

Biorobotic Fins for Investigations of Fish Locomotion

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Abstract—Experimental analyses of propulsion in freely-swimming fishes have led to the development of self-propelling pectoral and caudal fin robotic devices. These biorobotic models have been used in conjunction with biological and numerical studies to investigate the effects of the fin’s kinematic patterns and structural properties on forces and flows. Data from both biorobotic fins will be presented and discussed in terms of the utility of using robotic models for understanding fish locomotor dynamics. Through the use of the robotic fins, it was shown that subtle changes to the kinematics and/or the mechanical properties of fin rays can impact significantly the magnitude, direction, and time course of the 3d forces used in propulsion and maneuvers.

I. INTRODUCTION

BIOROBOTIC models of fish locomotor systems have proven to be useful tools in the evaluation of fish locomotor dynamics and behavior. A well functioning and validated biorobotic model allows for a controlled investigation of behaviors throughout a parameter space that may be difficult to reach with the biological system [1]. It can be very time consuming to instrument a fish sufficiently, and to film the fish at high speed and in high definition at all desired operating conditions, in order to experimentally determine the kinematics, forces, and flows created by their propulsive systems. It can also be difficult to entice a fish to perform behaviors that are outside of its normal operating envelope, and it is sometimes necessary to surgically alter the fish in order to evaluate the functional performance of a portion of the locomotor system. Although a rigorous analysis of the biological systems cannot – and should not – be avoided, experimentation can be simplified when a biorobotic system that models the important kinematic and structural properties of the biological system, and that produces biologically relevant forces and flows, is used in conjunction with biological studies.

For several years, we have used robotic fins to help investigate the function and performance of the median (caudal, dorsal, and anal) and paired (pectoral and pelvic) fins of the bluegill sunfish (*Lepomis macrochirus*). This work has coupled experimental studies of the sunfish’s

kinematics, anatomy, and hydrodynamics [2], [3], [4], numerical simulations of the biological fins with CFD based predictions of propulsive forces and fluid flows [5], [6], and the development of biorobotic systems that model important kinematic and structural elements of the biological fins [7], [8], [9]. Recent analysis of fish fin motions during locomotion shows that fins undergo much greater deformations than previously suspected. This deformation is modulated by the fish by using mechanisms that actively adjust fin surface curvature. Through numerical and biorobotic modeling, it has been shown that this deformation, and the dynamic interaction of the fin’s structure and the fluid, is critical to the effective generation and directional control of 3D forces and moments.

In this paper we will discuss the use of biorobotic caudal and pectoral fins (Fig. 1) to help investigate biological hypothesis regarding the influence that fin flexibility and kinematic patterns have on the production of forces and flows during steady swimming and maneuvers.



Fig.1. Biorobotic pectoral (left) and caudal (right) fins.

II. DESIGN ELEMENTS

The designs of the biorobotic fins evolved, and were improved, as part of a systematic development cycle that involved: 1) the detailed analyses of sunfish kinematics, anatomy, and hydrodynamics; 2) a distillation of the functional behaviors of the fish and its anatomy into rudimentary components that could be more easily replicated using human-engineered technologies; 3) the development of biorobotic models focused on particular aspects of sunfish swimming; 4) the comparison of the performance of the biological and biorobotic models; and finally 5) revisiting the biological model to refine and advance our understanding of fish swimming and fin design, and to expand the

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objectives for subsequent biorobotic fins.

A similar process was used for the design and manufacture of the pectoral and caudal fin robots. The process focused on modeling the mechanical properties and kinematics of the biological fin's fin rays and webbing. The geometry of the biological fin rays were evaluated using micro-tomography, and three point bending tests of excised fin rays were used to determine flexural rigidity along the fin ray's length. These properties were then scaled [10] so that the larger robotic fin, which used fewer fin rays, would exhibit similar bending properties when flapped in the water as the biological fin. Fin rays for the robotic fin were then manufactured using stereo lithography and fused deposition modeling so that the fins had similar structural properties as the biological fins from root to tip and across the chord. The fin rays were covered by a webbing made from a lycra-polyester blend and a thin coating of latex.

