

# Diversity, mechanics and performance of natural aquatic propulsors

F.E. Fish

*Department of Biology, West Chester University, West Chester, PA, USA.*

## Abstract

Both animals and engineered vehicles must contend with the same physical forces that dictate their performance during movement in water. Due to evolution, animals display a wide diversity of propulsive systems associated with swimming modes, body morphologies, and performance levels. Biologists have classified propulsive modes according to the animals' anatomy (e.g. axial, appendicular), kinematics (e.g. anguilliform, carangiform, thunniform), and propulsive forces (e.g. drag-based, lift-based, acceleration reaction). The various swimming modes are associated with different indices of performance (i.e. speed, acceleration, maneuverability) that are dependent on the ecology of the animal. High speed and high efficiency are associated with lift-based propulsion produced by oscillation of rigid, high-aspect ratio hydrofoils (i.e. thunniform mode). However, the propulsive systems and body morphology associated with high levels of acceleration and maneuverability diverge from systems designed for speed and efficiency. Drag-based systems, such as paddling, are relatively inefficient and used at low speeds but allow for precise maneuverability and generalized use of the propulsive appendages. In instances where energy economy is important, animals display behavioral mechanisms to extend range, increase swimming speed, and reduce energy costs. These behaviors include swimming in discrete formations (e.g. schooling, drafting), aerial leaps (e.g. porpoising), intermittent swimming (e.g. burst-and-coast), free-riding (e.g. wave and bow riding, hitchhiking), hydroplaning, and vorticity control. The evolution of aquatic animals has produced a great diversity of morphological designs and propulsive modes that can be exploited for biomimetic engineered systems. However, evolution is not a conscious process and is dictated by variation in the genetic code and multi-functional roles of animals in response to local environments. Strict application of biological systems into engineered systems without defining mission requirements may not produce optimal solution.

## 1 Introduction

Motion through the aquatic medium requires the development of thrust from the acceleration of fluid into a wake to counter the resistive drag and added mass force. To generate thrust and



effectively move in water, aquatic animals have evolved a diversity of propulsive mechanisms correlated with their biological role, evolutionary history, and association with the aquatic environment. For over 500 million years, fish and other animals have been able to function and adapt to a fluid environment that is 800 times denser and 60 times more viscous than air. Because of their swimming capabilities, aquatic animals have recently gained wide attention as models for underwater vehicles [1]. The mechanism of propulsion used by animals is considered a viable alternative to traditional marine propulsors. Indeed, aquatic animals are considered to be superior in their propulsive abilities compared to technologies developed from marine engineering [2, 3].

Machines that are required to work in the aquatic realm encompass the same physical forces as that of aquatic animals. Both natural and manufactured bodies are subjected to an environment where Archimedes Principle dominates and drag is a major hindrance to movement. The technology associated with the development of robots is becoming more dependent on biomimetics and biologically inspired designs. Copying nature by the biomimetic approach seeks common solutions from engineering and biology for increased efficiency and specialization [4]. A goal of this approach is to engineer machines capable of emulating outstanding animal performance based on novel structures [5]. Animals have inspired various technological developments including flight and robotics [2, 6–8]. As engineers move from the world of large, stiff, right-angled pieces of metal to one of small, compliant, curved-surface pieces of heterogeneous parts, nature will become a more influential teacher.

The propulsive systems of animals hold promise for improved performance related to efficiency, wakelessness, and stealth [9, 10]. Enhanced propulsion with respect to these areas may be possible by biomimetic mechanisms involved with oscillating propellers, flexible wings, boundary layer stabilization, laminar flow maintenance, and active vortex control. In addition, natural propulsive systems can be self-stabilizing and self-correcting. The potential benefits from biological innovations applied to manufactured systems operating in water are high speeds, reduced detection, energy economy, and enhanced maneuverability. New insights into aquatic propulsion by animals will permit the collection of information that can be exploited for the development of advanced technologies. These insights include an interpretation of the unsteady nature of animal movement, measurement of movement in two and three dimensions, the use of computational methods that model both the animal's movement and its effect on the fluid surrounding it, physiological and biomechanical studies of locomotor tissues in relation to thrust production and energy recycling and analysis of the use of appendages in thrust production, trajectory control and stability [11].

This report will focus on thrust and efficiency performance displayed by the various propulsive mechanisms exhibited by swimming animals. A survey of the biomechanical and hydrodynamic mechanisms of biological propulsive systems will permit identification of innovative mechanisms that may be transitioned to manufactured designs. In this regard, the examination of animal propulsive systems will be confined to high Reynolds number, inertial-based swimming. This mitigates scaling problems inherent in application of small, viscous-dominated systems to large-scale systems associated with current technologies and tasks. In addition, the methods and limitations of a biomimetic approach will be discussed.

## 2 Propulsive systems in aquatic animals

The aquatic propulsive modes of animals have been categorized by anatomy, kinematics and propulsive force. In all cases, the groupings merely reflect the predominant swimming mode used by an animal. For example, a sunfish can swim by paddling the pectoral fins at low speeds and when slowly turning, but will switch to body and caudal fin undulation at high and burst speeds.



Indeed, many organisms switch swimming mode or gait by using different combinations of propulsive appendages [12]. These gait changes are correlated with changes in speed, maneuverability, or position in the water column (i.e. surface, submerged).

## 2.1 Anatomical-based swimming modes

In the anatomical system, propulsive systems are divided into groups based on the body part that is affecting the swimming motion. Anatomically, the body extends posteriorly from the head to the trunk and tail. Depending on the animal group, various combinations of paired and unpaired appendages extend from the body. For fish, unpaired appendages are represented by dorsal, anal, and caudal fins, although the caudal fin is considered an extension of the tail. The paired appendages are composed of the pectoral appendages and pelvic appendages. Divisions of an anatomical propulsive system are:

*Axial locomotion:* body and tail used by lateral or dorsoventral deflection of the body axis.

The body and tail pass a wave posteriorly or the caudal region can be simply oscillated (e.g. leech, eel, shark, tuna, alligator, ichthyosaur, dolphin).

*Median fin propulsion:* dorsal and/or anal fins undulated or oscillated (e.g. electric eel, seahorse, triggerfish).

*Paraxial locomotion:* paired appendages used in combinations of pectoral, pelvic, and both.

The appendages are shaped as paddles (e.g. duck, beaver) or as high aspect ratio hydrofoils (e.g. pteropod, eurypterid, plesiosaur, penguin, sea lion, seal).

*Jetting:* uses a large internal chamber from which water is expelled through a restricted orifice (e.g. squid, frogfish).

## 2.2 Kinematics-based swimming modes

The kinematics associated with swimming fall into three broad categories, including undulatory, oscillatory, and jetting. In undulatory swimming, the body or appendage is thrown into a wave that travels through the body structure. The wave can be propagated with varying frequency and amplitude. Undulatory propulsors are characteristic of long-bodied animals. In fish, the eel (*Anguilla*) represents one extreme of undulatory axial swimmers with its flexible body (Anguilliform). The boxfish (*Ostracion*) represents the opposite extreme for axial undulators (Ostraciiform). The body of the boxfish is constrained by its dermal armor so that only the tail can undulate. Between these extremes is a continuum of animals in which the propulsive wave is produced over different lengths of the body (subcarangiform, carangiform, thunniform). Both paired and unpaired fins can be undulated with frequency and amplitude varying depending on the morphology (amiiform, gymnotiform, balistiform, rajiform, diodontiform, tetradontiform, labriform).

