# How fishes swim: flexible fin thrusters as an EAP platform

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## ABSTRACT

Fish are capable of remarkable locomotor performance and use their fins extensively for both propulsion and maneuvering. Recent interest in using fishes as inspiration for the design of a new generation of autonomous underwater vehicles has prompted both new experimental studies of fish locomotor function and efforts to use electroactive polymers (EAP) as actuators in fish-inspired propulsive devices. The fins of fishes allow precise control over body position and vectoring of thrust during propulsion and maneuvering. Recent experimental studies of fish locomotion have revealed that fins exhibit much greater flexibility than previously suspected and that there is considerable deformation of the fin surface during locomotion. The fins of the large group known as ray-finned fishes are supported by fin rays, which have a bilaminar structure that allows active curvature control of the ray and fin surface by the fin musculature. Fish have up to seven different fins, and these fins may interact with each other hydrodynamically during locomotion. Fish fins provide an excellent test platform for the use of electroactive polymer actuators as the frequency of movement is typically less than 5 Hz, and fin muscle strains typically range from 2 to 10%. Recent developments of biorobotic fish pectoral fins actuated with EAP are reviewed.

**Keywords:** Fish, fin, kinematics, hydrodynamics, fin ray, polymer, EAP, actuator.

## INTRODUCTION

There are over 28,000 species of fishes, and a key feature of this remarkable evolutionary diversity is a great variety of propulsive systems used by fishes for maneuvering in the aquatic environment (*1*). Fishes have numerous control surfaces (fins) which act to transfer momentum to the surrounding fluid during locomotion. In addition, fishes are unstable and must use several fin control surfaces simultaneously to maintain body position when hovering, maneuvering, and during propulsion. Fish typically possess up to seven different fins, some paired and some located on the body midline, that are used to generate thrust and to maintain body position during hovering and swimming. Fish thus actively use their fins during virtually every aspect of underwater activity, and these fin movements are achieved through discrete fin musculature that is separate from the main mass of body musculature.

Inspired by the abilities of fishes to hold station and maneuver in the water, engineers have increasingly examined the function of fishes during locomotion as a guide to designing the next generation of autonomous underwater vehicles (*2, 3*). Such efforts have included the use of flapping foil propulsion as a means of using the high-lift characteristics of unsteady oscillating propulsors (*4-6*) and, more recently, the use of electroactive polymer (EAP) actuators such as polypyrrole to power bio-inspired fin and foil control devices (*7-9*).

In this paper I will first provide an overview of the design of fish fins with the aim of providing background for the construction of biorobotic fins, then review the results of recent experimental kinematic, biomechanical, and hydrodynamic studies of fish fin function (*10-13*) with a special focus on possible applications of electroactive polymer (EAP) technology in aquatic robots, and finally consider some of the recent efforts to use EAP actuators in the design of robotic fish fins.

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## THE DESIGN OF FISH FINS

Fish possess both median (midline) and paired fins (Fig. 1), and each of these fins has a set of muscles at their base that allows active control over fin position and motion. Fish fins consist of a thin collagenous membrane that extends between adjacent fin rays (Fig. 2). Bluegill sunfish fin rays and membrane have an elastic modulus of about 1 GPa and 0.3 – 1 MPa respectively (*12*).

Fig. 1. Bluegill sunfish, *Lepomis macrochirus*, hovering in still water. The right pectoral fin is extended, while the paired pelvic fins can be seen below the head. The dorsal fin extends above the body, and the tail (caudal fin) extends toward the back. Portions of the anal fin can be seen below the pectoral but above the right pelvic fin. The fin rays that support the fin membrane can be seen in the pectoral fin.

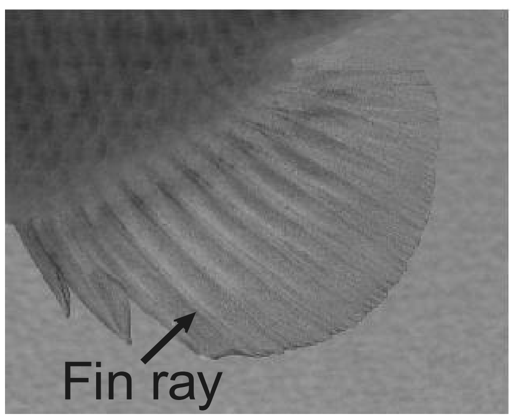


Fig. 2. Anal fin in a bluegill sunfish to show the fin spines at the leading edge of the fin, and the fin rays within the body of the fin. Fish fin rays support the fin and allow active control of fin surface conformation. These fin rays branch approximately half way along their length from the fin root to spread out along the fin margin.