The fin's movements were captured by filming fish, swimming in flow tanks, using up to six synchronous, calibrated, high speed, high definition cameras. The movements of the fins were digitized and the 3D coordinates of 10 to 20 points along individual fin rays were tracked [2]. The specific fin rays that best defined (visually) the shape of the fin through time and space were identified, and the motions of these fin rays were then modeled. To do so, it was assumed that the motion of the base of each fin ray, which is very stiff, represented the actuated motion of the fin, and that the motion of the fin ray towards its tip, which is very flexible, was the result of the driven kinematic and a dynamic bending. The pure translation of the fin rays was generally small, and therefore ignored. The rotational movements of the fin ray bases were then fitted with Fourier series via least squares. The number of terms was decided using the Aikake Information Criterion. These models of fin ray trajectories were then implemented using robotic fins with an appropriate number of actuated degrees of freedom.

III. BIORBOTIC FIN MODELS

A. Caudal fin robots

1) Fin and experimentation

Most carangiform and thunniform based swimming robots have been designed without considerable regard for the structural properties of the caudal fin or for the independent kinematics of the fin's individual fin rays. These factors have not been ignored, but the role they play in propulsion has not been considered as widely as, for example, the oscillatory motion of sections of the fish's body. Most typically, the caudal fin of a swimming robot is actuated from its base as a single entity or is allowed to move passively while the tail is actuated laterally. These approaches may be reasonable when modeling the high speed swimming of fish where the caudal fin is relatively stiff, but they are not, in general, a biologically accurate depiction of the structure or use of caudal fins. Caudal fins can be morphologically heterocercal,

as in the thresher shark, and even when morphologically homocercal, as in the bluegill sunfish, the fin may be actuated heterocercally. The function of the caudal fin is not just to produce propulsive thrust, but is to create forces and moments that propel, brake and orient the fish in three dimensions about its center of gravity.

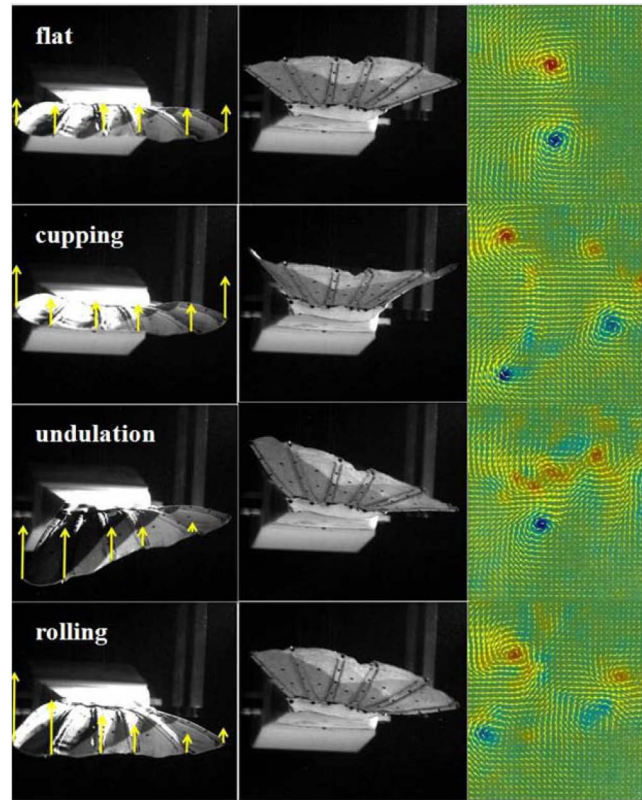


Fig. 2. Motions (left and center) for caudal fin executing the four kinematic patterns. Right panels show particle image velocimetry analyses of the flows produced by the oscillating tail fin. Velocity vectors are colored yellow; blue color indicates clockwise vorticity; red indicates counterclockwise vorticity. Note the asymmetrical wake produced by the undulatory and rolling motions.

