# **SYMPOSIUM**

# Use of Biorobotic Models of Highly Deformable Fins for Studying the Mechanics and Control of Fin Forces in Fishes

James Tangorra,<sup>1,\*</sup> Chris Phelan,\* Chris Esposito\* and George Lauder<sup>†</sup>

\*Department of Mechanical Engineering, Drexel University, Philadelphia, PA 19104, USA; <sup>†</sup>Museum of Comparative Zoology, Department of Organismic and Evolutionary Biology, Harvard University, 26 Oxford Street, Cambridge, MA 02138, USA

From the symposium "Bioinspiration: Applying Mechanical Design to Experimental Biology" presented at the annual meeting of the Society for Integrative and Comparative Biology, January 3–7, 2011, at Salt Lake City, Utah.

<sup>1</sup>E-mail: tangorra@coe.drexel.edu

**Synopsis** Bony fish swim with a level of agility that is unmatched in human-developed systems. This is due, in part, to the ability of the fish to carefully control hydrodynamic forces through the active modulation of the fins' kinematics and mechanical properties. To better understand how fish produce and control forces, biorobotic models of the bluegill sunfish's (*Lepomis macrochirus*) caudal fin and pectoral fins were developed. The designs of these systems were based on detailed analyses of the anatomy, kinematics, and hydrodynamics of the biological fins. The fin models have been used to investigate how fin kinematics and the mechanical properties of the fin-rays influence propulsive forces and to explore kinematic patterns that were inspired by biological motions but that were not explicitly performed by the fish. Results from studies conducted with the fin models indicate that subtle changes to the kinematics and mechanical properties of fin rays can significantly impact the magnitude, direction, and time course of the 3D forces used for propulsion and maneuvers. The magnitude of the force tends to scale with the fin's stiffness, but the direction of the force is not invariant, and this causes disproportional changes in the magnitude of the thrust, lift, and lateral components of force. Results from these studies shed light on the multiple strategies that are available to the fish to modulate fin forces.

# Introduction

Biorobotic models of the pectoral and caudal fins of the bluegill sunfish (Lepomis macrochirus) (Fig. 1) were created and used to investigate how highly deformable fins create and modulate propulsive forces. The robotic fins were designed to characterize specific aspects of the biological fins and were used to investigate how the fins' kinematic patterns, their spatially varying mechanical properties, and the fluid's rate of flow affected the magnitude and direction of each fin's propulsive forces. In many cases these experiments paralleled experiments conducted with freely swimming fish, but the use of the biorobotic models allowed for experimental parameters (e.g., fin ray kinematics) to be more tightly controlled and for experimental outcomes (e.g., fin forces) to be more easily measured. The use of the biorobotic fins also enabled us to explore kinematic

patterns that would not normally be exhibited by the sunfish. The results from these experiments are crucial for understanding the mechanisms that contribute to fin forces and for understanding strategies that the fish can use to modulate the forces required to control the orientation and motion of the body.

This research uses the bluegill sunfish as a biological model for studies of multi-fin swimming. The sunfish is representative of a large class of bony fish that use multiple fins and multiple swimming gaits and that integrate a great deal of sensory information to swim with extraordinary agility across a wide range of fluidic conditions. For example, at low speeds and at hover, the sunfish uses primarily its pectoral fins to create propulsive and stabilizing forces. The tail and the other five fins are moved only slightly, mainly to help stabilize the fish.



Fig. 1 Bluegill sunfish with fins extended during hover.

Although low-speed swimming appears effortless, the fish's body is unstable and negatively buoyant (Webb and Weihs 1994; Webb et al. 1996; Lauder 2006). When anesthetized, the sunfish will roll over and sink. So the alert fish is always using its fins to keep itself upright and to stabilize itself against fluidic perturbations. As the fish accelerates and its speed increases, the fish incorporates its tail, caudal, anal, and dorsal fins (Standen and Lauder 2005), and eventually stops using the pectoral fins and flattens them against the body. Finally, in many maneuvers, such as when the fish wants to stop suddenly, all the fins are coordinated and moved together.

It is obvious that principles learned about multi-fin swimming can be applied to underwater vehicles, but the applications are much broader. The remarkable swimming abilities of the sunfish are not due to the superior performance of any single system, but to the collective performance of many interacting subsystems. The manner in which the sunfish integrates the mechanics of the fins, distributed sensing and information processing, and neural control to create complex swimming behaviors can be generalized and applied to a broad range of engineered systems that have large numbers of actuators, distributed sensing, and the ability to modulate plant properties.

In this article, we discuss the process that was followed to model the biological fins with robotic systems and the design and construction of several biorobotics fins, and we highlight results that describe the manner in which forces are created and modulated by highly deformable, ray-finned fins.

# **Development process**

#### Overview

The biorobotic fins were developed using a systematic process that is based on product-development methodologies designed to ensure that a device addresses the needs of multiple stakeholders (Ulrich and Eppinger 2003). The process included: (1) defining scientific objectives for the robotic devices, (2) conducting detailed analyses of the biological system, (3) distilling the functional behaviors and characteristics of the fish into fundamental components that could be modeled using humanengineered technologies, (4) developing-and ideally integrating-mathematical and robotic models that captured specific characteristics of the biological system, (5) validating the mathematical and biorobotic models against the biological system, (6) conducting experiments with the model systems, and finally (7) revisiting the biological system to advance our understanding of how fish swim and to refine objectives for subsequent biorobotic systems. The process is iterative, and steps were revisited as new understandings developed. The structure was not intended to limit the activities of any of the laboratories involved, but to provide a framework that helped us to define each laboratory's responsibilities clearly and to understand how each laboratory's work contributed to the larger research effort.