While sharks and ray-finned fishes both have fins with internal fin ray supports, only the fin rays of ray-finned fishes possess the intricate design that allows for active control of fin surface conformation (Fig. 3) (*1, 12, 14*). Each fin ray in ray-finned fishes possesses a bilaminar structure that allows each half-ray (Fig. 3) to slide past the other half when muscles attaching to the fin ray base differentially move the two half rays. Alben et al. (*15*) provide a mechanical analysis of the functional design of fish fin rays. This fin ray design allows fishes to actively deform the surface of the fins, and to resist hydrodynamic loading imposed during locomotion (*14*).

One consequence of this fin design is that it is difficult to separate active from passive contributions to the conformation of fish fins during locomotion.

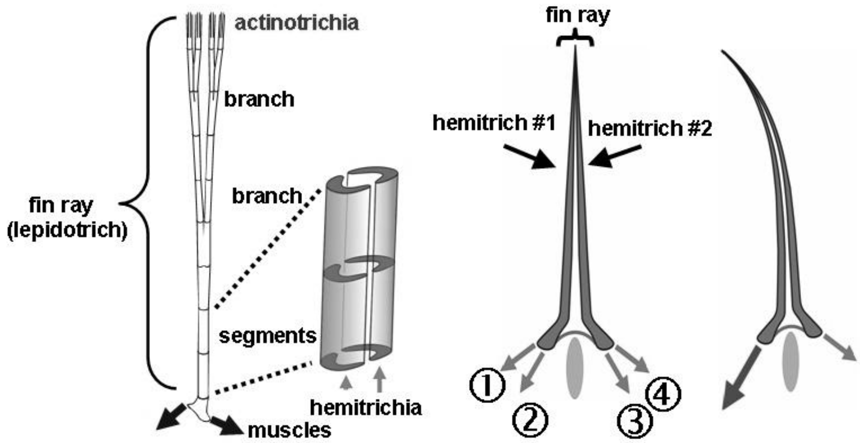


Fig. 3. Schematic of fin ray functional design in ray-finned fishes. Each fin ray (termed a lepidotrich) is segmented and each segment is composed of two halves (termed hemitrichia). Fin rays may branch at several times as shown, but fin rays in some fins are straight and do not branch. Four muscles attach to the base of each hemitrich, and can exert force on each half independently. Displacement of the base of one hemitrich relative to the other produces a curvature of the fin ray shown at right. Actuating multiple rays in this manner curves the entire fin surface.

## FISH FIN KINEMATICS

Recent high-resolution video analyses of fish fin movements during locomotion show that fins undergo much greater deformations than previously suspected (*11, 12, 16*). Figure 4 shows the pectoral fin of a bluegill sunfish during locomotion at a slow steady swimming speed of 0.5 body lengths/sec. At this speed, bluegill use primarily their pectoral fins, and other fins are inactive or only minimally active. Effectively all locomotor thrust is generated by the pectoral fins.

