Quantitative Characterization of Three-Dimensional Pectoral Fin Kinematics in Bluegill Sunfish, *Lepomis macrochirus*

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Nonscientific Abstract

A robotic pectoral fin is one possible solution to gain finer levels of control in the propulsion and maneuvering of autonomous undersea vehicles. Fish have two pectoral fins, located on each side of the body, behind the gills. Fish use these fins for precise maneuvering, braking, slow swimming, and hovering. In this project, we mathematically describe the three-dimensional kinematics (patterns of movement) of the pectoral fins in bluegill sunfish. Our model of kinematics will be calculated by digitizing high-speed video of sunfish swimming in flow tanks. Work already completed in our project reveals that pectoral fin kinematics are much more complicated than expected. While previous research assumed the fin would behave as a rigid plate, our observations show that it is much more flexible and under a higher level of control than anticipated. When complete, this quantitative model of pectoral fin kinematics will provide the engineering parameters necessary to build a biologically accurate robotic fin.

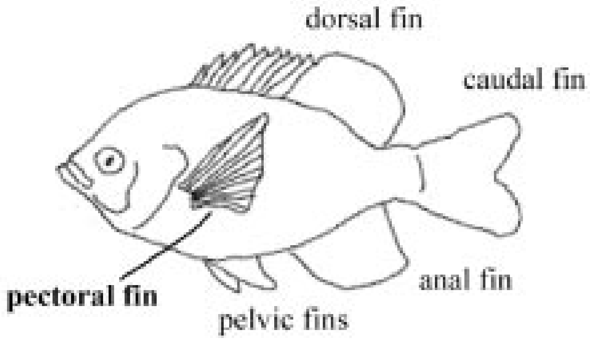

Figure 1. Fins of the bluegill sunfish, Lepomis macrochirus. Pectoral fins are located laterally, just behind the operculum.

Scientific Abstract

In this study, we will characterize quantitatively the complex three-dimensional kinematics of pectoral fin swimming in bluegill sunfish, *Lepomis macrochirus*. We will describe pectoral fin kinematics by digitizing high-speed videos of steady swimming at various speeds, braking, and vertical and horizontal maneuvers. Although past work has assumed that the fin acts as a rigid plate that follows the motion of only the most dorsal rays, our preliminary results indicate that pectoral fin kinematics are extremely complex, involving a wide range of motion and discrete active control of individual fin rays. Once complete, our model will be used in the construction of a biomimetic fin that will be employed in powering and steering autonomous undersea vehicles. The kinematic model will be used to predict hydrodynamic mechanisms, providing information essential to the design of the biomimetic fin.

Specific Aims

In this project, we will visualize and quantify the complex three-dimensional kinematics of pectoral fin locomotion in bluegill sunfish, *Lepomis macrochirus*, for the purpose of constructing a biomimetic pectoral fin. This robotic fin will be used for the propulsion and turning of autonomous undersea vehicles. A three-dimensional quantitative model of fin kinematics in freely swimming fish is necessary for the design and evaluation of an accurate biomimetic fin. We will obtain a quantitative kinematic model by achieving the following specific aims:

1. To visualize pectoral fin locomotion with high-speed, high-resolution digital video.
2. To quantify pectoral fin kinematics by digitizing video taped simultaneously from lateral and ventral perspectives.
3. To predict the fluid mechanics and hydrodynamic consequences of pectoral fin locomotion from the three-dimensional model of kinematics.

Background and Significance

A. Context

The kinematic model will be used in building a fully functioning biomimetic pectoral fin constructed of conducting polymers. In the relatively new and quickly advancing field of biological engineering, organisms are considered to possess machinelike capabilities, with performance characteristics that far surpass those attainable via current engineering approaches. A biomimetic pectoral fin will aid in building undersea vehicles that are not only silent and energy-efficient, but also have tremendous maneuverability and agility.[1] Construction of a biomimetic pectoral fin is a joint project involving laboratories in several universities across the United States. Most of the necessary background information is unknown and will need to be determined in the initial stages of the project.