A series of biorobotic caudal fins was developed to investigate the influence of fin stiffness and kinematic patterns on propulsive forces and flows. Fins were made that, like the caudal fin of the bluegill sunfish, were morphologically symmetric and had independently actuated fin rays. Three fins were made with fin rays that had flexural rigidities which were scaled along their length, and across the fin, to be 50, 100, and 200 times the flexural rigidities of the biological fin. A fourth fin was made with fin rays that were shaped differently than the rays of the other three fins, but that exhibited a similar resistance to bending as the rays scaled 100 times. For this study, four kinematic patterns were compared (Fig. 2) : 1) a flat motion where all the rays were actuated in phase and through the same amplitude (*flat*); 2) a cupping motion in which the fin rays were actuated in phase, but the angular displacement was larger for rays further away from the midline (*cupping*); 3) an undulation, in which the fin rays were all actuated through the same displacement, but

the phase of the oscillatory motion was delayed from dorsal to ventral (*undulation*); and 4) a rolling motion, in which all the fin rays were actuated in phase, but the displacement was smallest for the most ventral ray, and increased linearly towards the most dorsal ray (*rolling*). The flat and cupping motions are considered homocercal motions, with the cupping motion being the most similar to the pattern used by the sunfish when swimming at speeds greater than 1.5 body lengths per second. The undulation and rolling motions are considered heterocercal because of the asymmetry of the dorsal and ventral lobes about the midline. Fins were tested in flows of 90 mm/s, and were flapped at frequencies of 0.5, 1.0, 1.5, and 1.8 Hz. As described in [ref], thrust and lift forces were measured simultaneously and fin kinematics and PIV were recorded using high definition, high speed video.

2) Results

The kinematic pattern through which the fins rays were actuated had an enormous effect on the magnitude and direction of the forces and flows created by the fins. As expected, the homocercal motions (flat and cupping) produced forces and flows that were directed mainly along the rostral-caudal axis (Fig. 3). The heterocercal motions (undulation and rolling) produced slightly less thrust than the homocercal motions, but also generated a lift component that was often as large in magnitude as the thrust force. These force patterns are consistent with the numerical predictions of [11], and held for all three fins at all flapping frequencies. The magnitude of the forces generally increased with flapping frequency.

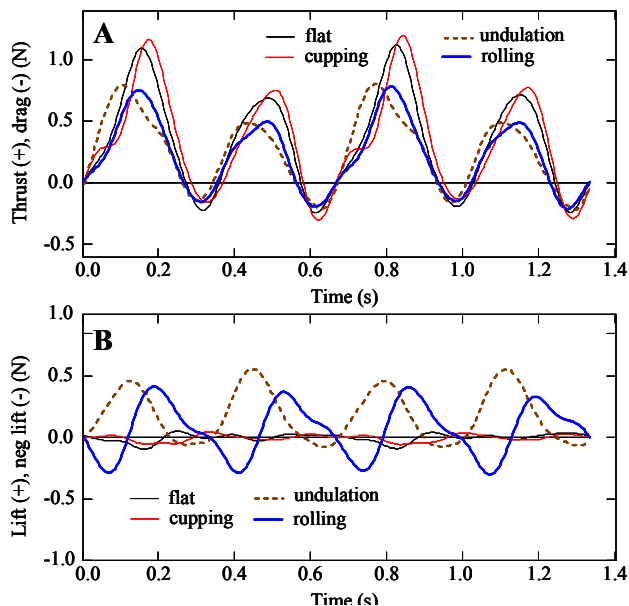


Fig. 3. Thrust (A) and lift (B) forces for caudal fin (50 \times) executing the four kinematic patterns at 1.5 Hz.