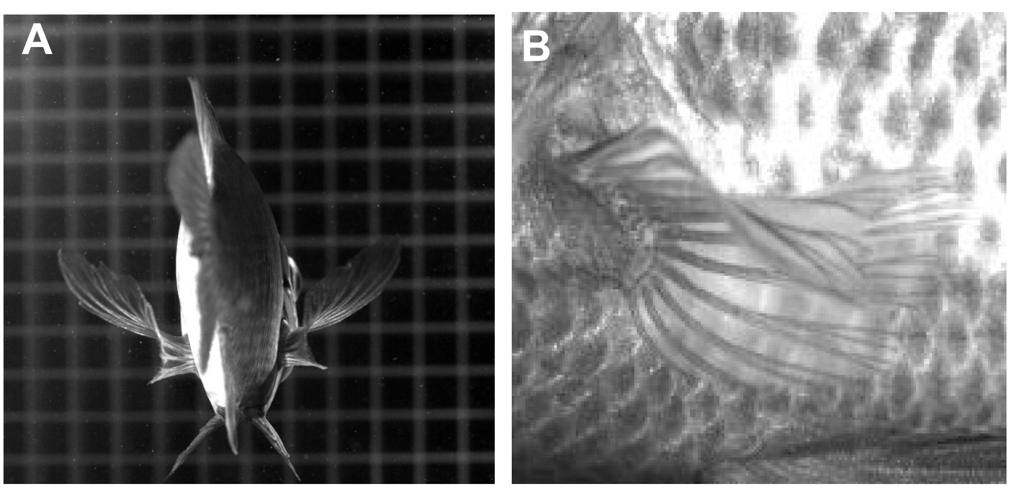


Fig. 4. Pectoral fin locomotion in bluegill sunfish during swimming at 0.5 body lengths/sec in an 18 cm long bluegill. Both panels show frames from high-speed (1024 * 1024 pixel, 250 Hz) digital movies of pectoral fin movement. Panel A shows the shape of the fin during mid-outstroke as viewed from behind the bluegill looking upstream. Note the cupped shape and that the surface of the upper third of the fin faces downstream at this time. Panel B shows a side view of the pectoral fin at the time of transition from outstroke to instroke. A wave of bending passes along the upper third of the fin from root to tip.

As the pectoral fins move out from the body on the outstroke or "downstroke", both the upper and lower edges of the fin move away from the body at the same time. The fin achieves a "cupped" configuration (Fig. 4A) with two leading edges, and the upper third of the fin surface faces downstream. As the fin transitions from the outstroke to return stroke, there is a wave of bending that passes along the fin from root to tip (Fig. 4B). At this time, there is considerable bending in several of the fin rays on the upper third of the fin. During the return stroke of the pectoral fin, the area increases and the fin moves back toward the body. The fin may hold position along the body for a "pause" phase (*17*) before beginning the next fin beat.

During maneuvering, pectoral fin conformation may be substantially different than during propulsion (Fig. 5). The lower edge of the fin leads out from the body (Fig. 5: panel 1), and the fin then undergoes a twisting about the root (Fig. 5: panels 2 and 3) before moving back toward the body (Fig. 5: panel 4). Bending of fin rays and curvature of the fin surface is much greater during maneuvering than during steady propulsion.

Recordings of electrical activity and muscle strain patterns show that during normal rectilinear propulsion, muscle strains vary from 1% to about 6% in the muscles that move the fin away from the body (*11*). The pairs of muscles that can act to bend fin rays (Fig. 3) are occasionally active antagonistically (*11*) and this may reduce peak strain values. However, during maneuvering peak strains can reach 23% reflecting both active contraction and passive stretching imposed on the muscle by fluid forces during maneuvering.

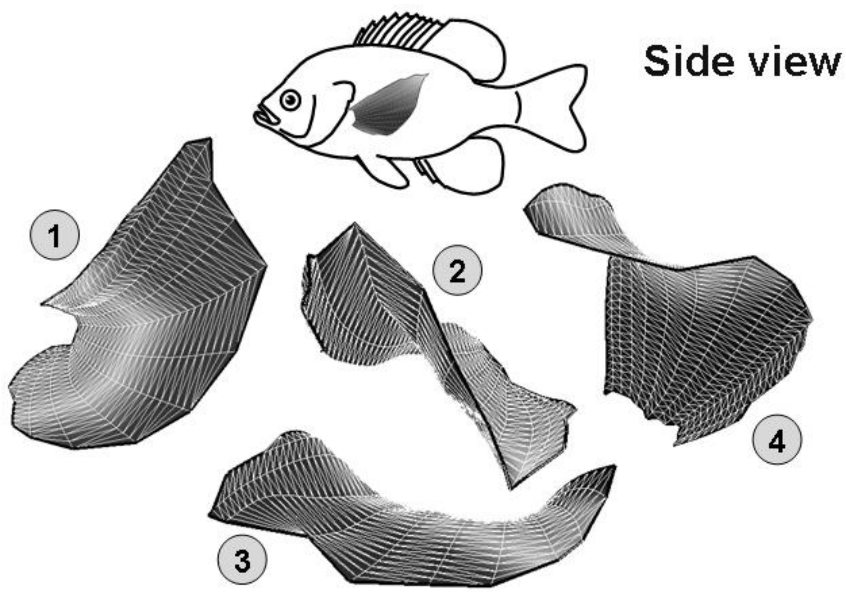


Fig. 5. Pectoral fin shapes at four separate times during a maneuver by bluegill sunfish. Fin conformations during maneuvering are very different than during steady swimming and involve much greater fin surface bending.