The first part of the project involves characterization of the biological features and function of the pectoral fin. The majority of the biological work will be conducted in the laboratory of George Lauder at Harvard University; this work includes characterization of the gross morphology of pectoral fins in *L. macrochirus*, definition of the basic dimensions of fin rays and their bony supports, and detailed dissection of the pectoral musculoskeletal system.[1] Lauder and his team are also responsible for characterizing three-dimensional kinematics during propulsion and maneuvering of live fish, which this proposal covers. A second team leader, Rajat Mittal at George Washington University, will analyze our quantitative model to make predictions about the fluid mechanics and hydrodynamic flow created by the pectoral fin. The final portion of the biological investigation is the description of the mechanical properties of fin rays and the fin membrane, which will be conducted in the laboratories of Tim Swager and Ian Hunter at MIT. As expressed in the project grant proposal, the biological work will "quantify fin architecture, distill functional principles from live sunfish, and extract critical design parameters needed to construct a functioning biorobotic fin".[1]

The second part of the joint project is the engineering aspect, which includes further research on electroactive polymer muscles and the eventual construction of the robotic fin. Teams led by Hunter and Swager at MIT will conduct this work. Lastly, the performance of the biorobotic fin will be quantified with experimental and computational fluid dynamics and validated via comparison with our model, created with experimental data from freely swimming fish. This validation process will begin early in the construction of the fin and will be repeated to revise the design many times throughout the final stages of the joint project.

A quantitative, three-dimensional model of pectoral fin kinematics is thus essential to the successful creation of a fully functioning biomimetic pectoral fin, a biorobotic fin that will have many applications in both experimental biology and undersea vehicle engineering.

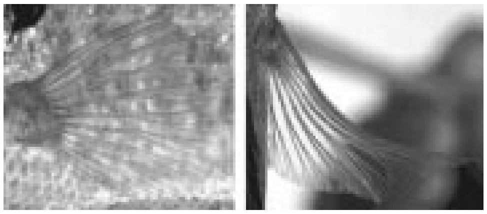

Figure 2. Simultaneous lateral and ventral views of bluegill #51 swimming at 1.0 TL/sec. Frame 200 of movie sequence 001. Video captured 10/17/03.

B. Current Knowledge

Pectoral fin swimming plays a crucial role in the locomotion of ray-finned fishes. Most species utilize the pectoral fins (Figure 1) for maneuvering, station holding or hovering, low-speed swimming, and braking, while surfperch (Family *Embiotocidae*), wrasses (Family *Labridae*), and other labriform swimmers rely on them almost exclusively for all swimming modes.[2] Historically, research has concentrated on whole-body and caudal fin locomotion, while few studies have examined pectoral fin swimming. Faced with the considerable difficulty of visualizing the detailed motion of the edges of the pectoral fin, most work has been theoretical, assuming that the fin behaves kinematically like a rigid paddle.[3,4,5] Gibb et al. (1994) attempted a three-dimensional analysis of pectoral fin motion of the bluegill sunfish *Lepomis*