In oscillatory swimming, usually paired appendages are beat backward and forward, and/or up and down and function like a paddle or hydrofoil [13–16]. The appendages can be oriented below the body for paddling (e.g. muskrat) or oriented lateral to the body for rowing (e.g. platypus). The oscillatory motion of hydrofoils is wing-like, producing thrust in a similar manner (e.g. *Mola*, sea lion). The caudal hydrofoil of tuna, lamnid sharks, ichthyosaurs, and cetaceans has been considered to move in an oscillatory manner, although the movement of the propulsor continues to reflect a basic undulatory motion [15]. This motion has been classified as thunniform or carangiform with semilunate tail [17].



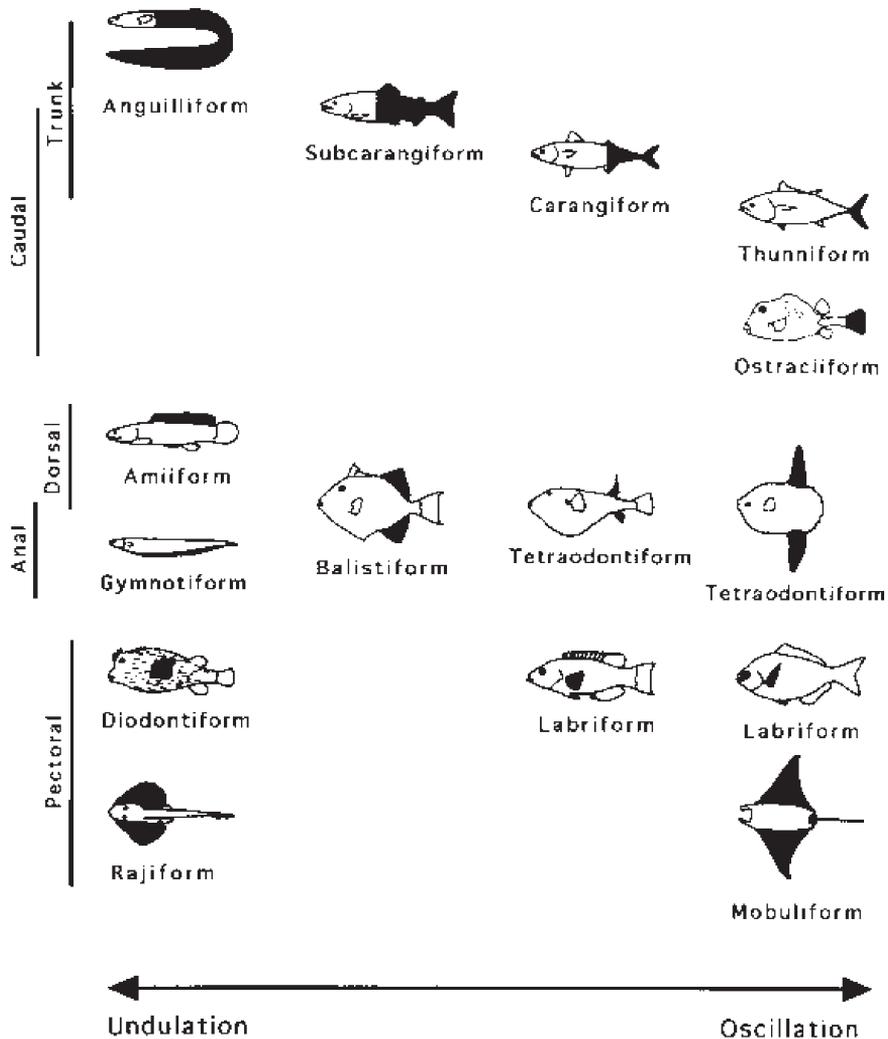


Figure 1: Swimming modes used by fish along a undulation–oscillation continuum. Black areas indicate surface used for propulsion. Vertical lines show overlapping propulsive surfaces between swimming modes.

Based on the descriptions of Breder [18], Webb [13, 19], Lindsey [20], and Webb and Blake [15], classification of propulsion based on kinematics of fish, Fig. 1, is as follows:

**Axial undulation**

*Anguilliform mode:* whole body thrown into a wave with at least one half wavelength within the body and more than one complete wavelength. Amplitude large over whole body length. Body typically thin and long (e.g. eel).

*Subcarangiform mode:* body and caudal fin thrown into a wave, with more than one half-wavelength within the length of the body. Amplitude rapidly increases over the posterior half of the body. Body shape fusiform with deep caudal peduncle (e.g. shark, trout).



*Carangiform mode*: body and caudal fin usually thrown into wave, with up to one half-wavelength within length of body. Amplitude increasing over posterior third of body. Body shape fusiform with narrow peduncle (e.g. mackerel).

*Thunniform mode*: body movements carangiform with flexion at base of caudal propulsor. Amplitude increasing over caudal peduncle. High aspect ratio and relatively stiff caudal hydrofoil. Body shape fusiform with narrow caudal peduncle (e.g. tuna, dolphin).

*Ostraciiform mode*: body rigid and not thrown into wave. Propulsion by caudal fin oscillation. Body shape not streamlined (e.g. boxfish, cowfish).

*Escosiform mode*: used for rapid acceleration and bursts. Posterior body and caudal fin flexed. Body is elongate with median fins located in posterior portion of fish (e.g. pike).

#### Appendicular undulation

*Amiiform mode*: extended dorsal fin thrown into waves. Body remains rigid (e.g. bowfin).

*Gymnotiform mode*: extended ventral (anal) fin thrown into wave. Body remains rigid (e.g. electric eel).

*Balistiform mode*: extended dorsal and ventral fins thrown into waves. Body remains rigid (e.g. triggerfish).

*Rajiform mode*: extended pectoral fins thrown into waves. Body remains rigid (e.g. skate, ray).

*Diodontiform mode*: use short pectoral fins with short wavelength movements. Body remains rigid (e.g. porcupine fish).

#### Appendicular oscillatory

*Tetradontiform mode*: short dorsal and ventral fins used. Body remains rigid (e.g. puffer fish).

*Molariform mode*: extended dorsal and ventral fins oscillated. Body remains rigid (e.g. ocean sunfish).

*Labriform mode*: use pectoral fins with long wavelength movements in the horizontal plane so fins behave as paddles. Body remains rigid (e.g. sunfish).

*Embiotociform mode*: use pectoral fins with long wavelength movements in vertical plane so fins behave as oscillating wings. Body remains rigid (e.g. surfperch).

*Mobuliform mode*: extended pectoral fins move in vertical plane so fins behave as oscillating wing. Body remains rigid (e.g. manta ray).

*Jetting*: water is expelled out of constricted opercular opening. Body remains rigid (e.g. squid, frogfish).

While these modes have been applied generally to describe the swimming of axial swimmers, such as urodele amphibians, snakes, ichthyosaurs, crocodylians, and cetaceans, the descriptions of tetradontiform, embiotociform, mobuliform, and labriform for fish swimming have not been applied to oscillation of the appendages for other vertebrates and invertebrates. Indeed, non-piscine representatives of these modes would be platypus (labriform), and sea lion and penguin (Embiotociform). However, animals that paddle using all four limbs (e.g. mink) or just the hind limbs (e.g. muskrat) and row with all four limbs (e.g. turtles) would not be included in the classification based on fish swimming modes. Braun and Reif [14] categorized swimming in all vertebrates by more finely dividing the classification scheme, but still relied upon the basic swimming modes used for fish.



### 2.3 Force-based swimming modes

Swimming modes can more simply be classified without regard to taxonomic relationships by analysis of the forces used to generate thrust. For animals, the pertinent forces are pressure drag, acceleration reaction, and lift [15, 21, 22].