## FISH FIN HYDRODYNAMICS

Experimental hydrodynamic analyses of fish fin function have used the technique of digital particle image velocimetry (PIV) to quantify flows around the fins of freely-swimming fishes (*1, 10-12, 18-28*). By swimming fish in recirculating flow tanks seeded with small (10-20 um) reflective particles and illuminating these particles with laser light (Fig. 6) high-speed (200 – 1000 Hz) images of particle motion through the laser light sheet can be used to analyze fin-induced water flow patterns. Cross-correlation analysis of particle images yields matrices of velocity vectors which are then used to estimate the direction and magnitude of forces applied by fins to the water.

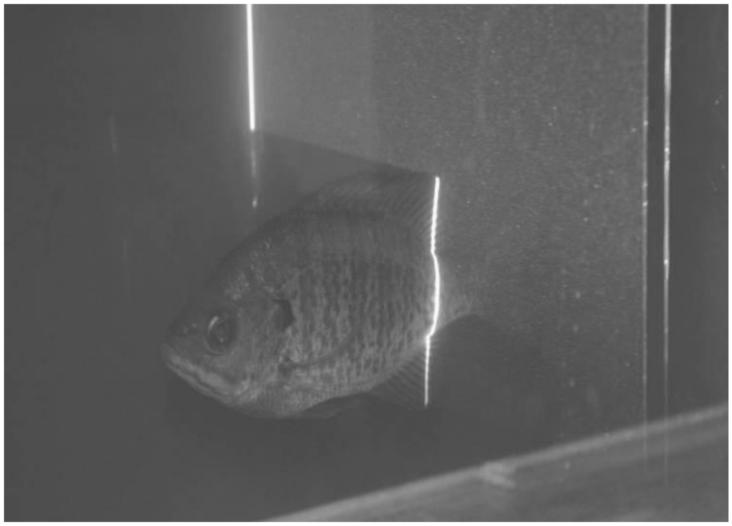

Fig. 6. Bluegill sunfish swimming in a flow tank that has been seeded with small reflective particles. Light from an argon-ion laser has been focused into a light sheet and projected into the tank to intercept the body of the sunfish transversely. The pectoral fin is beating upstream of the light sheet, and free-stream flow in the tank is from left to right. Flow from the pectoral fin travels downstream and through the light sheet, and is imaged with cameras located downstream of the light sheet that are viewing the flow coming toward the camera sensors.

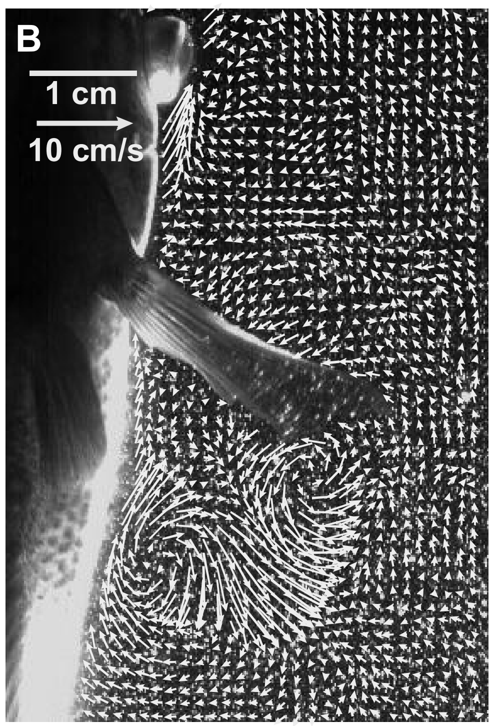


Fig. 7. Pattern of water flow from the pectoral fin of a bluegill sunfish as imaged with particle image velocimetry. Fin wake flows are seen from below the fish, and a distinct vortex has been shed into the wake. The fin is at the end of the outstroke. Free stream flow is from the top toward the bottom of the figure, and has been subtracted from each vector to better visualize the vortical structures shed by the fin.

Fish fins generate discrete vortices as a result of their motion and such vortices are readily visualized using particle image velocimetry (Fig. 7). Experimental analysis of bluegill sunfish pectoral fin flow momentum coupled with computational fluid dynamic analyses demonstrates that sunfish fins generate thrust throughout the fin beat cycle (*11, 13*) with no periods of drag. This contrasts with experimental and computational data from heaving and pitching foils, often studied as propulsive devices, in which there is usually a period of net drag force produced as the foil reversed direction. Sunfish pectoral fins appear to be able to generate thrust throughout the fin beat cycle because of the flexibility of the fin which ensures that at every point during the fin beat some portion of the fin is generating thrust.