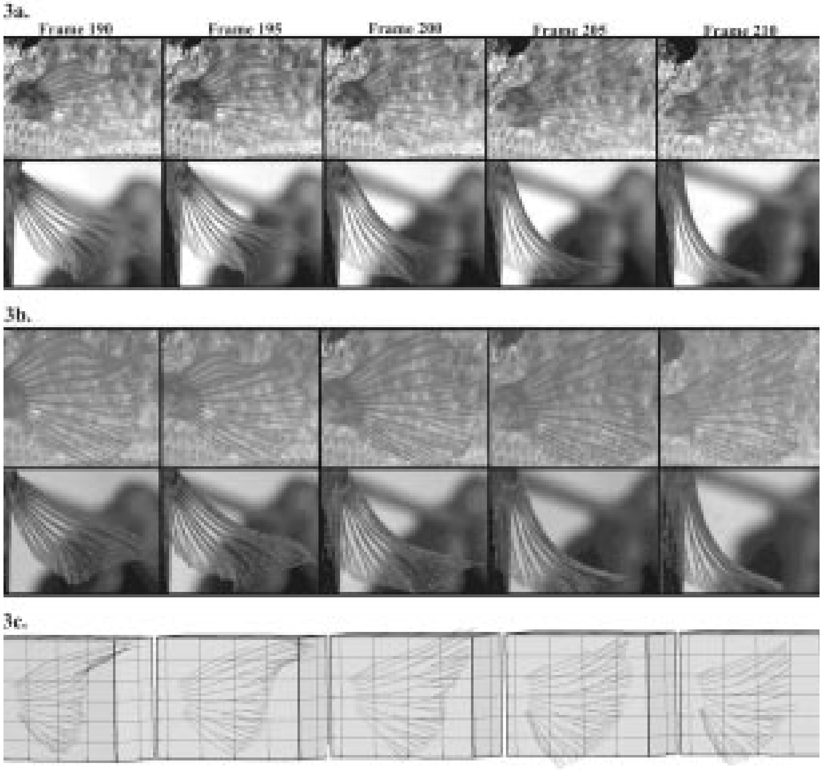

Figure 3. Frames 190, 195, 200, 205, and 210. **3a:** Original images of each frame from lateral (top) and ventral (bottom) videos. **3b:** Digitized points overlaid on frame images. These are the images that resulted from the Digimovie program depicted in Figure 3. **3c:** Real-world x,y,z-coordinate points from each frame as displayed in three dimensions in TecPlot (viewed from a direct lateral position).

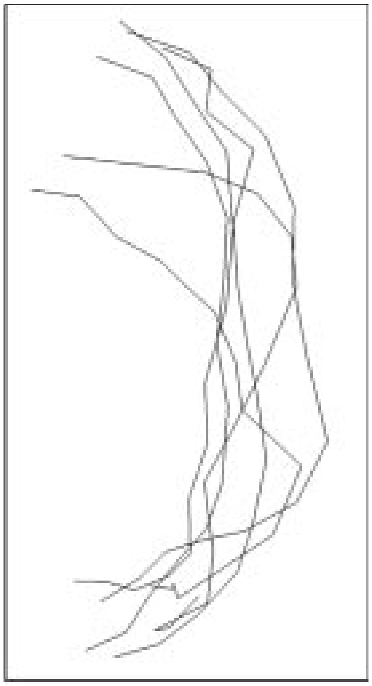

Figure 4. Range of motion seen in the bases of all the fin rays from frame 120 to 215. Bases have been connected by a line for ease of viewing. This large, extended range indicates that the fish has active control over each fin ray.

macrochirus, marking four points on the fin and then videotaping steady swimming. Their observations indicate that the kinematics of highly compliant pectoral fins do not resemble rigid plates, though the study was limited because marker placement could have affected all kinetic variables measured. Because the markers were placed on the outer fin edge, no fin ray internal bending was observed, nor could it be included in the kinematic analysis.[6]

Pectoral fins can produce thrust in three ways: a drag-based mechanism, a lift-based mechanism, or with the acceleration reaction.[7,8] In a drag-based mechanism, the pectoral fin surface is oriented perpendicular to the intended direction and the fin rotates in the horizontal plane, whereas in a lift-based system, the fin downstroke/upstroke cycle is vertical and the surface is tilted toward the direction of overall motion. Thrust can also be generated by the acceleration reaction: As the fin decelerates, water that is moving behind the fin at the original velocity creates force on the posterior fin surface.[6] From observation of marked pectoral fins, Gibb et al. (1994) concluded that fin kinematics are actually intermediate and combine all three mechanisms in a complex system of motion. The detailed kinematics cannot be sufficiently described with a single mechanism; in quantifying fin motion, this study will further elucidate the complicated interaction of these mechanisms.

Preliminary Results

Preliminary results revealed that the perciform pectoral fin is highly compliant and under active control; it allows precise, well-defined maneuvers, and provides hovering capability and brake control. Work began with video capture of pectoral fin motion during steady swimming. The first fin beat to be digitized was recorded from a bluegill swimming at 1.0 TL s^{-1}, where TL equals the total length of the fish, from head to the end of the caudal fin. For this fin beat, we digitized a total of 27 frames evenly spaced throughout the beat. Frame 200 from both lateral and ventral videos is shown in Figure 2.