The development of a series of biorobotic pectoral fins will be explained to illustrate this design process. The steps outlined for the pectoral fin robots are representative of those used to develop a biorobotic caudal fin and that are being used to create biologically derived sensory systems (Phelan et al. 2010) and multi-fin robots.

#### Objective

The primary objective was to develop a series of biorobotic pectoral fins that enabled us to investigate how the kinematics of the fin and the mechanical properties of the fin rays affected propulsive forces and wake flows. Extensive lists of "stakeholder needs" and "target specifications" were created to define how the fins had to perform to satisfy this objective. As discussed by Ulrich and Eppinger (2003), a great deal of discussion between the engineers and biologists and a significant amount of preliminary experimentation were required in order to generate needs and specifications that were useful and comprehensive.

#### **Biological studies**

The pectoral fin's anatomy, the mechanical properties of the fin rays and the webbing, and the fin's kinematics and hydrodynamics during low-speed (<1.5 body lengths per second) swimming and maneuvers were analyzed in detail. Although the sunfish has been studied for many years by the Lauder Laboratory, it was beneficial to revisit the data and to recast the information so that it could be more easily interpreted for a robotic implementation of the fin.

The pectoral fin is able to create its motions and forces due to an architecture that gives the fish great control over the fin's kinematics and structural properties (Drucker and Jensen 1996; Walker and Westneat 2002; Lauder et al. 2006). The fin is comprised of 14 bony fin rays that are sandwiched in a thin and flexible webbing. Each fin ray is split into two halves (hemitrichia) and is driven by two abductor and two adductor muscle pairs. These muscles, and the manner by which they connect the fin rays to the pectoral girdle, enable each fin ray to be rotated about the anterior-posterior and dorsal-ventral axes and enable the entire fin to be translated and rotated by a small amount. The most dorsal fin ray has an additional three muscles that increase its controllability. The fin rays are thick at the base and become thinner and bifurcate towards their distal ends. This geometry makes the fin stiff near the base and very flexible towards the tip. Three-point bending tests were conducted on newly excised fin rays and determined that the flexural rigidity (EI) of an individual fin ray decreased approximately exponentially from base to tip, and that there was more than a 10-fold difference between the flexural rigidities of the most rigid and most compliant fin rays. Flexural rigidities were typically on the order of 1 to  $10 \times 10^{-6}$  Nm<sup>2</sup>. Uniaxial tensile testing of the fin webbing determined that the webbing behaved nonlinearly, as would be expected for a biological material that contains collagen fibers, and had a tensile modulus that ranged from approximately  $100 \times 10^3 \text{ N/m}^2$  at low strains to over  $1000 \times 10^3$  N/m<sup>2</sup> at high strains. A particularly elegant feature of the fin ray is that its stiffness and curvature can be modulated by displacing the base of one hemitrich relative to the other. So, although the fin is thin, very flexible, and has no muscles or tendon attachments within the webbing, the fish has active control over the fin's movement, shape, and stiffness.

The kinematics of steady swimming and of yaw-turn gaits were studied as the fish swam in a flow tank. The fins were imaged using high-speed (250–500 fps), high definition  $(1024 \times 1024 \text{ pixels})$ video, and the 3D coordinates of 10-20 points along each fin ray were extracted throughout the fin beat. In steady swimming, the two pectoral fins are very flexible and execute a graceful motion that is led by dorsal and ventral leading edges. As the two pectoral fins move synchronously into the flow during the outstroke from the body, they cup about their spanwise axes and the distal portions of the fins bend back. The fins then rotate at their bases and expand in area as they move back toward the body. The motions create strong vortical flow patterns along the fins' upper and lower surfaces, and the vortices are shed into the flow along with jets near the end of the outstroke and instroke (Mittal et al. 2006; Dong et al. 2010). The steady-swimming gait seems very well suited for propulsion-it can create positive thrust throughout the entire fin beat, and the magnitudes of the peak lateral and lift forces are similar to, or smaller than, the magnitude of the peak thrust. This differs from dorsal-ventral flapping, where existing data for rigid fins show that the peak lift and lateral forces are significantly greater than peak thrust (Isogai et al. 1999; Lewin and Haj-Hariri 2003; Mittal 2004; Triantafyllou et al. 2004; Dong et al. 2006; Mittal et al. 2006). Thrust, lift, and a contralateral force are created by each fin during the outstroke, and thrust, downward lift, and an ipsilateral force are created during the instroke. The magnitudes of these forces were estimated by calculating the momentum added to the flow by the fish from the flow's velocity profile (Lauder and Madden 2007, 2008). To execute a maneuver that moves the fish away from an obstacle placed in the flow, the

kinematics of the fins change so that forces are directed more laterally and so that rotational moments about the fish's turning center are created (Gottlieb et al. 2010). The two pectoral fins move differently from each other during this maneuver. The fin on the outside of the turn creates large forces that drive the fish's motion. The fin on the inside of the turn moves only through small displacements, and produces forces that help stabilize the fish. The motion of the outside fin is led by the fin's ventral edge. This creates drag that reduces the fish's swimming speed and a ventral force that pushes the fish downward in the flow. The dorsal half of the fin then accelerates forward and rolls over the ventral half of the fin. This motion creates a negative thrust and a contralateral force (directed towards the side opposite the fin) with a magnitude that can be nearly six times as large as the peak magnitude of the thrust. These forces rotate the fish away from the obstacle. The dorsal half of the fin then follows the ventral half back towards the body. This motion creates thrust and an ipsilateral force that reorients the fish into the flow.