Pressure drag is a resultant of the asymmetry of the fore and aft flow around an appendage. This asymmetry creates a pressure difference which is the basis of the drag and can be used for propulsion. Drag-based propulsion is associated with paddling and rowing where the limbs are oriented either in the vertical parasagittal plane or horizontal plane, respectively. Paired appendages are oscillated either alternately or simultaneously. The stroke cycle is divided into power and recovery phases [23, 24]. During the power phase, the posterior sweep of the appendage generates drag which is used to provide an anterior thrust to the animal. The appendage is shaped as a paddle with area increasing through the distal tip [25]. The recovery phase repositions the appendage. To prevent an increased pressure drag on the appendage that will negate the thrust generated, the appendage is collapsed or feathered. Examples of drag-based swimmers include labriform fish, frogs, turtles, ducks, and semi-aquatic mammals.

In lift-based propulsion, a relatively stiff hydrofoil is oscillated at a controlled angle of attack [17, 26–29]. The angle of attack is generally a small angle corresponding to the deflection of the hydrofoil from the flow. Lift arises from asymmetries in the flow. The asymmetry generates a pressure difference between the sides of the hydrofoil with a net force normal to the incident flow. Due to both heaving and pitching of the hydrofoil, lift is directed perpendicular to the pathway traversed by the hydrofoil and can be resolved into an anteriorly directed thrust [30, 31]. Thrust is generated continuously throughout a stroke cycle. Although some resistive drag is produced by the hydrofoil, it is small compared to the lift. The high lift-to-drag ratio is a function of the high aspect ratio of the hydrofoil [13, 27, 28, 32]. Lift-based swimmers include thunniform, embiotociform, molariform, mobuliform fish, ichthyosaurs, plesiosaurs, sea turtles, penguins, cetaceans, dugongs, sea lions, and phocid seals.

Drag-based and lift-based propulsion differs in performance (Figs 2 and 3). Drag-based propulsive systems are limited by swimming speed and operate most effectively at low speeds; however, lift-based hydrofoils perform best at higher speeds. A flow field needs to be established only in case of stationary lifting surfaces (fixed airfoils) to function. Drag-based paddles can be used when the incident fluid velocity is zero, such as when a body is stationary. Lift-based unsteady propulsion is employed by animals when starting from rest (zero free-stream velocity). A paddle of large area can impart sufficient momentum to a mass of water to induce a recoil to the stationary body effecting motion. Because the thrust production by a paddle is dependent on its movement in the direction opposite the body movement, thrust decreases as the velocity of the body increases. At a speed where the body and paddle speeds are equivalent, thrust can no longer be produced [33].

Acceleration reaction results from changes in the kinetic energy of water accelerated by action of the propulsive body structure [21, 34]. The acceleration reaction is dependent on an additional inertial mass, the added mass that, when added to the inertia of the body accelerating in the water, balances the momentum changes [34, 35]. The acceleration reaction differs from drag in that (1) the acceleration reaction is directly proportional to the mass of an object while drag is proportional to the surface or cross-sectional area, and (2) the acceleration reaction depends on changes in velocity of an object, resisting both acceleration and deceleration, while drag depends on the instantaneous velocity of the object, resisting acceleration but augmenting deceleration [34]. Some resistive drag accompanies this mode of swimming due to viscous effects. Animals which swim by undulation of the body (anguilliform to carangiform fish, sea snakes) or appendages (ostraciiform, gymnotiform, balistiform, rajiform, and diodontiform fish) use the acceleration reaction for swimming



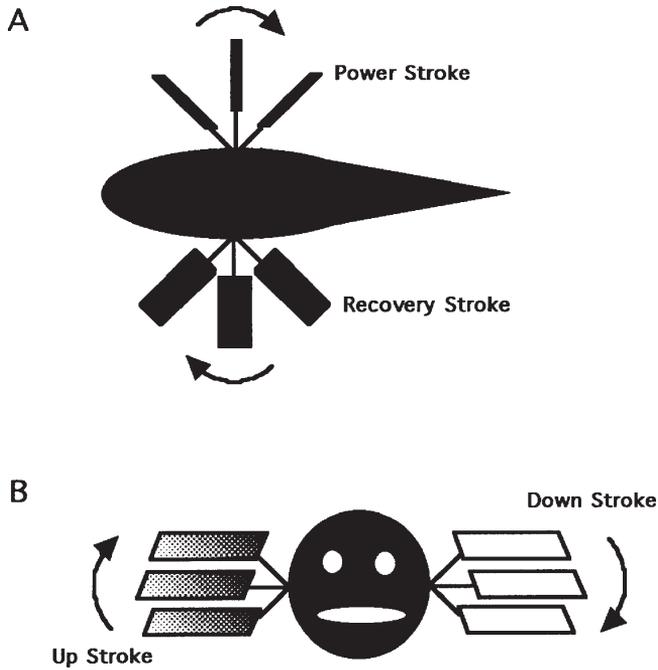


Figure 2: Simplified motion of drag-based paddle (A) and lift-based hydrofoil (B). The paddling motions are shown from top view, the movements of the hydrofoil are shown from a front view. Redrawn from [33].

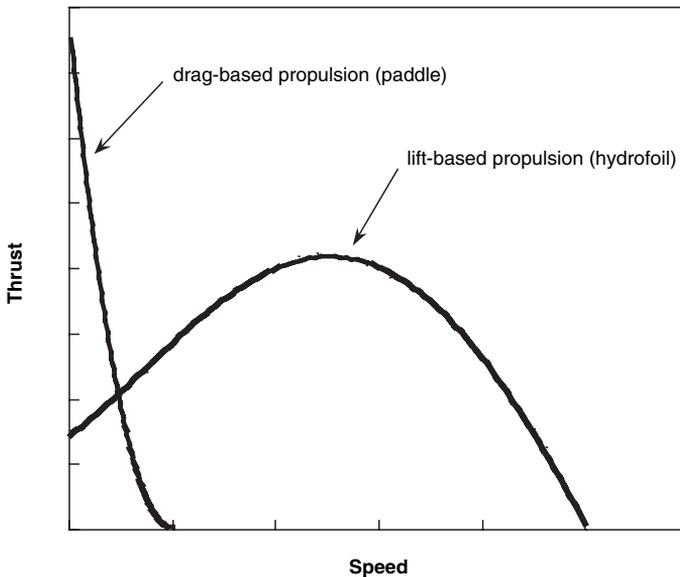


Figure 3: Comparison of lift-based and drag-based thrust production in relation to swimming speed. Redrawn from [33].

[13, 21, 35, 36]. Flattening of the undulatory surface enhances the magnitude of inertial effects [17, 37, 38]. Because undulations can be continuously generated by the swimmer, thrust production is constant.

Use of the acceleration reaction is constrained by size [21]. As animals get larger, the ability of the muscle to generate force relative to inertial forces decreases [35, 39]. Large animals, which lack the ability for high accelerations, use lift-based propulsion as employed in the thunniform mode [21].

Acceleration reaction is used also for jet propulsion [34]. Thrust results from the forceful expulsion of a mass of water from some internal cavity.

### 3 Energetics and efficiency

#### 3.1 Propulsive efficiency

The propulsive efficiency ( $\eta_p$ ) is computed as the ratio of the thrust power to the total mechanical power output and is also known as the mechanical efficiency, propeller efficiency, and Froude efficiency. The propulsive efficiency is dependent on the swimming mode, speed, design of the propulsive structure, and the degree of aquatic specialization [16, 30, 31].