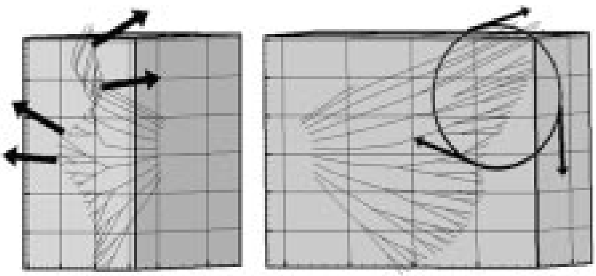

Figure 5. Frame 200, viewed from a caudal, distal position. Water is pushed rearward and inward off the dorsal edge and forward and outward off the middle portion. This creates a tilted vortex ring.

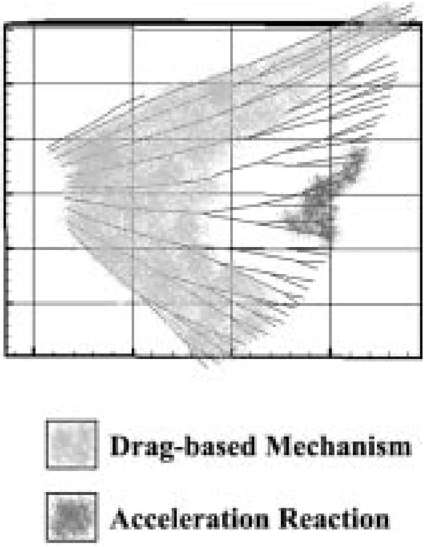

Figure 6. Thrust produced on different areas of the fin by the drag-based mechanism and acceleration reaction. The majority of the area of the fin is involved in producing thrust via the drag-based mechanism.

This individual fish has 14 fin rays, with rays 2 through 13 bifurcating at least once. Rays 7 and 8, as counted from the dorsal edge, exemplify the inherent complexity that is the source of most of the difficulty in accurately quantifying pectoral fin kinematics—these rays split seven times; each has eight tips and 15 segments. Even if only the base points, internal nodes, and tips of this pectoral fin were digitized, 80 points would still be required to define the fin, and much of the information regarding its curvature (and thus its velocity and acceleration) would be lost. To prevent this loss of potentially valuable data, we digitized multiple internal points for each ray segment (points between the base, the branching points, and the tips). For the 27 frames we have completed, an average of 399 points was obtained from each frame.

After real-world coordinates have been calculated for each point, MATLAB files will be visualized in TecPlot v.10 (Amtec Engineering, Inc., 2003). One can rotate TecPlot figures in three-dimensions and can load multiple frames in the same view. TecPlot also animates frames, thus allowing visualization of fin motion. In later stages of the project, we plan to use TecPlot to view the velocity, acceleration, and curvature of the fin surface, on both the continuous surface and at discrete locations.

Analysis of a Partial Rearward Fin Stroke

Frame 200 (Figure 2) is slightly past the beginning of the rearward stroke. The fish is moving the base of rays caudally and the tips of the rays follow this motion, moving backward: They flare out as the fish pulls the fin inward. Figure 3a displays a sequence of lateral- and ventral-view frames, from 190 to 210, with frame 200 in the center. Figure 3b shows the digitization points of these frames in MATLAB, and Figure 3c depicts the same data in three dimensions in TecPlot.

Even in this short sequence (80 msec), the fin is observed to be highly flexible, especially on the distal portions. This fin motion could only appear as it does if the fish has active control over most, if not all of its fin rays. If only the most dorsal rays were controlled, we would expect the remainder of the rays to be dragged along by connection of the fin membrane and follow the motion pattern of the first rays. Instead, the base of *every* fin ray appears to move independently, suggesting that the fish is actively moving the rays; we will be able to confirm these results when more frames have been digitized. The range of motion in the fin ray base is much greater than anticipated, especially for the bases of the more ventral fin rays. This range of motion is shown in Figure 4. The motion would be observed only if the fish is actively controlling the fin ray bases; this is not the motion that would result if all the fin rays were simply "following along" with the most dorsal ray. Rather, the fish maintains active, precise control of each individual ray, increasing the ability to maneuver and to control pectoral fin involvement in locomotion.