#### Numerical models

A computational fluid dynamic (CFD) simulation of the fin was developed and used to predict the forces and flows created by motions of the fin (Mittal et al. 2006). These predictions added fidelity to the estimates of force and flow that had been determined from the experimental studies of the sunfish. Importantly, the CFD simulation allowed for motions that were derived from actual movements of the fin, but that were not explicitly exhibited by the sunfish, to be evaluated, and thus for the components of the fin's motion that were fundamental to the production of force to be identified.

The complete motions of the fin were decomposed into modal components using proper orthogonal decomposition (POD; Bozkurttas et al. 2009). The individual modes, and combinations of the modes, were then simulated in the CFD analysis to understand how each contributed to the fin's forces. Of the 19 modes that were identified for steady swimming, the first three modes accounted for two-thirds of the fin's dynamic motion. Mode 1 captured the motion of the fin as it sweeps forward and cups about its spanwise axis. Mode 2 captured the expansion of the fin during the fin's instroke back to the body. Mode 3 captured a dynamic "flick" of the distal tip of the fin. When combined, these three components produced over 95% of the thrust predicted for the full motion of the fin. Similarly, for the turn maneuver, a combination of just a few component motions was able to create the main features of the force profile. The understanding of the component motions greatly simplified the engineering requirements for the robotic system. Rather than having to recreate the complete motion of the fin to produce propulsive forces, the robotic system could focus on modeling only the components that mattered most. The trajectories of the component modes were easier to define mathematically than the full motion of the fin and could be implemented well using far fewer than the 14 fin rays and 59 muscles used by the fish.

#### Design of the fins

Several designs were developed and evaluated over the course of this work (Figs. 2 and 3). The most recent version of the pectoral fin creates approximations of the motions used by the sunfish for steady swimming, yaw-turn maneuvers, and hover and can also be controlled to create other movements that are inspired by biology or that are simply interesting to explore. The system also includes sensory elements so that closed-loop, sensory-based control of the fin can be investigated (Phelan et al. 2010). The designs of the multi-DOF mechanisms that drive the fin rays evolved from three generations of fins that had focused on individual patterns of gait. The first fin was designed to investigate how the four dominant components of the pectoral fin's motion contributed to the production of steady-swimming thrust. Its design and performance were discussed in detail by Tangorra et al. (2007b). The second generation fin executed the dominant kinematic pattern for steady swimming very accurately, and focused on the interplay between the fin's kinematics and its mechanical properties (Tangorra et al. 2011). The third generation fin focused on turn maneuvers (Gottlieb et al. 2010). Each version of the fin required a significant redesign of the mechanisms that drove the fin rays in order to execute the desired motions properly, and it was very challenging to execute all the motions well using a single robot with an architecture that was simple relative to the biological anatomy.

The biorobotic fin has five flexible fin rays that are covered by an elastic membrane (Fig. 3). The size of the fin is approximately four times the size of an average biological pectoral fin. The five fin rays represent fin rays 1, 4, 7, 10, and 14 of the biological fin and were selected because they bound groups of fin rays that were observed to move together during steady-swimming and turn maneuvers. The fin rays have rectangular cross-sections that taper in area from base to tip and which are scaled so that they



Fig. 2 Three generations of biorobotic pectoral fins executing fundamental motions. Generation one (A) sweeping the fin's dorsal edge into the flow. Generation two (B) executing the cupping and sweep motion. Generation three (C) leading with the ventral edge for a turn maneuver.



Fig. 3 The fourth generation biorobotic pectoral fin (A) and a detail of its drive mechanism (B). Each fin ray can have up to three actuated degrees of freedom, which enables the fin to create the large range of motions used in steady swimming and for maneuvers. Cupping and sweep (C), in-plane rotation (D) (with ghost image of rotated fin), and the active curl of fin rays (E1 and 2) can be coordinated or executed independently.

have flexural properties similar to those of the biological fin rays (Tangorra et al. 2011). This helps the biorobotic fin achieve curvatures like the biological fin as it is moved through the water. The fins rays were manufactured using rapid prototyping methods (Three-Dimensional Systems, Rock Hill, NC, USA, and Stratasys Inc., Eden Prairie, MN, USA). The fin's webbing is made using a thin (0.35 mm) 80%/ 20% polyester and elastane blend that, depending on the experiment, is sometimes coated with a layer of latex to alter its porosity and the manner in which the webbing adheres to an acrylic wall that represents the flank of the fish's body.