In 14 of the 16 test conditions (4 fins \times 4 flapping frequencies), the cupping motion produced greater thrust than the corresponding flat motion. On average, the mean thrust created by the cupping motion was 26% \pm 20%

greater than that created by the flat motion. This seems to have been the result of the cupping fin producing higher velocity vortices, and a smaller, but higher velocity jet as the fin swept through the water (Fig. 2). Vortices developed on the upper and lower edges of the fins during both types of motion, but the vortices were pushed into the flow in a wider path by the flat fin. The cupping motion appeared to contain and direct the vortices toward the midline of the fin's wake. These results suggest that the cupping pattern, which is more similar to the kinematics used by the sunfish [4], is more efficient, as well as more effective, at producing thrust forces. It created greater thrust despite the fact that motion of four of its six rays was reduced when compared to the flat patterns. The cupping motion was created by moving the middle four fin rays through smaller angular displacements, and with lower velocities, than all the rays of the flat kinematic.

The undulation and rolling motions generated similar levels of thrust to each other, but the undulation motion was significantly more effective at producing positive lift forces. The power in the lift (and downward lift) signals produced by the two patterns were often very similar, but the lift forces created by the undulation were biased more towards positive lift. Negative lift was generated only briefly during the undulation as the fin changed its direction of movement at the top and bottom of its stroke (Fig. 3, B). In contrast, the rowing motion produced a significant downward lift during the portions of the fin beat whenever the fin was moving inward toward the midline, which occurs for half the cycle.

Neither the undulation, the rolling, nor the cupping pattern should be considered better at producing force than the others. The usefulness of the kinematic pattern depends specifically on what is required by the fish for the type of swimming or maneuver being conducted. What is clear, however, is that the direction and magnitude of thrust and lift can be controlled through changes in the kinematic pattern. Through relatively simple changes in amplitude and/or phase, the fin forces can be modulated throughout the lift-thrust plane to have significant effect on the moments applied on the fish body by the fin.

The stiffness of the caudal fin affected forces and flows, but the effect was less pronounced than those created by changes in the fin's kinematics. The four fins each produced similar patterns of force for each of the kinematic modes, but in the vast majority of trials the most compliant fin (50 \times) produced greater mean thrust than the stiffer fins. Mean thrust was very small at 0.5 Hz, and thus it was difficult to distinguish between the mean forces from different fins, but at higher flapping frequencies the forces were larger and their differences more easy to distinguish. The most compliant fin (50 \times) produced greater mean thrust than the three stiffer fins in 10 of the 12 test conditions at frequencies of 1.0, 1.5, and 1.8 Hz, and greatest mean lift for the undulation at all frequencies.

B. Pectoral fins

1) Fin and experimentation

At low speeds, sunfish use their pectoral fin as their primary means of propulsion. As described in [3], during steady swimming the fin is very flexible and its fin beat is characterized by a cupping and sweep motion during abduction (Fig. 4), an expansion in area and paddling motion during adduction, and large bending deformations throughout. An important consequence of this complex, dynamics motion is that the fin is able to produce positive thrust throughout the entire fin beat (Fig. 5) [5].

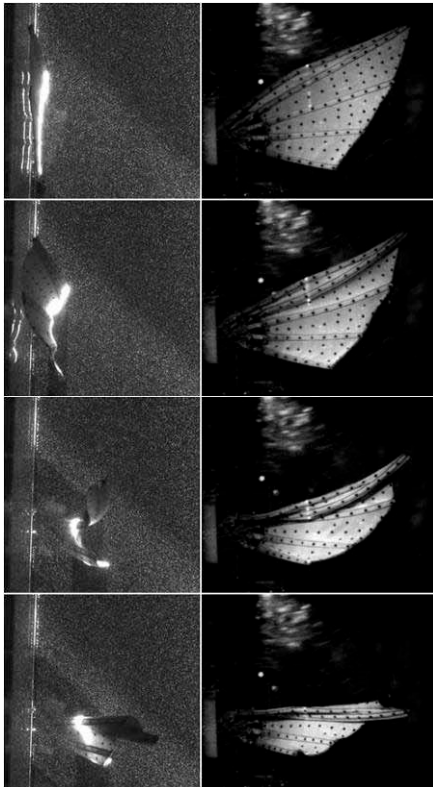


Fig. 4. Biorobotic pectoral fin executing outstroke (adduction) of fin beat. Posterior (left) and lateral (right) views.