Drag-based oscillation (paddling, rowing, labriform mode) has a low propulsive efficiency of  $\leq 0.33$ , based on blade-element models for rotating propulsors [23, 24, 40]. This low efficiency occurs because thrust is generated through only half of the stroke cycle [24]. Energy is lost to increased resistive drag as the paddle is repositioned during the recovery phase. In addition, approximately 40–50% of the total energy expended throughout the stroke is lost in acceleration of the mass of the limb and the water entrained to the foot [31]. Blake [23, 41] found that the efficiency of the power stroke of the pectoral fin of an angelfish was 0.26, but was reduced to 0.16 when energy losses due to added mass of entrained fluid and increased drag on the fin during the recovery stroke were considered. Propulsive efficiency for the drag-based oscillation is higher at low speeds; whereas the other propulsive modes have maximum efficiency at high speeds [33, 42, 43].

Reliance on swimming by body and tail propulsion for the diverse assemblage of vertebrate animals occurs because it is highly efficient [44]. Animals, which swim solely by body and tail undulation (anguilliform to carangiform), exhibit a mechanical efficiency of 0.45–0.85 from a bulk momentum model from elongate body theory [33, 45–49]. Efficiency is dependent on the ratio of the swimming speed to the backward speed of the travelling wave in the body. The Froude efficiency of carangiform fish is greater than 0.7 when the ratio of swim speed to wave speed was between 0.54 and 0.86 [49].

Using a three-dimensional computational fluid dynamic model, Liu *et al.* [50] found the Froude efficiency of frog tadpoles (anguilliform mode) to be 0.45. This low efficiency may be explained by the increased drag due to the globose body shape, increased swimming cost due to large inertial recoil motions, and a tail which tapers at the tip [51, 52]. Webb [45] measured the propeller efficiency for rainbow trout (subcarangiform mode) of over 0.7 near the maximum cruising speed. At lower speeds the efficiency decreases.

The hydrodynamic interactions between discontinuous median fins and the caudal fin could help to enhance efficiency [37, 53]. While swimming, a vortex sheet is shed by any sharp body edge, such as a fin. The vortex sheet travels downstream following a wavelike path which is determined by both the incoming velocity and by the kinematics of the motion of the trailing edge of the fin that produced the sheet. The vortex sheet carries momentum as determined from the



fin motions and dimensions. The momentum will contribute to the mean thrust and power [54, 55]. When there is a downstream fin, the vortex sheet will impinge on the leading edge of that fin. If the gap between the fins is small, there is no significant contribution of the vortex sheet to the thrust generated by the downstream fin. However if the gap is large, a large phase difference between the fins will have the momentum from the vortex sheet interact with the downstream fin [37]. This action may occur as vorticity shed from a fish's dorsal fin interacts with the caudal fin. The work performed by the anterior fin against the momentum shed from its trailing edge with the increased incident velocity of the downstream fin increases the total power output and efficiency [37]. Blake [56] considered that resorption of the vortex sheet occurs at the leading edge of the caudal fin.

Undulatory swimming using the dorsal fin in the amiiform mode shows similarities in efficiencies with body and tail undulatory swimming. The electric fish (*Gymnarchus niloticus*) was calculated to have a propulsive efficiency of 0.50–0.71 which increased with swimming speed [57]. The electric fish sweeps out a large area at the leading edge of its dorsal fin and propagates the waveform at a low frequency. The seahorse (*Hippocampus hudsonius*) has a relatively short dorsal fin which undulates at a high frequency. The propulsive efficiency of the seahorse was low ranging from 0.23 to 0.40 [57]. This may not be a disadvantage for the fish as these swimmers are highly maneuverable, although swimming at low speeds. Blake [56], pointed out that electric eels and knifefish (gymnotiform mode) have efficiencies that are high (0.6–0.9) compared to subcarangiform swimmers at low absolute speeds [56, 58].

High efficiency for high-speed swimming is accomplished with lift-based thrust production in the thunniform mode [13, 16, 17, 27, 28]. Lift-based oscillation is associated with the radiation into pelagic habitats where steady swimming is required [59]. Because of the high lift-to-drag ratio of the propulsors and nearly continuous production of thrust, this mode is characterized by high propulsive efficiencies. Wu [60] estimated that the propulsive efficiency of a dolphin could be as high as 0.99. This efficiency was assumed to be an over-estimate because Wu used a two-dimensional analysis that underestimated trailing vorticity and wake energy loss [61, 62]. Competing three-dimensional models of lunate tail swimming predict different levels for efficiency. The quasi-vortex-lattice method used by Liu and Bose [63] produced higher values of propulsive efficiency compared to values generated from the unsteady lifting theory model of Lighthill [37] and Chopra and Kambe [64] for some of the same species [13, 27, 29, 65]. The inviscid nature of different models means that the peak values of propulsive efficiency will be reduced in practice by frictional forces [63]. For tunas, dolphins and phocid seals, which all swim in the thunniform mode, propulsive efficiency appears to range between 0.70 and 0.92. Experiments on an oscillating foil (NACA 0012) were able to produce a maximum efficiency of 0.87 [66].

Efficiencies on thunniform swimmers may be higher than predicted by all the models, because the models assume that the hydrofoil is a rigid plate. Dolphin flukes exhibit both spanwise and chordwise flexibility [67, 68]. Katz and Weihs [69] found chordwise flexibility of a foil to increase propulsive efficiency by 20% with only a slight decrease in thrust compared to a rigid foil. Furthermore, the high efficiencies associated with thunniform swimmers are dependent on propulsor design. The aspect ratio is the most important morphological parameter for enhanced efficiency [13, 63–65, 70]. Thunniform swimmers have high-aspect ratio propulsors (i.e. caudal fin, flukes) [17, 71]. A high aspect ratio along with tapering tips of the propulsor limits the energy loss from vorticity shed at the tips and the induced drag from lift generation. Induced drag also is limited by the sweep of the propulsor. van Dam [72] showed that a tapered wing with a sweptback or crescent design could reduce the induced drag by 8.8% compared to a wing with an elliptical planform. Minimal induced drag is fostered by a swept wing planform with a root chord greater than the chord at the tips giving a triangular shape [73, 74]. Sweep of the propulsor together with taper has



the effect of concentrating the surface area toward the trailing edge. This would effectively shift the lift distribution posterior of the center of gravity affecting pitching equilibrium [13]. Lighthill [37] and Wu [54] suggested that a minimum in wasted energy would be realized when the pitching axis was moved to the 0.75 chord position.

Lift-based oscillatory swimming using the paired appendages demonstrates lower propulsive efficiencies than for caudal oscillatory swimming (thunniform mode). Webb [75] investigated the swimming energetics of the surfperch (*Cymatogaster aggregata*) which uses the embiotociform mode. This lift-based pectoral fin system was calculated to have a propulsive efficiency of 0.60–0.65. The sea lion (*Zalophus*) produces a maximum efficiency of 0.8 by oscillations of its foreflippers [32]. However, similar swimming movements by penguins were found to have a maximum efficiency of between 0.3 and 0.35 at 1.39 m/s [76]. This efficiency may have been low in that it was well below the maximum speed of 4.5 m/s for the penguin [77] and test conditions restricted the penguin to the water surface [76, 78].

Jet propulsion is not considered to be efficient compared to the undulatory movements of fins or use of paddles due to the high acceleration of a relatively small mass of fluid to effect propulsion [33]. Weihs [79] considered that pulsed jets could improve the efficiency of jet propulsion. The Froude efficiency of various cephalopods ranges from 0.15 for *Nautilus pompilius* to 0.42 for the squid (*Illex illecebrosus*) [80].

## 4 Energy conservation and flow

### 4.1 Schooling

Energy economy for swimming by fish has been suggested as a possible advantage to schooling. Increased energy savings would be advantageous by permitting faster swimming speeds during foraging and increasing range particularly for migration. The pattern of the school is hypothesized to be dependent on the undulatory movements of the fish, which produce a series of counter-rotating vortices in its wake as a thrust-type vortex street (reverse Kármán vortex street) [81, 82].