The fin rays are actuated using servomotors (HSR-5990TGs, Hitec RCD USA, Poway, CA) that are connected to the bases of the fin ray using low-stretch nylon lines. This allows the servomotors to be positioned above the waterline of the fin so

that they do not have to be waterproofed. Linear Lorentz force actuators, conducting polymers, and shape-memory alloy actuators (SMA) have also been used to actuate the fin rays (Tangorra et al. 2007a; Phelan et al. 2009). Although each of these alternative actuation methods offered an advantage over the traditional servomotors-for example, the Nitinol SMA was light and could be integrated into the design more like a biological muscle-none of the technologies could simultaneously produce the force, displacement, and speed of a rotational servomotor with similar cost, weight, and ease of implementation. The poor availability of off-the-shelf, muscle-like actuators with practical engineering characteristics (i.e., force, speed, and displacement as opposed to stress, strain rate, and strain) significantly impairs the ability to manufacture devices using a biologically based architecture.

Each fin ray is mounted onto a mechanism that allows the fin ray to be driven with up to three actuated degrees of freedom (DOF)-rostral-caudal sweep (outstroke and instroke), in-plane rotation, and curvature control (Fig. 3). Since the complexity of the fin's drive mechanisms, the potential for failure, and the number of actuators increases with each actuated DOF, fin rays are provided with only the DOF required to execute a desired set of experiments. Fin rays that must only execute sweep are mounted onto a simple hinge which is mounted in a stationary base. When sweep and lateral motions are required, the hinge is mounted onto a cylinder that can be rotated about its long axis. To decouple one rotation from the other, the nylon lines that drive the fin rays pass through the center of the cylinder, and are routed to the servomotors through mandrel-bent tubes. Curvature of the fin ray is modulated using a nylon line that runs along the length of a fin ray and terminates at the fin ray's tip (Phelan et al. 2009). The line is tensioned using either a dedicated servomotor or an SMA wire. An advantage of the servomotor is that it can tension the tendon along a continuum, whereas the SMA is difficult to control except in a binary-tensioned or not tensioned-fashion. A disadvantage to the servomotor is that it affects the sweep of the fin ray when it tensions the line used to control curvature. In contrast, the SMA can be placed along the length of the fin ray, in parallel or in lieu of the nylon line, so that it does not interfere with the sweep motions. The positioning of the drive mechanisms, and the angle at which each fin ray is attached to its base, are arranged so that the fin naturally cups about its spanwise axis as it is swept forward. This is the fundamental movement underlying steady swimming.

The in-plane rotation allows for significant deviation from the cupping motion. For example, the entire fin can be rotated, expanded, or collapsed in area, and coordination of the sweep and in plane rotation enables sweep to occur with nearly no cupping (Fig. 3).

#### Validation

To trust that results had relevance to the biological system, the biorobotic fins were validated as models by comparing their motions, forces, and flows against those of the biological fins and of the CFD simulations. Since the robotic fins had not been designed to replicate the biological fins, it was not necessary for them to perform exactly as the biological fin. However, it was very important that they exhibit the dynamic movements that are essential to the production of forces and to create forces and flows that had the key features of the biological profiles.

When a fin's stiffness was correct along the span and the chord and the base of the fin rays were driven by the proper trajectories, the robotic fins moved and bent like the biological fins and produced good approximations of the biological force profiles and flow patterns. Although the robotic fins used purely passive fin rays and were driven with trajectories derived from just a few of the underlying modes, the fins exhibited the complex bending and curvatures of the biological fins (Fig. 4) and developed vortices along the dorsal and ventral leading edges very much like the biological fin. The magnitude of the forces created by the fins did not always match the magnitudes predicted by CFD exactly, but properly tuned pectoral fins did create peaks of thrust during the steady swimming outstroke and instroke (Fig. 4), and as well created strong lateral jets and large lateral forces when the gait was shifted to the turn maneuver.

#### **Experimentation and results**

To help understand the strategies that fish can use to modulate propulsive forces, experiments were conducted with the biorobotic fins to determine the effects of kinematic patterns and of flexural rigidity of the fin ray on the force exerted by the fin. Trials were conducted using pectoral fins with flexural rigidities scaled to 400, 600, 800, 1000, and 2000 times ( $\times$ ) the flexural rigidities of the sunfish pectoral fin. These flexural rigidities were selected so that the larger, five-ray robotic fins would bend like the biological fin when moved through the water. This scaling is presented in detail by Tangorra et al. (2011). The pectoral fins were flapped at frequencies from 0.5 Hz to 2.0 Hz and were tested in smooth flows



Fig. 4 The biorobotic fins' motions and forces were verified against those of the biological fin. Motions were compared visually (A and B) and using the 3D coordinates (C and D) of the biological (left in panel) and robotic fins (right in panel) as the fin executed its beat. Similar to the biological fin during steady swimming, the robotic fin produced thrust throughout the fin beat, lift during the outstroke, and a downward force during the instroke (E). Forces are shown for the pectoral fin flapping at a frequency of 1.65 Hz in a flow of 90 mm/s<sup>-1</sup>.

with speeds that ranged from  $0 \text{ mm/s}^{-1}$  to 270 mm/s<sup>-1</sup>. Steady swimming gaits were tested over the full range of conditions and yaw-turn maneuvers were tested over a reduced, but still large, range of conditions. Several kinematic patterns that

were inspired by the motion of sunfish's fins, but that were not derived from actual biological patterns, were also evaluated. Biorobotic caudal fins with six independent fin rays and flexural rigidities scaled to 150, 250, 500, and 1000 times those of the biological