In a manner similar to that followed for the caudal fin, a series of robotic pectoral fins was developed which modeled the biological fin's structural properties and the kinematics of its steady swimming fin beat. Experimentation was conducted so that the mechanisms of thrust production during steady swimming could be better understood. As described in [9], robotic pectoral fins were built with fin rays which had flexural rigidities that were scaled to 500, 600, 1000, 2000, and 5000 times those of the biological fin. The fins were tested at flapping frequencies that ranged from 0.5 Hz to above 2.0 Hz, and at flow speeds from 0 mm/s to 360 mm/s. Trials were also conducted during which the robotic fins were made to execute motions that were derived from, but that did not replicate, the sunfish's steady swimming beat. This was done to investigate how different portions of the fin and of the fin beat contributed to force production. These "non-biological" motions included: outstroke and instroke alone; and dorsal and ventral halves moved through

partial strokes (so not to damage fin); cupping with a reduced sweep.

2) Results

a) Steady swimming forces and flows

The ability of the robotic pectoral fins to produce thrust during the fin's outstroke was highly dependent on the stiffness of the fin rays. The magnitudes of the other force components were sensitive to stiffness, but in all trials, lift was produced during the outstroke, and thrust and negative lift were produced during the instroke. When the fin's stiffness was matched well to the operating conditions (flapping frequency and freestream speed), positive thrust was generated throughout the entire fin beat (Fig. 5). The peak magnitude and average thrust during the instroke was always larger than during the outstroke. In the 2D thrust lift plane, the forces would drive the biorobotic fin up and forward during the outstroke, and downward and forward during the instroke.

The robotic pectoral fin only produced thrust during the outstroke when the distal end of the fin was flexible and able to bend and push flow backwards during the outstroke. This occurred with fins that had flexural rigidities scaled between $500\times$ and $1000\times$, and could be visualized clearly in the PIV wake patterns. The stiffer fins ($2000\times$ and $5000\times$) produced similar patterns for lift, but produced drag, not thrust, during the fin's outstroke.

A more thorough presentation of the effects of fin stiffness on propulsive forces is presented in [10].

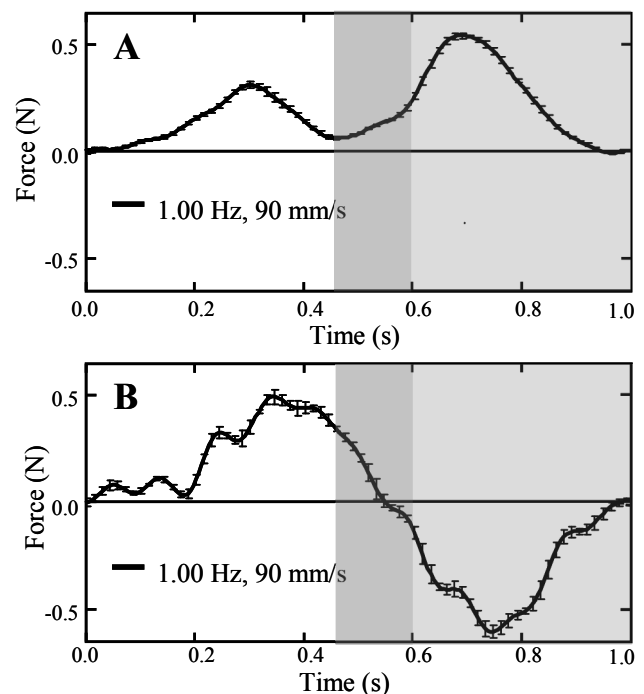


Fig. 5. Thrust (A) and lift (B) forces (with standard errors) for pectoral fin robot ($1000\times$) at 1.0 Hz and 90 mm/s.