The vorticity in thrust production is necessary to transport momentum from the propulsor into the fluid. Each vortex is formed from the reversal in direction of the propulsor, requiring a reversal in circulation of the bound vortex. At the end of each half-stroke, the bound vortex is shed from the propulsor and as the propulsor is reaccelerated in the opposite direction a new bound vortex is formed with a reversed circulation [33]. The shed vortex is known as the ‘stopping vortex.’ The oscillating motion of the propulsor thus produces two parallel trails of staggered vortices perpendicular to the plane of oscillation and with opposite circulations. The direction of the circulation is oriented so that the tangential velocity is parallel to the trails and directed posteriorly between the trails and anteriorly on the outside of the trails.

The thrust-type vortex street is a two-dimensional representation of the flow field shed from an oscillating propulsor. In three dimensions, the stopping vortices are actually connected by tip vortices, forming a folded chain of vortex rings [33]. Such a flow field is essential to the generation of thrust in swimming fish. Although the vorticity convected into the wake represents an energy loss, the vortex street has possibilities for reduction in energy costs by schooling fish [82]. The thrust-type vortex system reduces the drag on individuals positioned parallel and lateral to the street. Thus, a low relative velocity and high energetic advantage is achieved by a fish swimming diagonally behind another. Due to the rotation of the vortices, a fish following directly behind another will experience a higher relative velocity and would have to expend a greater amount of energy [82].



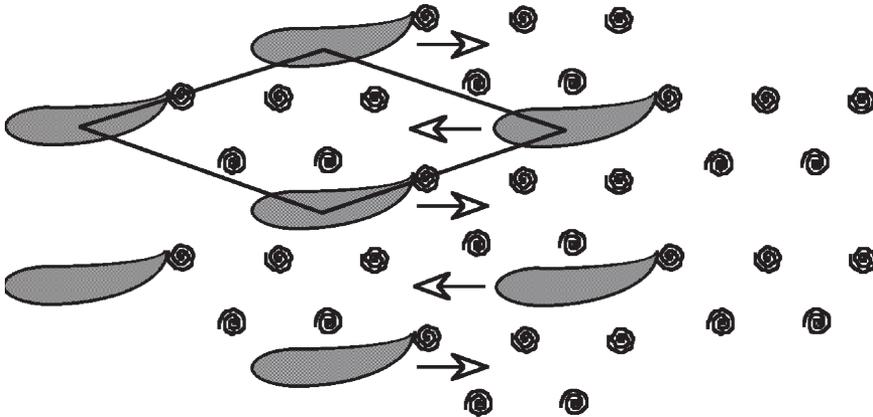


Figure 4: Optimal arrangement for maximum energy savings of a fish school swimming in a horizontal layer. Vortex patterns in the wake of the fish are illustrated. Arrows show direction of induced flow relative to vortices. The diamond configuration of fish is shown by the solid lines. From Weihs [82] and Fish [83].

A three-dimensional, inviscid flow model by Weihs [82] determined the optimal configuration between fish in a school for energy conservation. The model considered the structure of an infinite array of identical fish swimming in an oncoming flow. The fish were organized in discrete layers and in evenly spaced rows so that fish in the trailing row were staggered and centered between two fish in the leading row. The stationary position of the fish in the flow is maintained by the oscillatory sideways propulsive motions of the fish from its body and caudal fin. The propulsive motions produce the vortex wake in which the rate of change of momentum in the water is equal and opposite to the thrust which opposes the total drag on the body (Fig. 4). Equality of thrust and drag is maintained as the fish swims at constant velocity.

Considering only one layer of a theoretical school consisting of an infinite three-dimensional array of similarly sized fish, the model predicted that the relative velocity directly behind a fish would be high, whereas the relative velocity would be lowest outside the vortex street [81, 82]. Because the vortex wake takes time to fully develop and then dissipate further downstream, the optimal configuration is a diamond or shallow rhombus pattern with a leading fish, two fish in the second row, and a fish in the third row (Fig. 4). The angles within the pattern are  $30^\circ$  and  $150^\circ$  [82].

The first row of fish swimming into undisturbed water will have the same relative and absolute velocities. Fish in the second row experience a relative velocity 40–50% of the free-stream velocity and a reduction of the force generated for swimming by a factor of 4–6 [82]. However, the decrease in relative velocity is not maintained with each successive row due to destructive interference. The vortex wakes of two successive rows will cancel because the vortices from each row are in line and have opposite vorticity when the lateral distances between adjacent fish is twice the width of the vortex street. The third row thus encounters undisturbed flow and incurs no reduction in relative velocity and drag. The reduced relative velocity occurs with alternate rows. Integrated over the entire formation, the school will have only a 50% savings in energy of the second row [82].

Individual fish in alternate rows not experiencing reduced drag from the interaction of the vortex wake of the previous row may still derive a benefit from effects due to lateral spacing. As spacing decreases there is a channeling effect (constriction of flow) so that the force produced by

a fish in a row may be twice that of a single fish [82]. The channeling effect is not added to the energy savings of the row encountering the effects of the vortex wake. The two effects may not be superimposed, because the trailing row has a reduced relative velocity which decreases lateral interactions.

## 4.2 Drafting

Energy saving by animals in linear formations parallel to the direction of movement uses the techniques of ‘drafting’ or ‘slipstreaming’. The vortex street shed behind a rigid body has a different pattern compared to the vortex street generated by an oscillating propulsor [33]. As a bluff (non-streamlined) body moves through a fluid, the flow about the body is non-steady. Flow separates alternately from each side of the body producing two staggered rows of vortices which are shed into the wake. Like the thrust-type vortex street, all the vortices in one row rotate in the same direction, but opposite to that of the other row. However the rotation of the vortices is opposite to the pattern found in the thrust-type vortex street. This flow pattern around a bluff body is a drag-type of vortex street and is known as the Kármán vortex street. The vortex pattern is stable for a long distance downstream if the distance between successive vortices on the same side is 3.56 times the distance between the two rows [33].

The generation of the Kármán vortex street has been suggested to reduce the cost of locomotion in bodies that move in single-file formations between the parallel vortex rows [83]. Race cars, cyclists, lobster queues, and swimming ducklings arranged in such formations can provide energy economy [83].

The occurrence of highly organized formations by cetaceans has been suggested as an adaptation for energy economy [84, 85]. Formation swimmers influence water flow around adjacent individuals resulting in decreased drag with a concomitant decrease in overall energy cost of locomotion [82]. Small whales often position themselves beside and slightly behind the maximum diameter of a larger animal [86]. While the larger whale will experience increased drag, the smaller whale gains an energetic benefit [84, 85]. This effect is beneficial particularly for young whales in order to maintain speed with their mothers [86]. A neonate can gain up to 90% of the thrust needed to move alongside the mother at swimming speeds up to 2.4 m/s.

A variant of drafting is the use by animals of the wake from obstructions in a flow stream [87, 88]. By swimming behind an object shedding a vortex wake an animal could extract energy from the flow. Osborne [89] proposed that salmon migrating upstream could take advantage of irregularities in the bottom contour to reduce energy costs. Cod and plaice are able to take advantage of substratum ripples to find areas of retarded flow to station-hold [90, 91]. Swimming against a flow near an interface with a solid body allows the animal to reduce its energy cost by decreasing its relative velocity [92]. The animal can swim in the boundary layer where the flow velocity is lower than the free-stream velocity of the flow.