Fig. 5 Two of the five caudal fin patterns. A symmetric cupping (A and B) and an asymmetric undulation (C and D) as executed by the fish (left) and the robotic caudal fin (right). The arrows indicate each fin's direction of motion.

fins were evaluated at flapping frequencies of 0.5–2.0 Hz, in flows of 0 and 90 mm/s<sup>-1</sup>. Five gait patterns were used: A flat profile, a cupped profile, a "w" profile, an undulation, and a rolling motion (Fig. 5). For all patterns except the rolling motion, the fin rays followed sinusoidal trajectories and were swept through the same amplitudes. In the flat pattern, there was no difference in phase among the fin rays. In the cupping motion, the most distal and ventral fin rays led the motion, the fin rays in the middle of the dorsal and ventral lobes lagged by  $10^{\circ}$ , and the two middle fin rays lagged by 20°. The "w" profile was similar to the cupping motion, but the two middle fin rays were advanced so that they moved with the distal and ventral edges. The undulatory motion was led by the dorsal fin ray and there was a  $10^{\circ}$  lag in phase between subsequent fin rays. For the rolling motion, all fin rays moved sinusoidally and in phase, but the amplitude of the sinusoid decreased linearly from the dorsal to the ventral fin ray.

The robotic fins were supported from an air-bearing carriage that was mounted above the tank. The carriage allowed the fins to swim freely against the flow, and could be locked against force transducers so that forces could be measured in two directions. Pectoral fins were oriented so that thrust and lateral force and thrust and lift forces were measured. The caudal fin was oriented so that thrust and lift forces were measured.

#### Pectoral fin kinematics

Changes to the kinematics of the fin included switching the gait, making less extreme changes to the trajectories or to the phase relationships of the fin rays within a gait, and altering the frequency at which the fin was flapped.

As expected, changing the gait resulted in gross changes to the magnitude, direction, and profile of the fin's forces. For example, the motions of the pectoral fin during steady swimming and during the turn maneuver are quite different, and so were the resultant forces. In steady swimming, the fin is led by an upper and lower leading edge, cups about its spanwise axis, and bends back a great deal as it moves into the flow A beautiful vortex pattern is shed from the upper and lower leading edges (Dong et al. 2010), and thrust, lift, and a contralateral force are created during the fin's outstroke, and thrust, downward lift, and an ipsilateral force are created during the instroke (Figs. 4E and 6A and B). When executing the yaw-turn maneuver, the motion of the fin during the outstroke is led by the fin's ventral edge (Fig. 2C). The ventral edge moves away from the fish's body and then the dorsal part of the fin quickly accelerates and rolls over the ventral half. This causes a strong lateral jet to be created and results in drag, which slows the fish and a large contralateral force which rotates the fish (Gottlieb et al. 2010). The peak lateral force is nearly four times the peak drag force, whereas during steady swimming, the peak thrust and peak lateral forces are about equal. During the instroke, thrust and an ipsilateral force are created which reorient the fish back towards the flow.

Significant changes to the pectoral fin's force also occurred when the coordination of the fin rays within a gait was changed. For example, rather than driving the fin rays synchronously (in phase) as in normal steady swimming, the fin rays were driven out of phase to create an undulatory motion. Each fin ray traveled the same path and with the same velocity as for normal steady swimming, but the motion was led by the dorsal fin ray,



Fig. 6 Thrust (horizontal) and lift (vertical) forces for pectoral fins executing normal and modified steady-swimming gaits. Normal, full-fin steady swimming for three levels of stiffness (A). Mean values of the force during the outstroke and instroke (B). Forces from the fin when a linearly increasing lag in phase was used for subsequent rays (C and D). Forces from the individual dorsal (E) and ventral (F) halves when the other half was held still. The forces can be moved around the thrust-lift space without switching the underlying gait pattern by altering the stiffness and the coordination of the fin rays.

and subsequent rays were delayed by a phase of  $10^{\circ}$  (i.e., the lag for Ray 2 was  $10^{\circ}$ , for Ray 3 was  $20^{\circ}$ , and so on). This undulatory motion looked very different from the normal cupping and sweep motion, and redirected fin forces so that a great amount of

lift and a net drag was created (Fig. 6C and D). The undulation could also be led by ventral most fin ray, which resulted in a strong downward force and a net thrust (Fig. 6). Smaller differences in phase between fin rays resulted in less significant changes to the baseline forces of steady swimming. Altogether, this demonstrates that steady-swimming forces can be shaped and moved throughout the thrust-lift plane without switching gait patterns, but by adjusting the coordination of the fin rays within an underlying gait pattern.