Flows around the biorobotic fins were similar to those observed around the biological fin (Figure 5). Vortices

developed on the upper and lower leading edges as the fin pulled away from the acrylic plate. The vortices developed in strength during the outstroke, progressed along the leading edges, and were shed into the flow towards the end of the outstroke. Vortices developed again during the instroke, but on the other surface of the fin. A jet of fluid could be observed to move rearward and downward from the biorobotic fin at the end of the outstroke, as the vortices were shed, in a direction approximately opposite the direction shown for the force during the outstroke.

b) Isolated outstroke and instroke

The forces created by the fin during isolated outstroke and instroke motions (Fig. 6) differed slightly from the forces created during the outstroke and instroke portions of a cyclic (repeated) steady swimming fin beat. Positive thrust and lift were created during the outstroke, like during the cyclic beats, and in all cases the magnitude of these forces was slightly greater than during cyclic swimming. The most obvious difference was the occurrence of a

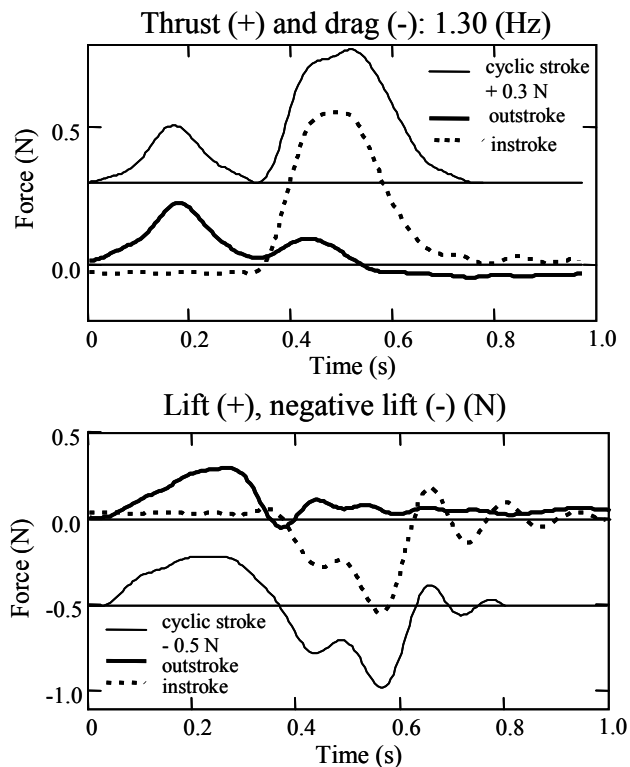


Fig. 6. Thrust (top) and lift (bottom) forces created during isolated outstroke and instroke compared to forces during a cyclic fin beat.

second peak of thrust after the fin had stopped at the end of the outstroke (Fig. 6., top). High definition video of the flow showed that water, which had been accelerated by the fin during the outstroke, washed into the stationary fin and pushed the fin forward. In the representative example shown in Fig. 6, the peak thrust during the isolated outstroke was 0.23 N as compared to 0.20 N during cyclic beats, and because of the greater duration over which thrust was created, the fin imparted an impulse to the water of 50×10^{-3}

N·s as compared to 30×10^{-3} N·s during cyclic beating. Thrust and negative lift were created during the isolated and cyclic instrokes. Magnitudes were again larger for the isolated instroke than for the cyclic instroke (e.g. 0.55 N v. 0.47 N for thrust), but the impulse imparted to the water was more similar than during the outstroke because of the similar duration over which forces were created (105×10^{-3} N·s v. 104×10^{-3} N·s for thrust). The forces measured during the isolated outstroke did not end at zero, and the forces measured during the isolated instroke did not begin at zero, because the fin ends and begins, respectively, extended into the oncoming flow.

c) Isolated dorsal and ventral halves

The forces produced by the dorsal half of the fin were qualitatively similar to the forces produced when the entire fin was flapped (Fig. 7), which is strong evidence for the importance of the dorsal half and its kinematics to force production in steady swimming. Thrust was produced during both the outstroke and the instroke, but in contrast to the full fin, in the majority of trials the impulse and magnitude of the thrust during the outstroke was greater than during the instroke. To prevent the fin rays from fracturing or the