As the rearward stroke progresses, a wave is passed ventrally along the distal edge. The distal tips of the second and third rays move caudally at the same time that the tips of the sixth and seventh rays flick outward and forward. The caudal-directed motion at the top of the fin and anterior-directed motion at the center of the fin spin the water coming off the fin into a vortex (see Figure 5). As the water turns in the vortex, the water pushes the fin–and consequently the fish–forward. This generation of thrust is an example of the acceleration reaction mechanism. Simultaneously, the fin is pushing on the water *as a whole* as the fin moves rearward; the water's inertia to being pushed provides resistance and forces the fish to move forward. This thrust generation is accomplished through the drag-based mechanism. Thrust from this mechanism is concentrated in the more proximal half of the fin, while thrust from the acceleration reaction occurs at the distal edges of the fin. The magnitude of drag-based thrust is much more than the acceleration-based thrust, as the surface area of the fin that is involved (and thus the mass of water) is much greater (Figure 6), though the drag-based thrust occurs at a shorter distance from the base of the fin and therefore provides the fish with comparatively less leverage.

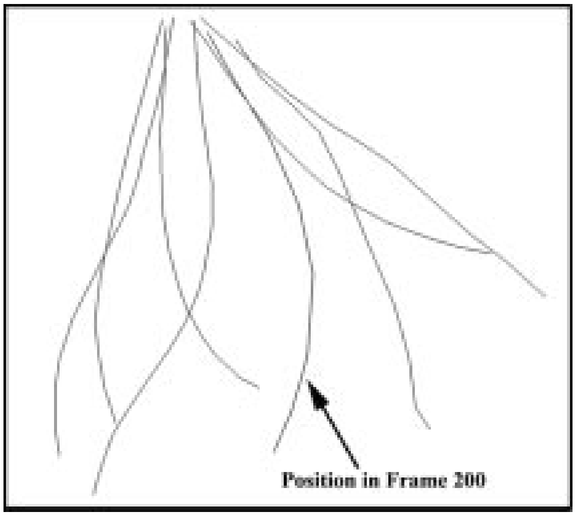

Figure 7. A wave passes distally through the more dorsal rays as the rearward stroke progresses. The wave begins near the base of the rays and continues out to the tips. This figure displays the third fin ray, as seen from above, in a sequence of frames from frame 120 to 215. The ray's position in frame 200 is indicated.

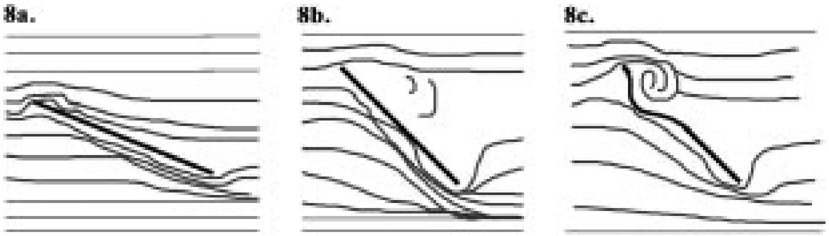

Figure 8. How angles of attack influence flow around an airfoil and how the fish may be preventing stall by passing a wave down the more dorsal fin rays. **8a:** Relatively smooth flow at a low angle of attack. **8b:** At high angles of attack, stall may occur if the leading-edge vortex becomes disconnected from the airfoil surface. **8c:** By passing a wave from the fin ray bases to their tips, the fin may hold the leading-edge vortex to itself and thus prevent stall, allowing a continuous generation of thrust.

A second wave is created during the rearward stroke. A wave passes from the base of the first through fourth rays out to the tips. This motion begins at the transition from forward stroke to rearward stroke and is eventually translated into the flicking whiplash effect seen in the tips of the sixth and seventh rays at the conclusion of the rearward stroke. This wave is shown from a dorsal view in Figure 7. We hypothesize that this wave of motion functions to hold the leading-edge vortex (discussed in the previous paragraph) to the fin's caudal surface. At high angles of attack, leading-edge vortices tend to "fall off" an airfoil's surface, creating stall. This wave along the dorsal edge may work to prevent stall during the rearward stroke by drawing water forward. Figure 8a displays an airfoil at a low angle of attack: Air flows around it smoothly. At higher angles of attack (Figure 8b), the fluid becomes disconnected from the top/rear surface of the stiff airfoil. The low-pressure zone in that area is lost and stall occurs. A wave passing down the dorsal edge (Figure 8c) may hold onto the leading-edge vortex, preventing stall and allowing thrust to be generated throughout the fin stroke cycle.