The asymmetrical shape of the fin causes the dorsal half-which is longer and has greater area-to dominate the production of force. However, the ventral half is very important for producing a balanced force and, as in the yaw turn, to shape the force so that the fish's body is moved in the desired direction throughout the fin beat. To better understand the importance of the pectoral fin's dorsal and ventral halves in creating the steady-swimming forces, individual halves of the biorobotic fin were moved using the normal fin beat, while the other half was held stationary. To prevent the fin rays from fracturing or the opposing half of the fin from being pulled into the flow, the isolated dorsal and ventral halves were swept through a smaller displacement than was the full fin. This was an experiment that would have been very difficult to conduct with real fish. A sunfish's fins could have been surgically altered, but the fish may not have swum using a normal steady swimming gait. The forces produced by the dorsal half of the fin were qualitatively similar to the forces produced when the entire fin was flapped (Fig. 6E). Thrust was produced during both the outstroke and the instroke, but in contrast to the full fin, in the majority of trials the magnitude of the thrust during the outstroke was greater than during the instroke. Despite the limited displacement of the fin, 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 from the dorsal half would have the tendency to drive the fish upward and forward during the outstroke, and downward and forward during the instroke. The ventral half of the fin created a small amount of drag and negative lift during the outstroke, and created 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 opposite to the forces created by the dorsal half of the fin. If operated alone, the ventral half of the fin would have the tendency to move the fish downward and slightly back during its outstroke followed by upward and forward during its instroke. This is exactly what was observed for the yaw-turn

maneuver, during which the ventral half of the fin led much of the movement.

#### Caudal fin kinematics

Although caudal fins have often been modeled simply as foils that oscillate back and forth, similar to the pectoral fin, the caudal fin exhibits a wide range of motions and these motions produce significantly different force profiles. In this work, a "gross change" to the kinematic pattern of the caudal fin may be considered the difference between the symmetric (e.g., flat) and the asymmetric motions (e.g., undulation), while a "subtle change" may be considered as the difference between the two symmetrical motions (flat and cupping) or an adjustment of the phase relations between fin rays during the undulation. Although each of the five kinematic patterns produced a unique force trace, the force profiles were similar among the three symmetrical motions (flat, cupping, and "w") and among the two asymmetrical motions (undulation and rolling). In general, the symmetric motions produced a peak of thrust as the fin passed the midline of the robot-fish's body (Fig. 5). The magnitude of the thrust dropped and became drag as the fin slowed at the end of the fin beat and changed direction. Lift forces were very small relative to the thrust, and, as expected, were on average, zero. The asymmetric motions produced a thrust profile that was similar to thrust for the symmetric motions, but in contrast to the symmetric motions, they also produced lift (Fig. 7). For example, when the undulation was led by the dorsal-most fin ray, peaks of lift were created that could be as strong as the thrust. The magnitude of the lift, relative to the thrust, could be adjusted by altering the phase difference between the fin rays, and the direction of the lift could be shifted to negative by leading with the ventral ray. The control of force by the caudal fin is believed to be very important since the fin is often far from the fish's center of rotation, and as a result the forces from the caudal fin are able to exert large moments and control the orientation of the fish body.

#### Fin-beat frequency and flow speed

Compared to other factors that affected force, the frequency at which the fin was flapped and the speed of the flow past the fin tended to affect the magnitude of the fin's force more than the direction of the force. As long as a fin was flapped sufficiently fast to cause an appropriate dynamic interaction with the fluid, forces tended to increase with increases in the frequency of flapping and



Fig. 7 Caudal fin forces. Lift and thrust from a caudal fin flapped at 1.5 Hz in a flow of 90 mm/s. Forces are shown for one cycle of the cupping profile (A and C) and for the undulation (B and C). Mean values for fins with different levels of stiffness are shown in (D). The magnitude changes with stiffness but the direction of the average force vector changes little.

with decreases in the speed of flow. The direction of the forces created during the fin beat remained similar, although the timing of the peaks in the force profile changed slightly with respect to the motion of the fin's base. The peaks occurred later in the fin's fin cycle when the frequency of the fin increased. This is consistent with the fin's surface bending more when the fin moved through the water faster.

An interesting phenomenon was observed in several of the datasets. At the highest frequencies of flapping, forces decreased. This is believed to have been caused by the flexible fins behaving like a well-damped, low pass system [1]. At low frequencies, the distal end of the fin moved through the full angular displacement actuated at the fin's base. However, at the highest flapping frequencies, the flexible distal end was not able to travel through the same displacement before being pulled in the opposite direction by the fin's base. This response was most evident in the caudal fin. Unfortunately, this behavior occurred at frequencies near the upper limit of the servomotors and so could not be evaluated thoroughly. Studies conducted with flapping ribbons (Lauder et al. 2007, Lauder GV et al.,

manuscript in preparation) support these findings, but also indicate that propulsive forces may increase and decrease cyclically as the frequency of flapping is increased.

#### Flexural rigidity of the fin ray

Perhaps the most interesting results detailed the importance of structural properties of the fin ray for creating the appropriate propulsive forces, and demonstrated that significant changes to both the magnitude and the direction of the force could be made by actively altering the stiffness of the fin rays. The relationship between fin force and flexural rigidity of the fin ray is discussed in detail for the pectoral fin by Tangorra et al. (2011).

Although the patterns traced by the force vector over the course of the fin beat looked similar as stiffness of the pectoral fin changed, the magnitude and direction of the forces changed. The average magnitude of the 2D force vector—thrust and lift combined (Fig. 6A and B) or thrust and lateral force combined—increased consistently with stiffness of the fin ray. This held in the vast majority of trials over the entire beat of the fin, and separately for the outstroke and the instroke. However, the increased magnitude did not result in all components of the force increasing proportionately, as the direction at which the fin acted upon the water sometimes changed considerably, particularly during the fin's outstroke. During both the steady-swimming and the modified-gait patterns, and over the instroke and the outstroke, lateral and lift forces tended to increase with stiffness. Thrust, though, did not change consistently during the outstroke, but tended to switch from being positive for the more compliant pectoral fins, to being negative for the stiffest fins. For example, in Fig. 6, thrust was positive throughout most of the outstroke for the  $600 \times$  fin and increased when the fin's stiffness was increased to 1000×. However, for the stiffest fin  $(2000 \times)$ , the thrust force was predominantly negative.