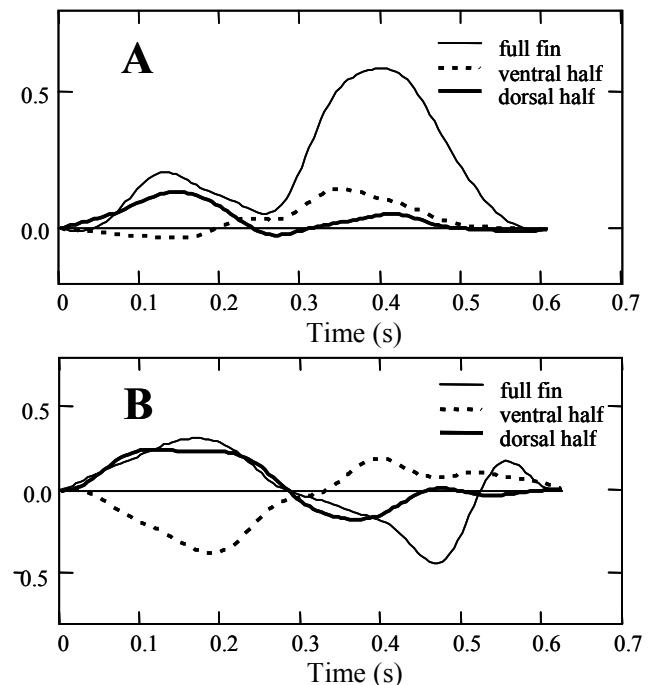


Fig. 7. Thrust (A) and lift (B) forces for isolated movements of the fin's dorsal and ventral halves.

opposing half of the fin from being pulled into the flow, the isolated dorsal and ventral halves were swept through a smaller displacement than the full fin. Despite this, the thrust and the lift created by the dorsal half of the fin during the outstroke were similar in magnitude to those created by the full fin. However, the thrust and lift produced during the instroke were significantly smaller in magnitude. Like the

full fin, the combined thrust and lift forces from the dorsal half would have the tendency to drive the fish upwards and forwards during the outstroke, and downward and forward during the instroke (Figure 10C).

The ventral half of the fin created a small amount of drag and negative lift during the outstroke, and thrust and lift during the instroke. With the exception of the thrust during the instroke, the forces from the ventral half of the fin were in opposition to the forces created by dorsal half of the fin. If operated alone, the ventral half of the fin would have the tendency to move the fish or AUV downwards during the instroke followed by upwards and forward during the instroke.

IV. CONCLUSIONS AND FUTURE WORK

The use of biorobotic fins has enabled us to understand, in more depth, how sections of the fin, its kinematics, and the fin's structural properties affect the production and control of 3D forces and flows. The use of biorobotic models, like the use of numerical models, allowed for experimentation to be conducted with quick, systematic changes to the fin and to the manner in which it was used. The results demonstrate that relatively subtle changes to a fin's kinematic patterns, its mechanical properties, or to its operating conditions can significantly alter the magnitude and direction of the force produced by the propulsor, and therefore to the moment applied to the fish body. The forces produced by the pectoral fin were more sensitive to fin stiffness than for the caudal fin. When the pectoral fin was made too stiff, forces during the fin's outstroke changed from being a usable pulse of thrust, to a drag force. EMG studies (Lauder, unpublished) of the muscles in the pectoral fin girdle suggest that the fish uses a strategy of co-contraction to modulate the stiffness and curvature of the fin rays, and it has been seen that the fish will stiffen the pectoral fin so that it is able to quickly produce a drag force during the fin's outstroke to execute a maneuver [12].

Our future work will include biorobotic modeling of the sensorimotor control of the fins. It is evident that propulsive forces are the result of a dynamic exchange of energy between the fin and the fluid. As these highly deformable fins move through the fluid and bend and unbend, energy is stored and released through the creation of vortices and fluidic jets. This fin-fluid interaction is highly dependent on the mechanical properties of the fin which can be modulated by the fish. We believe that this modulation is the result of closed loop sensing and control of the fin and the hydrodynamic phenomena. A merging of smart biorobotics, behavioral biology, and neurobiology will enable us to investigate this sensorimotor control system.

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