## BIOROBOTIC FISH FINS AND EAP APPLICATIONS

The flexibility and surface deformation of fish fins, the considerable data now available on fin function in freely-swimming fishes, and the relatively low frequencies of movement which typically range from 1 to 5 Hz, coupled with the modest strains recorded for steady swimming in fishes, make fish fins an excellent test platform for the use of electroactive polymer actuators. Prior to constructing polymer-actuated fins, Tangorra et al. (*9, 29*) assembled a biorobotic fin with conventional actuators (Fig. 8). This fin uses nylon tendons to actuate fin rays that possess the bilaminar structure similar to fish fin rays, and that allows each fin ray to be curled and altered in shape. The entire fin can be reoriented by altering the position of the base in a manner similar to that observed for fish pectoral fins (*27*). A flexible urethane membrane connects adjacent fin rays and allows for expansion and contraction of the fin surface area. Sufficient degrees of freedom were designed into the system to allow production of a biologically realistic range of motion.

The robotic pectoral fin is mounted above the flow tank for testing on a carriage that is attached to low friction air bearings (Fig. 8). This allows motion in the upstream-downstream direction and the robotic fin can thus self-propel when actuated. Testing of the robotic fin using different movement parameters showed that the fin can replicate the pattern of force production seen in biological fins by generating two thrust peaks with nearly continuous thrust throughout the fin beat. Imposing different movement patterns produced force versus time traces with increased drag at the transition from outstroke to instroke, or primarily drag on the outstroke when a sweep-only motion was used.

Construction of a polymer-actuated pectoral fin by Tangorra et al. (*9*) used a polypyrrole EAP trilayer encapsulated in a polyethylene film (Fig. 9). Previous work has shown that such trilayers, when moved against load cells, can be used to generate forces on the order of several mN (*8*), similar to the force magnitudes produced by fish fins during locomotion (*10, 28, 30*).

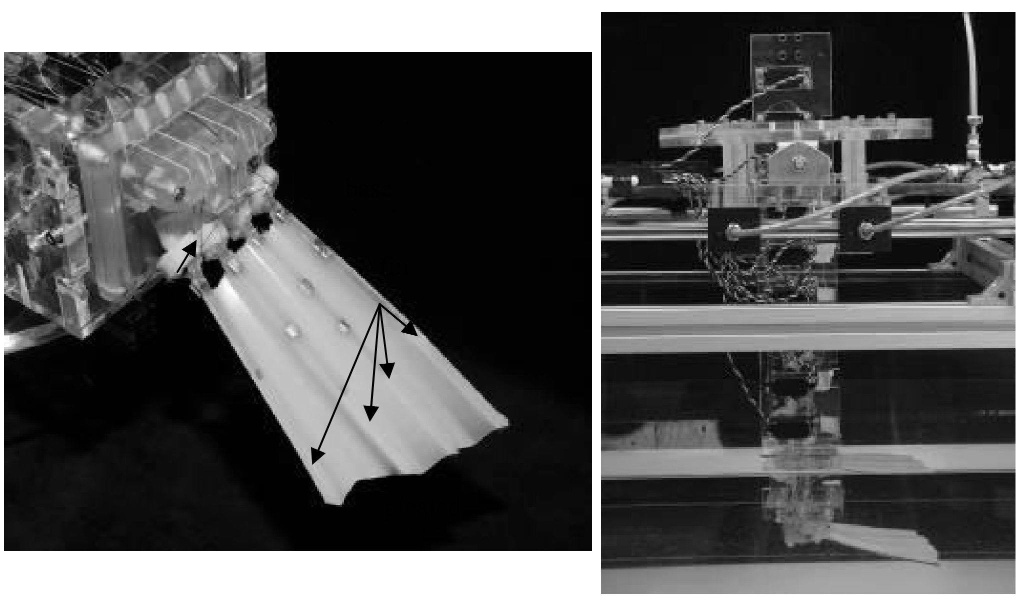

Fig. 8. Biorobotic flexible pectoral fin modeled on the pectoral fin of a bluegill sunfish. The flexible pectoral fin with four fin rays connected by a folded webbing that allows fin expansion and conformation change is shown on the left. The fin is attached to a carriage mounted on air bearings and placed in a testing flow tank as shown on the right. See Tangorra et al. (*9, 29*).