Similar to the pectoral fin, the patterns traced by the caudal fin's thrust-lift force vector during each of the gaits looked similar as stiffness was increased, and the average magnitude of the force increased consistently with the fin's stiffness (Fig. 7). In a manner that was dissimilar to the pectoral fin during its outstroke, there was little change in the direction of the 2D force vector as the caudal fin's stiffness was increased. For example, in Fig. 7, the average forces from the undulatory motion as stiffness increased were all angled at 21.8° with a standard deviation of only 1.4°. The average forces from the flat profiles as stiffness increased were directed at  $-0.4^{\circ}$  with a standard deviation of  $1.8^{\circ}$ . The lack of change in direction may be explained by the simplicity of the caudal fin's kinematics and its effect on force. Uniform scaling of the caudal fin's structural properties changes the shape along the span and across the chord similarly, and thus lift and thrust forces scale together. In contrast, the bending of the pectoral fin, particularly during the outstroke, is much more complex, and relatively small changes in how the fin bends backwards can easily shift the direction the fin adds momentum to the water and changes the thrust to drag.

# **Conclusions and comments**

The forces created by highly deformable, ray-finned fins are the result of a dynamic interaction between the fin and the water. The fin moves, pushes against the water, bends, stores and releases energy, and creates vortices and jets that are shed into the flow. Any factor that affects the motion and bending of the fin and how the fin adds energy to the flow affects the magnitude and/or the direction of the fin force. Results from experiments conducted using biorobotic models of the pectoral and caudal fins demonstrated that swimming forces can be modulated by altering gait patterns, and motions, speed of beating, and the mechanical properties of fin rays. As expected, switching the gait caused gross changes in the shape of the force trace, while subtle adjustments made to the trajectories of fin rays tended to move the force along a continuum. In some instances, though, subtle changes made to the trajectories of the fin rays altered the interaction of the fin and fluid enough that the fin no longer excited a dynamic required for a specific force. This occurred during the steady-swimming beat of the pectoral fin when the ability of the fin to produce thrust during the outstroke was very sensitive to the bending, and thus the loading of the fin rays. In general, the speed of flapping of the fin and the speed of the flow past the fin altered the magnitude of the fin's force, but did not alter the direction much. Finally, and perhaps most importantly, the flexural rigidity of the fin rays, and therefore the stiffness of the fin, significantly affected both the magnitude and the direction of the fin's forces. Altering stiffness may provide a quick way for the fish to alter the forces within a fin beat. This would allow, for example, the fish to quickly redirect forces in response to perturbations in the flow, or to control its body, without altering the basic gait pattern. Adjustments made to stiffness may also provide a way for the fish to tune the fin so that it is most effective as swimming speed changes. The effect that modulation of stiffness has on the direction of the force is enhanced when the shape of the fin and its interaction with flow is complex. In these cases a change to stiffness can dramatically alter the resultant shape of the fin.

Some final comments address the development and use of robotic models for biological studies. First, a great benefit of biorobotic models is that they enable controlled experiments to be performed that may be difficult to conduct with biological systems. When operating well, biorobotic models vary little from experiment to experiment and can be made to execute the same prescribed motions even when physically altered. It is very powerful, experimentally, to be able to evaluate how changes to single and specific combinations of experimental variables affect performance while holding other variables constant. This allows, for example, fins from different species of fish, or changes to the structural properties of a fin, to be tested using the same kinematic pattern. In contrast, it can be very difficult to convince a fish to swim using its normal gait if its fins have been surgically altered or if fluidic conditions are changed. Also, in support of the experiments, biorobotic models can be instrumented with

sensors (e.g., force transducers) that may not be tolerated well by the biological system.

Second, a distinct advantage of mechanical models (robots) over numerical models (computer simulations) is that the real environment does not have to be simulated (Walker 2002). Interactions which are extremely difficult to simulate, such as the dynamic interaction between a flexible structure and a fluid, are automatically and correctly in place. Experiments conducted with physical models, therefore, are influenced by the same phenomena that biological systems experience, but that numerical simulations are unaware of or are unable to capture.

Third, it is important for the characteristics of the robotic system to be derived from, and validated against, the biological system. If we are to extract meaning about the biological system from experiments using a robot, there must be a clear and direct link between the robotic and biological systems. This link exists best when the robotic system is developed by biologists and engineers together so that the mechanical system models more than superficial characteristics of the biological system.

Last, results from experiments conducted using biorobotic models can provide great insight into a biological system, but we must be careful when interpreting results to explain biology. Biorobotic models are approximations of very complex living systems. Although engineers are often very confident in the accuracy of our models, differences between the model and the living systems necessarily exist. These differences affect how precisely the experimental outcomes represent outcomes that would have occurred with the biological system, so they must be understood. Therefore, just as with the development of the model, the execution of experiments and the analysis of data should be conducted as a joint effort between engineers and biologists so that limitations of the model and their effects on the experiment are incorporated into the interpretation of results.