Although this is a simplified analysis of only a short sequence of frames that comprise less than 20 percent of a full fin beat, it is very apparent that the kinematics of pectoral fin locomotion are much more complex than previously thought. Our work up to this point leads us to make three conclusions: (1) The fin is highly compliant and certainly does not behave as a rigid plate; (2) The fish possess active control over most, if not all of the fin rays; and (3) continuous thrust is produced by at least two mechanisms simultaneously. We expect further digitization will reveal more detailed kinematics and help define that which we already observed. Such complicated locomotion will certainly be difficult to mimic in a biorobotic fin, but a biomimetic pectoral fin will provide autonomous undersea vehicles with greater range of motion and control over maneuverability than any system of propulsion currently available.

Research Design and Methodology

We will obtain a three-dimensional quantitative model of pectoral fin kinematics by digitizing high-res-

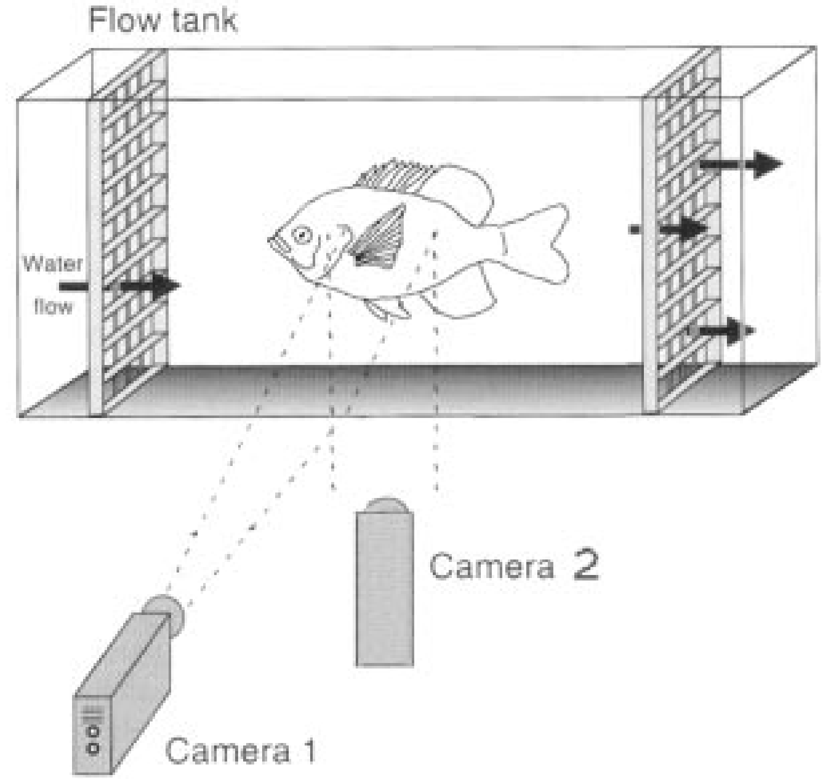

Figure 9. Schematic illustration of digital video technique. Fish will be taped swimming in a flow tank at 0.5, 1.0, and 1.5 TL s^{-1}. High-speed (500 fps), high-resolution (1024 x 1024 pixels) video will capture the detailed motion of the pectoral fin in simultaneous lateral and ventral views (modified after Gibb et al, 1994).