Copper tape running the length of the fin provided electrical contact to the different fin regions (Fig. 9: top panels). This fin was able to produce the fin cupping motion in which the two edges move toward each other, but completion of this motion took nearly 10 seconds (*9*). A second fin design (Fig. 9: bottom panels) used flexible urethane fin rays covered in conductive copper wrapping, and the entire fin was built from polypyrrole trilayer film which was sewn onto the fin ray scaffold in sections. Again, actuation of this fin was slow, and further designs allowed more complex geometric deformations of the fin surface, but still at slow speeds on the order of seconds (*9*).

Future EAP application to fish pectoral fin function could use EAP as actuators alone, rather than as the entire fin surface. Such polymer-based actuation increases the flexibility in construction and permits use of more traditional materials to take fluid-loads and form structural materials within the fin.

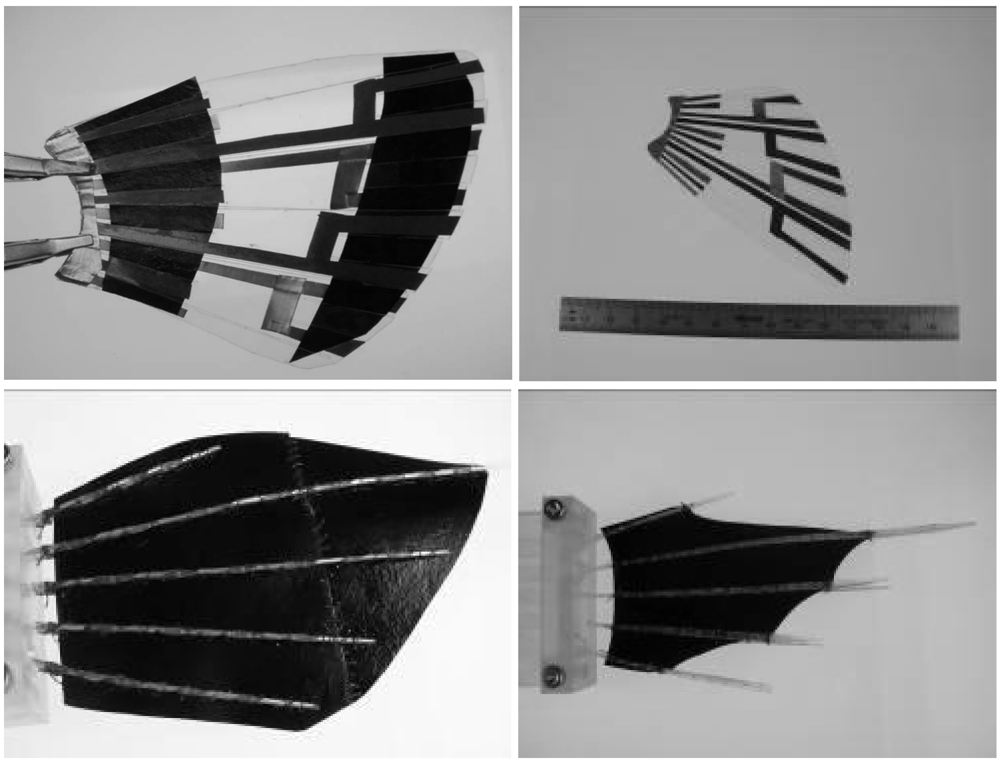

Fig. 9. Biomimetic fish fins constructed with conducting polymer by Tangorra et al. (*9*). Upper left, first iteration of an all conducting polymer fin with a basal and distal region of actuation connected by copper tape (upper right). The conducting polymer is supported by a Mylar film. Second iteration of an all conducting polymer fin (bottom). The entire fin web was made using conducting polymer trilayers. Copper electrodes are wrapped around each of the fin rays.

## CONCLUSIONS

Fish fins are intricate biological structures that exhibit complex three-dimensional patterns of motion. While fish fins have been subject to increasing kinematic and experimental hydrodynamic study during the past twenty years, only in the past two years have biorobotic fin models been constructed, and the first EAP-based robotic fish fins are just appearing now. The first generation EAP pectoral fins that have been produced have yet to generate biologically realistic patterns of motion or thrust. But progress in recent years has been rapid. Contractile characteristics of EAPs continue to improve as development proceeds, and improved methods for encapsulation and fabrication of EAP will allow an increased diversity of fish fin designs. Currently one of the greatest challenges is assembling materials into a functional fin that can be realistically actuated, so many of the immediate challenges will be ones of assembly and design, not materials research.

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