## 4.3 Porpoising

Porpoising behavior is performed by penguins and the fastest mammalian swimmers [77, 93] and consists of rhythmic, serial-leaping [93]. At high speeds, the energy required to leap a given distance is considered less than the energy to swim an equivalent at the water surface. Au and Weihs [94] and Blake [95] proposed models which showed that the energy to swim a given distance increases with swimming speed faster than the energy to leap that distance. Therefore, above a critical swimming speed,  $U_c$ , where the energies converge, there is an energetic advantage to swimming by porpoising (Fig. 5).



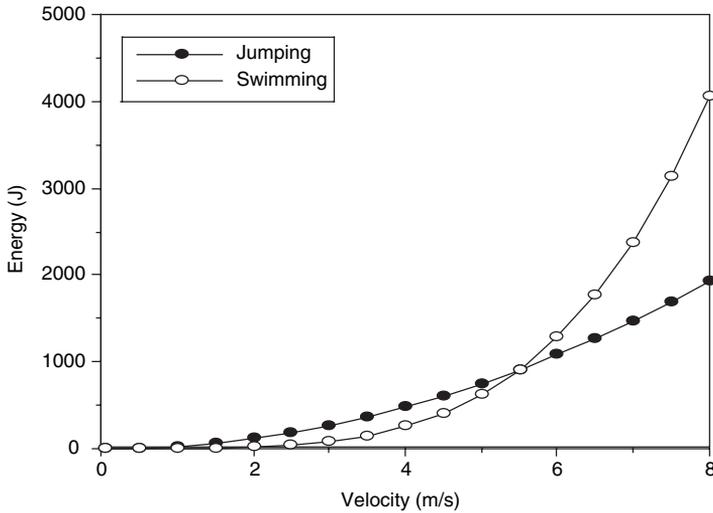


Figure 5: The energies required for swimming close to the water surface and for jumping according to the model proposed by Au and Weihs [94] from Fish and Rohr [99]. The dolphin was assumed to be neutrally buoyant with a volume of  $0.1 \text{ m}^3$ , drag coefficient of 0.02, and drag augmentation factor of 4.5. The crossover velocity (i.e. where it becomes more economical to jump a given distance than to swim) was at approximately 5.5 m/s.

Fish and Hui [93] questioned the concept of  $U_c$  based on field data. Porpoising *Stenella* swim twice the distance they leap, whereas the assumption of  $U_c$  predict that dolphins would spend more time leaping than swimming at  $> U_c$  [96]. Swimming bouts may actually occur at a depth that does not incur increased energy costs from wave drag. Video data of free-ranging dolphins indicated a graded transition from minimal blowhole exposure at the surface at the low swimming speeds, to quasi-leaps in which the dolphin is never completely out of the water at any instant at the medium swimming speeds, and to complete porpoising leaps at the highest swimming speeds [97]. These observations are consistent with maintaining a minimum blowhole exposure time for respiratory inhalation as swimming speed increases.

To maintain their forward speed during porpoising, it was argued that fast-swimming animals should use an emergence angle of  $30^\circ$  [98], which is the compromise between maximum distance and maximum forward speed of a leap. Au and Weihs [94] assumed that the animals would maximize leap distance by employing an emergence angle of  $45^\circ$ . Emergence angles of leaps by dolphins and penguins were widely distributed between a  $25^\circ$  angle for maximum speed and a  $45^\circ$  angle [77, 97]. For animals with low weight-to-thrust ratios, energy gains of 40% can be obtained by porpoising at high swimming speeds [98]. Porpoising may be an energy conservation behavior which is directed more to economical breathing than as an energetically cheap method of swimming [77, 93, 97]. The greater energetic demands of rapid swimming necessitate the ability to prolong ventilation without potential interference from waves.

#### 4.4 Burst-and-coast swimming

Burst-and-coast swimming is a behavioral strategy that exploits the lower drag of a rigid, non-flexing animal compared to when it is actively swimming [30]. Many fish swim intermittently



using a two-phase periodic behavior of alternating accelerations (burst phase) interspersed with periods of glides (coast phase). Fish that use this behavior have a body morphology within a range of fineness ratio (body length/maximum girth) of 4.0 and 6.5 [100]. The hydrodynamic drag of a flexing fish body is three to five times higher than when the fish is straight and coasting at the same speed [13, 38].

Weih's [101] developed a theoretical model that estimates that efficiency on the initial and final speeds and the difference between the drag associated with active swimming and coasting. The optimal condition was obtained at low average speeds. Weih's [101] estimated that an energy savings of over 50% was possible by alternating accelerated motion with powerless glides. Burst-and-coast swimming becomes more economical as the animal's size or speed increases [102]. In addition, burst-time is reduced by trailing fish in a school, resulting in a 29% energy savings compared to burst-and-coast swimming by solitary fish [103].

A variant of the burst-and-coast behavior was applied to negatively buoyant fish [104, 105]. Energy is conserved by gliding downward with no propulsive motions and then regaining altitude by active swimming [30]. Weih's [104] calculated an energy savings of 20% for a fish using this technique to traverse the same horizontal distance in 7% more time. Energy savings for other tuna were estimated at 7% for skipjack tuna and 16% for albacore [27]. Increased energy savings are possible if the angle between the plane of the surface and downward trajectory of the fish on the glide is kept small [104].

The burst-and-glide strategy for energy savings is employed by marine mammals during dives [106]. The diving mammals are able to exploit their change in buoyancy to decrease swimming costs upon both descent and ascent of a dive. As the mammal descends, the air-filled lungs are compressed due to increasing pressure with depth resulting in reduced buoyancy. Although the initial descent is powered by active swimming, the loss of buoyancy allows the mammal to maintain momentum while passively gliding to deeper depths [107]. On ascent, active swimming is used to accelerate the mammal until the lungs have sufficiently expanded at shallower depths and the animal glides to the surface. By modifying locomotor patterns to take advantage of the energy savings by gliding, bottlenose dolphins and Weddell seals can realize a theoretical 10–21% and 9.2–59.6% energy savings, respectively [106, 107].

#### 4.5 Wave-riding

Dolphins and sea lions are well known to ride the pressure (bow) waves of ships and large whales [86, 93, 108–110]. This behavior is complex, with any energy savings to the animal related to bow design, swimming depth, body orientation, and distance from the ship [93]. Dolphins also readily change positions [110] and their flukes are not maintained in any specific orientation [111].

Newman [112] numerically modeled wave-riding as swimming in a non-uniform flow by applying the slender-body theory. The dolphin body experiences a thrust equal to the buoyant forces times the longitudinal pressure gradient of the flow [55]. The longitudinal pressure gradient in the bow wave is created by the steady flow past the ship. A dolphin near the surface is in equilibrium with the bow wave at 6 m/s with a wave slope of  $7^\circ$  [112]. This wave slope is below the maximal slope of  $30^\circ$ , but slope decreases exponentially with depth. The model also predicts that to travel in the same direction as the ship the dolphin must be directly in front of the bow. The movement of the bow wave occurs laterally at an acute angle. Because of an additional lateral force in both horizontal and vertical directions from the diverging wave system, a wave-riding dolphin positioned off the bow is expected to swim on its side with its flukes in the vertical plane [55, 112]. When shifting from between port and starboard sides of the front of a bow wave, dolphins will roll from side to side [110, 111].



The ability to utilize ship generated waves to free-ride is largely responsible for many of the misconceptions and erroneous conclusions regarding dolphin swimming speeds and hydrodynamics. Williams *et al.* [113] found that wave-riding dolphins could swim at a higher speed while reducing or maintaining metabolic rate.