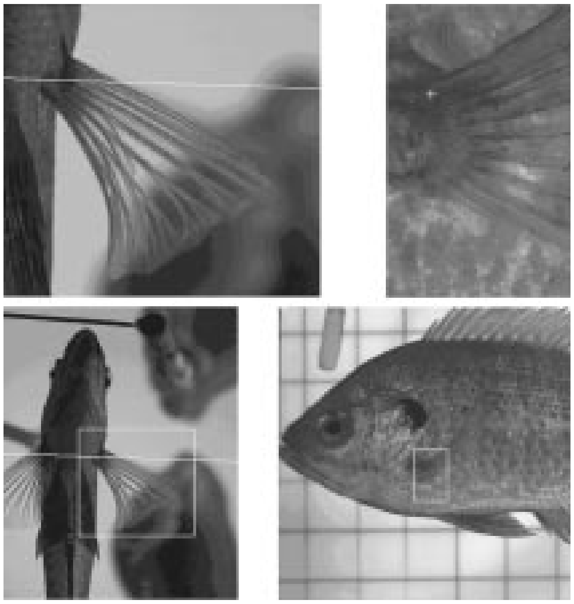

Figure 10. Screen shot of Digimovie program in MATLAB. A video frame from the ventral perspective is shown in the lower left; above this is a zoomed view. A video frame from the lateral perspective and its zoomed view are on the right. The small cross in the upper-right image indicates the first point clicked. Its corresponding x-coordinates in the ventral view are indicated by the line in the upper-left-hand image. The next point clicked would be along this line, on the same ray as the point clicked in the lateral view opposite.

olution, high-speed video taken simultaneously from lateral and ventral perspectives. Bluegill sunfish (*L. macrochirus*) will be taped swimming at various speeds with two cameras at orthogonal angles (see Figure 9). Simultaneous lateral and ventral views will be digitized, and digital segments of individual fin rays will be fit with splines, short curves that approximate the ray between digitized points. Further analysis will include defining fin surface curvature, velocity, and acceleration and comparison of kinematics during steady swimming, braking, and maneuvering.

Specimens

Bluegill sunfish (*Lepomis macrochirus*) will be captured in shallow water in the Charles River, Cambridge, Mass., with beach seining. We chose this species for its generalized shape and swimming mode as well as its tendency to swim with the pectoral fins at low speeds. This fish species is also easily managed in the laboratory. Full-size fish of similar length will be selected to minimize size effects. Fish will be kept in freshwater holding tanks at 20° C and fed earthworms twice weekly.

Videography

Fish will be taped swimming at three speeds: 0.5, 1.0, and 1.5 total lengths per second (TL s^{-1}); total length is the length measured from head to end of caudal fin. These speeds cover the range over which pectoral fins are used for locomotion. Fish will swim in an experimental arena that is 45 cm long by 18 cm wide by 18 cm high, in a flow tank with an approximate total volume of 1000L. Video will be captured at 500 frames per second (fps) with a two-camera high-speed digital video system, with one camera directed laterally and one ventrally, as shown in Figure 9. The laterally directed camera will be the Photron APX; its specifications include full 1024 x 1024 resolution up to 2000 fps, a maximum frame capture rate of 100,000 fps, and a data transfer rate of 2 GB/s. The ventrally directed camera will be the Photron FastCam-X 1280 PCI, which provides 1280 x 1024 resolution at 500 fps and records at speeds up to 16,000 fps. We will record at 1024 x 1024 resolution at 500 fps with both cameras.

Fish will be trained to swim at an even horizontal level and at mid-depth in the tank by introducing probes into different locations in their environment (G. V. Lauder, personal communication). After fish are sufficiently trained, videos of pectoral fin swimming will be taken simultaneously from the lateral and ventral views. Approximately four fin beats of steady swimming will be filmed at each speed for each fish, along with several fin beats of braking and several of maneuvering. Braking behavior will be observed when the fish moves to capture an earthworm held at the water surface, while maneuvering behavior will be induced with specific placement of the probes. We plan to include four bluegill sunfish in the study.

Digitization

Videos will be viewed with the Photron Motion Tools Player (Photon USA, Inc., San Diego, CA). Preliminary work shows that the duration of a fin beat typically ranges between 240 and 300 frames; we will digitize to 20-30 evenly spaced frames per beat (spaced about every 0.02 sec.). Videos of pectoral fin swimming will be digitized with MATLAB v.6.5 and the MATLAB Image Processing Toolbox v.3.0 (The MathWorks, Inc., Natick, MA). The selected frame will be imported into MATLAB, and fin rays will be digitized individually with the program Digimovie v0.2 (Peter Madden, Harvard University, 2003). Digitization points are selected manually. A screen shot of this program is displayed in Figure 10; when a point is selected in either the lateral or ventral view, Digimovie draws a line of the corresponding *x*-axis values in the opposite view. A point along this line on the same ray is then selected to match lateral and ventral views and to give one three-dimensional (*x*,*y*,*z*) digital point. Finally, Digimovie converts these coordinates into real-world coordinates with a direct linear transformation function (P. Madden, personal communication).