### Funding

This work was supported by the Office of Naval Research (N00014-09-1-0352) and the National Science Foundation (EFRI-0938043).

#### References

Bozkurttas M, Mittal R, Dong H, Lauder GV, Madden P. 2009. Low-dimensional models and performance scaling of a highly deformable fish pectoral fin. J Fluid Mech 631:311–42.

- Dong H, Bozkurttas M, Mittal R, Madden P, Lauder GV. 2010. Computational modeling and analysis of the hydrodynamics of a highly deformable fish pectoral fin. J Fluid Mech 645:345–73.
- Dong H, Mittal R, Najjar F. 2006. Wake topology and hydrodynamic performance of low aspect-ratio flapping foils. J Fluid Mech 566:309–43.
- Drucker EG, Jensen J. 1996. Pectoral fin locomotion in the striped surfperch. I. Kinematic effects of swimming speed and body size. J Exp Biol 199:2235–42.
- Gottlieb J, Tangorra J, Esposito C, Lauder GV. 2010. A biologically derived pectoral fin for yaw turn manoeuvres. Applied Bionics and Biomechanics 7:41–55.
- Isogai K, Shinmoto Y, Watanabe Y. 1999. Effects of dynamic stall on propulsive efficiency and thrust of flapping foil. AIAA J 37:1145–51.
- Lauder G. 2006. Locomotion. In: Evans DH, Claiborne JB, editors. The physiology of fishes. 3rd Edition. Boca Raton: CRC Press. p. 3–46.
- Lauder GV, Anderson E, Tangorra J, Madden P. 2007. Fish biorobotics: kinematics and hydrodynamics of self-propulsion. J Exp Biol 210:2767–80.
- Lauder GV, Madden P. 2007. Fish locomotion: kinematics and hydrodynamics of flexible foil-like fins. Exp Fluids 43:641–53.
- Lauder GV, Madden PGA. 2008. Advances in comparative physiology from high-speed imaging of animal and fluid motion. Ann Rev Physiol 70:143–63.
- Lauder GV, Madden P, Mittal R, Dong H, Bozkurttas M. 2006. Locomotion with flexible propulsors I: experimental analysis of pectoral fin swimming in sunfish. Bioinsp Biomimet 1:S25–34.
- Lewin GC, Haj-Hariri H. 2003. Modeling thrust generation of a low dimensional heaving airfoil in a viscous flow. J Fluid Mech 492:339–62.
- Mittal R. 2004. Computational modeling in biohydrodynamics: trends, challenges and recent advances. IEEE J Oceanic Eng 29:595–604.
- Mittal R, Dong H, Bozkurttas M, Lauder GV, Madden P. 2006. Locomotion with flexible propulsors: II. Computational modeling of pectoral fin swimming in sunfish. Bioinspir Biomim 1:S35–41.
- Phelan C, MacDonald R, Tangorra J. 2009. Artificial muscle actuators in biorobotic fish fins. IEEE Engineering in Medicine and Biology. Minneapolis, MN.
- Phelan C, Tangorra J, Lauder GV, Hale M. 2010. A biorobotic model of the sunfish pectoral fin for investigations of fin sensorimotor control. Bioinspir Biomim published online (doi:10.1088/1748-3182/5/3/035003).
- Standen EM, Lauder GV. 2005. Dorsal and anal fin function in bluegill sunfish (Lepomis macrochirus): threedimensional kinematics during propulsion and maneuvering. J Exp Biol 205:2753–63.
- Tangorra J, Anquetil P, Fofonoff T, Chen A, Del Zio M, Hunter I. 2007a. The application of conducting polymers to a biorobotic fin propulsor. Bioinspir Biomim 2:6.

- Tangorra J, Davidson SN, Hunter I, Madden P, Lauder GV, Dong H, Bozkurttas M, Mittal R. 2007b. The development of a biologically inspired propulsor for unmanned underwater vehicles. IEEE J Ocean Eng 32:533–50.
- Tangorra J, Lauder GV, Hunter I, Mittal R, Madden P, Bozkurttas M. 2011. The effect of fin ray flexural rigidity on the propulsive forces generated by a biorbotic fish pectoral fin. J Exp Biol 213:4043–54.
- Triantafyllou MS, Techet AH, Hover FS. 2004. Review of experimental work in biomimetic foils. IEEE J Ocean Eng 29:585–94.
- Ulrich K, Eppinger S. 2003. Product design and development. New York: McGraw-Hill.

- Walker JA. 2002. Functional morphology and virtual models: physical constraints on the design of oscillating wings, fins, legs, and feet at intermediate Reynolds numbers. Integ and Comp Biol 42:232–42.
- Walker JA, Westneat M. 2002. Performance limits of labriform propulsion and correlates with fin shape and motion. J Exp Biol 205:177–87.
- Webb PW, Laliberte GD, Schrank AJ. 1996. Maneuverability of three species of teleostean fishes with different body and fin plans. Env Biol Fish. 46:7–14.
- Webb PW, Weihs D. 1994. Hydrostatic stability of fish with swim bladders: not all fish are unstable. Can J Zool 72:1149–54.