Wind-wave riding and surf-wave riding also can reduce the energy of surface swimming [109]. These behaviors differ from bow wave-riding because they use the interaction of the dolphin's weight and slope of the wave front to effect movement analogous to human surfers [110]. Dolphins have been observed to ride on breakers or breaking wind-waves [86]. Dolphins are able to ride waves with a forward slope of 10–18° at velocities of 5–6 m/s [114].

Extraction of energy from the waves by oscillating a hydrofoil has been hypothesized as a mechanism to reduce energy expenditure for propulsion [115]. Wind-generated ocean waves were considered to provide a large whale with up to 25% of its propulsive power in head seas and 33% in following seas [116]. By synchronizing the motion of the wave with the motion of the flukes, large whales could theoretically increase the relative velocity experienced by the flukes and thereby increase the lift and thrust generated.

#### 4.6 Hitchhiking

Hitchhiking is a mechanism to reduce locomotor costs by direct attachment to an animal in motion. For this behavior to be of benefit to the hitchhiker without being a detriment to the other animal, the hitchhiker must be much smaller in body size compared to the other animal. In the dolphin (*Platanista*) the young are said to bite on the flipper of the mother and be dragged along [117]. The finless porpoise (*Neophocaena*) carry their young out of the water on their backs [117]. The young porpoise is carried at a position on the mother's back where the skin is not smooth, but covered with small wart-like excrescences. The remora or sharksucker (Echeneididae) attaches to much larger fish, turtles, or whales. Attachment is by a suction disk which is the modified dorsal fin of the remora.

#### 4.7 Currents

Fish will often migrate to areas where constant current or tidal currents are present [30]. Selective tidal-stream transport by fish has been shown theoretically to provide a means of energy conservation [118]. When tidal-current speeds are high, the fish can save 50% or more of its energy by swimming in midwater in the same direction of the current and resting on the bottom when the tide is moving in the opposite direction [30, 118]. The cost of swimming for migrating plaice using tidal stream transport is about 20% less than the cost for continuous swimming [119]. Even greater energy saving can be realized by these flatfish if burst-and-coast swimming is employed and metabolic rate is reduced when resting on the bottom.

#### 4.8 Hydroplaning

When moving at the water surface, displacement vessels, whether ships or ducks, are constrained in their speed by the formation of surface waves. As a displacement hull moves at the surface, it will produce two distinct series of waves, which are referred to as the bow wave system and the stern wave system. These systems are composed of diverging and transverse waves which each contributes half of the wave drag [120]. The diverging waves from bow and stern cannot interfere with one another; however, the transverse bow waves can be superimposed on the transverse stern waves because wavelength is variable and dependent on the speed of the body [120, 121].



With increasing speed, the wavelength of the bow wave system increases and interacts with the waves generated at the stern. Depending on the phase relationship, bow and stern waves can produce a positive or negative interference. Thus, the drag on a body can be exaggerated when wave crests are synchronized and reduced when a wave crest and wave trough interfere destructively.

The wavelength of the transverse waves increases until the wavelength of the bow wave matches the hull length, so that the second crest of the bow wave is superimposed upon the first crest of the stern wave [121]. This produces a constructive interference of transverse waves created at the bow and stern of a hull of a ship or body of an animal. At that time, the animal becomes trapped in a wave trough of its own creation and further increases in speed would only be possible by expending large amounts of energy to swim through or over the bow wave [122]. This speed is referred to as 'hull speed'. Surface swimming animals rarely exceed hull speed and only do so by using extraordinary behaviors [122, 123].

Mallard ducklings (*Anas platyrhynchos*) are capable of exceeding hull speed by hydroplaning or skimming on the water surface [123]. Ducklings were capable of hydroplaning at speeds up to 2.54 m/s (18.5 body lengths/s), which was 5.9 times greater than hull speed. Hydroplaning was maintained by the generation of dynamic lift from the paddling by the feet. In effect, the hull is 'outrunning' its own pressure disturbance (i.e. bow wave). The body of these animals has design features similar to hydroplaning hulls with a flattened underside, small length/beam ratio and shallow draft [121]. A low length/beam ratio in concert with the high buoyancy from air in the plumage and respiratory system provides the duckling with a shallow draft. Hydroplaning is demonstrated also by steamer ducks (*Tachyeres* spp.), which rapidly propel themselves at the water surface using their feet and wings [124]. Steamer ducks swim continuously over distances of 1 km and at speeds up to 6.67 m/s, which is 7.5 times the predicted hull speed!

#### 4.9 Vorticity control

The generation of vortices is one of the prerequisites of the propulsive motions of animals in a fluid. As a shearing action is imposed on a separating flow, it induces a rotation in the form of a vortex. A vortex has a double function: (1) As a 'free vortex' to transport momentum into the fluid and (2) as a 'bound vortex' to generate additional forces from flow interaction. Vorticity can then be used in the generation of thrust [125, 126]. However, the vorticity responsible for the creation of vortices will demand the expenditure of energy and lower propulsive efficiency. Thus, there has been interest in using vorticity to enhance propulsive performance.

Rosen [127] developed the vortex peg hypothesis. He observed crossflows around the dorsal and ventral surfaces of a sprinting fish. The crossflows produced vortices on alternate sides of the body. Rosen postulated that the fish actively produced the vortices to act as quasi-static pegs. The fish was hypothesized to push off the vortices to affect propulsion. This mechanism was assumed to propel the fish with a drag near zero. However, the velocity of flow adjacent to the fish from the vorticity would be higher than the free-stream velocity, resulting in higher drag [13].

More recently, there is the idea that vorticity (rotating fluid due to the velocity gradient) generated along the body or leading edge of the tail of a swimming fish upstream of the trailing edge of the propulsive caudal fin could enhance thrust production and increase efficiency [1, 128–132]. The vortex excitation/destruction model was developed in which a starting vortex is produced before being acted upon as the fin is quickly reversed [128]. This action produces new vortices on the opposite side of the fin which gain strength at the expense of the primary vortex. Higher power is achieved. This mechanism is particularly applicable to starts from rest.

Vorticity is developed along the sides of an undulating fish in a manner similar to flow along an undulating plate [132]. The bound vorticity is conducted toward the trailing edge of the caudal fin



and when shed to produce an amplified vortex. The next set of vortices shed into the wake has the opposite rotation. This produces a pair of counter-rotating vortices and a thrust jet. Continuous vortex shedding produces a wake with the thrust type reverse Karman vortex street [81, 132, 133]. It is postulated that this mechanism of propulsion is dependent on active control involving co-ordination of the body/caudal fin motion [133].

Use of vorticity generated along the body to enhance wake structure is limited in high-performance thunniform swimmers. These animals are relatively stiff anteriorly, have nearly circular or elliptical cross-sections, and display extreme narrow-necking [13]. These morphological features should not promote the production and conduction of bound vorticity along the body. However, the heaving and pitching motions of the relatively stiff, high-aspect ratio caudal propulsor could produce leading-edge vortices which would impact the wake structure [1]. The development of leading-edge vortices from dynamic stall has been experimentally demonstrated to produce high-lift forces [134–137]. The leading-edge vortex would interact with the trailing-edge vortex to produce thrust. This vorticity control is the principle mechanism by which high efficiency (>85%) is achieved.

Experiments with the biologically inspired RoboTuna showed that under a particular set of kinematic conditions the swimming robot could reduce its drag in excess of 70% compared to the same body towed straight and rigid [131]. However, deviation from the optimal settings of kinematic parameters for RoboTuna resulted in a drag augmentation of 300% [131].

## 5 Application of biomimetics from aquatic animals

It has been a long-standing idea that new technologies can be developed from nature [3, 7]. Animals have served as the inspiration for various technological developments. Biomimetics attempts to produce engineered systems that possess characteristics, resemble, or function like living systems [7]. The goal of biomimetics in the field of robotics is to use biological inspiration to engineer machines that emulate the performance of animals [5, 8] particularly in instances where the animal's performance exceeds current mechanical technology.