This process will be repeated for each selected frame in each fin beat to generate a complete quantitative model of pectoral fin kinematics. Initial work has shown that between 280 and 500 points are needed to fully describe all of the rays of the fin within each frame; the average frame requires 399 points. Digitizing every fifth frame in a set of 140 frames per fin beat–for four fin beats per speed per fish, for four fish–means we will amass over 536,000 data points for steady swimming kinematics alone. Videos of braking and maneuvering will also require digitization.

Analysis

For each frame, fin ray points will be mapped onto three-dimensional Cartesian coordinates for graphical analysis. These points will be fit with splines; each segment of each ray will be defined with a curve, thus translating discrete data points into equations. Next, the fin surface will be defined numerically by coupling adjacent rays by connecting two points on one ray with one point on another, creating a surface of triangles. Surfaces from successive frames will then be linked, allowing animation and analysis of motion including surface curvature, relative and absolute velocity, and acceleration. Data for individual fish will be averaged to quantitatively describe steady swimming at each of the three swimming speeds, braking, and maneuvering, producing a comprehensive model of three-dimensional pectoral fin kinematics.

Timeline

Fall 2003 – Spring 2004	Begin data collection (video capture) and digitization, qualitative modeling, and design of programs to create quantitative model.
Spring 2004	Complete digitization and quantitative modeling of forward swimming at various speeds.
Spring – Summer 2004	Complete model of pectoral fin kinematics with quantification of braking and maneuvering.
Summer 2004	Begin fluid mechanical analysis of model and definition of engineering parameters. Send data to engineering lab to begin construction of biomimetic fin.

References

1. Hunter, I., T. Swager, G. Lauder, R. Mittal, and J. Walker. 2003. Development of an integrated artificial muscle, high-lift, bio-hydrodynamic mechanism for biorobotic autonomous undersea vehicles. Preproposal submitted to the Office of Naval Research.
2. Helfman, G.S., B.B. Collette, and D.E. Facey. 1997. The diversity of fishes. Malden, Mass.: Blackwell Science.
3. Webb, P.W. 1974. Hydrodynamics and energetics of fish propulsion. Bull. Fish. Res. Bd Can. 190:1–158.
4. Blake, R.W. 1979. The mechanics of labriform locomotion. I. Labriform locomotion in the angelfish (*Pterophyllum eimekei*): an analysis of the power stroke. J. *Exp. Bio.* 82:255–271.
5. Blake, R.W. 1980. The mechanics of labriform locomotion. II. An analysis of the recovery stroke and the overall fin-beat cycle propulsive efficiency in the angelfish. *J. Exp. Biol.* 85:337–342.
6. Gibb, A.C., B.C. Jayne, and G.V. Lauder. 1994. Kinematics of Pectoral Fin Locomotion in the Bluegill Sunfish Lepomis macrochirus. *J. Exp. Biol.* 189:133–161.
7. Daniel, T.L. 1984. Unsteady aspects of aquatic locomotion. *Am. Zool.* 24:121–134.
8. Webb, P.W., and R.W. Blake. 1985. *Swimming. In Functional Vertebrate Morphology* (ed. M. Hildebrand, D.M. Bramble, K.F. Liem, and D.B. Wake), pp. 110–128. Cambridge, Mass.: Harvard University Press.
9. Archer, S.D., and I.A. Johnston. 1989. Kinematics of labriform and subcarangiform swimming in the Antarctic fish *Notothenia neglecta. J. Exp. Biol.* 143:195–210.
10. Drucker, E.G. and G.V. Lauder. 2003. Function of pectoral fins in rainbow trout: behavioral repertoire and hydrodynamic forces. *J. Exp. Biol.* 206:813–826.
11. Geerlink, P.J. 1983. Pectoral fin kinematics of Coris formosa (*Labridae, Teleostei*). *Neth. J. Zool.* 33:515–531.
12. Geerlink, P.J. 1989. Pectoral fin morphology: a simple relation with movement pattern? *Neth. J. Zool.* 39:166–193.