on the propulsion velocity, propulsion force, propulsion power consumption, and propulsion efficiency generated by the undulatory fin.

By virtue of Taguchi's orthogonal scheme, a complete parametric study can be performed by reducing the required experimental runs from 1024 to 32. An ANOVA was used to identify the significance of the five selected parameters. Finally, the effect of these parameters on the propulsion velocity, propulsion force, propulsion power consumption, and propulsion efficiency was investigated experimentally and systematically.

The results from the statistical tests were shown that all the parameters have an effect on the propulsion performance of robotic undulatory fin. In particular, the fin shape is one of the most important factors that affect the propulsion performance. Judging from the experimental results, the fin shape has a significant effect on the propulsion velocity, the efficiency of the robotic fin, and the propulsion force as well. However, the interaction between fin shape and undulatory pattern has no significant effect on the fin propulsion performance. In

conclusion, the kinematic parameters (frequency, amplitude, and wavelength) affect significantly on the propulsion performance of undulatory fin. In the optimization design of bionic undulatory fins, one should first consider the geometry parameters, including fin shape, fin material, fin aspect ratio, fin surface area, and the dip angle of fin ray, *etc.* The next important factors to consider are the gait parameters, for example, frequency, amplitude, wavelength, and motion patterns, *etc.*

The proposed statistical method for experimentation allows for an objective and thorough analysis of the effects of individual or combinations of parameters on the swimming performance. The advantage of using the proposed statistical methodology would become obvious for the cases of fish robots involving more actuators and controllable parameters.

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