Copying animals by the biomimetic approach attempts to seek common solutions from engineering and biology for increased efficiency and specialization. Because biological designs resulted from the evolutionary Darwinian process of 'natural selection', it is considered that animals have already performed the 'cost-benefit analysis', optimizing particular designs for specific functions. The diverse morphological specializations exhibited by animals may be targeted by engineers for technology transfer and effectively reduce the time of development of innovative technological solutions.

What are the limits to the biomimetic approach? Differences between engineered systems and animal systems are apparent. Engineered systems are relatively large in size, are composed of rigid materials, use rotation motors, and are controlled by computational systems that have limited sensory feedback; whereas animals are generally small in size, are composed of compliant materials, use translational movements produced by muscles, and are controlled by complex neural networks with multiple sensory inputs. In addition, animals are functionally multifaceted (i.e. they move, feed, and reproduce) and must compromise optimal solutions for specialized functions to perform adequately rather than maximally. The potential for the development of new and superior technological designs for enhanced performance based on animal systems has been tantalizing, although elusive [3, 7]. Strict adherence to biological designs is considered to rarely produce any practical results and in some cases can impede the development of engineered systems [3, 7].



## 5.1 Convergence of design

It is no accident that the optimal shape for drag reduction of submerged bodies is possessed by modern submarines and dolphins. Both have fusiform body shapes that reduce the pressure drag. This design delays separation to closer to the trailing edge, producing a smaller wake and reduced energy loss.

The identification of animals as streamlined bodies with application to manufactured devices for drag was reported in the Renaissance. Between 1505 and 1508, Leonardo da Vinci wrote on the function of streamlined bodies in reducing drag [1] da Vinci recognized the streamlined shape of a fish and demonstrated a similar design with the hull shape of ships. He argued that the fish could move through the water with little resistance, because its streamlined shape allowed the water to flow smoothly over the afterbody without prematurely separating.

The streamlined body shapes of a trout and a dolphin were examined later by Cayley in 1809 as solids of least-resistance design [6]. Cayley's streamlined body for the fish is similar in design to low-drag airfoils. Application by Cayley of the natural design for a boat hull, however, did not meet with success [7]. The rounded design was unstable with respect to roll, and low drag did not occur. While appropriate for movement underwater, this shape is limited at the water surface.

## 5.2 Copying

In convergence, the resulting similarity between animals and engineered systems is merely coincidental. Indeed biologists typically note these similarities only after engineers have developed structures with defined functions and described the principles by which they work. The similarity results from a finite number of possible solutions for dealing with particular forces which impinge upon defined functions. Convergence is of limited utility in developing innovation as it is recognized in hindsight. However, convergence provides a natural validation of a similarly engineered system, defines common environmental constraints, and helps to identify novel natural adaptations. Even subtle differences between natural features and their artificial analogs that can maximize performance may be exploited for improvement of already existing engineered designs.

Innovation by biomimetics, however, results from deliberate attempts to directly copy natural systems, once they have been identified as functionally novel. The focuses of this attention are features in organisms that convey superiority compared to human technology. The fantastic diversity of animals exhibits a multitude of natural innovations that can be used as a source of ideas and solutions for integration into engineered systems. For aquatic systems, the prime features to be copied are the abilities to function for prolonged periods of time while submerged, operate at high speeds, reduce energy consumption by increased propeller efficiency, maintain a high level of stability regardless of environmental perturbations, enhance maneuverability, and proceed with stealth.

An early attempt to copy nature in a submarine design was described by Borelli [138], which incorporated ideas based on hydrostatic control and propulsive systems of animals. Buoyancy control was based on the swim bladders of fish. Propulsion would be accomplished by oars acting like the paddling feet of frogs or geese. Despite the elaborate design for its time, it is doubtful if this early biomimetic experiment was successful [139].

The investigation and application of special mechanisms for drag reduction by dolphins has been highly contentious [93]. The controversy, known as 'Gray's Paradox', was the result of the first attempt to evaluate swimming energetics in animals [140]. Based on a simple hydrodynamic model, the drag power was computed for a dolphin and a porpoise swimming at high speeds. The results indicated that the estimated drag power could not be reconciled with the available



power generated by the muscles. For his calculations, Gray assumed that turbulent boundary flow conditions existed, because of the speed and size of the animals. Gray's resolution to the problem was that the drag on the dolphin would have had to be lower by maintenance of a fully laminar boundary layer. The basic premise of Gray's Paradox, however, was flawed, because of potential errors in estimation of dolphin swimming speed and inconsistencies between dolphin swimming performance and data on muscle power outputs. This mechanism was largely ignored in subsequent work, whereas, the basic premise that dolphins could maintain laminar boundary conditions remained and became the focus and justification of much of the work on dolphin hydrodynamics for the next 60 years [93, 99].

The work of Kramer [141, 142] considered a resolution of Gray's Paradox. Kramer claimed that a laminar boundary layer without separation could be achieved at high Reynolds number ( $Re$ ; ratio of inertial to viscous forces) by artificially increasing the viscosity at the body surface. Kramer [141] coated a torpedo with an artificial skin based on the skin of a dolphin. The dolphin integument is composed of a smooth, hairless epidermal surface forming an elastic membrane [143] and is anchored to the underlying dermis with its blubber layer by longitudinal dermal crests with rows of papillae, which penetrate the lower epidermis [144]. Kramer's analogous skin was composed of a heavy rubber diaphragm supported by rubber studs with the intervening spaces filled with a viscous silicone fluid [141, 142]. The diaphragm would be sensitive to pressure changes and transmit the pressure oscillations below to the viscous fluid. The fluid would flow beneath the diaphragm to absorb part of the turbulent energy. It was hypothesized that the coating would dampen out perturbations in the flow and prevent or delay transition. When a towed body was coated with the artificial skin, anterior of the maximum thickness, a 59% reduction in drag was achieved, compared to a rigid reference model with fully turbulent flow.

The structure of Kramer's skin coating and the skin and underlying blubber of dolphins is both structurally and mechanically different. Despite these differences, research on compliant coatings was accelerated during the 1960s [93, 143, 144]. However, attempts to verify Kramer's results subsequently failed [144, 145], although tuned compliant panels do have a drag reduction benefit [146]. Experiments on live dolphins and a review of the available literature on dolphin swimming performance showed no evidence for drag reduction from special mechanisms [99, 147].

A more successful application of copying natural designs for drag reduction was found for riblets. The development of riblets to reduce turbulent skin friction came in part from the study of shark scales or dermal denticles [147]. Riblets are streamwise microgrooves that act as fences to break up spanwise vortices and reduce the surface shear stress and momentum loss. Fast-swimming sharks have scales that are different from other sharks. These scales have flat crowns and sharp ridges oriented longitudinally with rounded valleys [148, 149]. Although the ridges are discontinuous due to the distribution of the scales, a 7–8% drag reduction is possible as measured for continuous riblets [150, 151]. Because the fine microgrooves are prone to fouling, riblets are limited to short duration usage. However, riblets were applied to the hull of the Stars & Stripes, the 1987 America's Cup winner. Riblets were believed to reduce drag by 2–4% in skin friction [152]. Recently, Speedo developed a competitive, whole-body swim suit called Fastskin™ that is based on shark scales.

The potential for enhanced performance by emulating nature also has focused on propulsive systems. The thrust performance of fish and dolphin tails is considered superior to screw propellers [2]. Early versions of propellers could not change their pitch with speed, because of the fixed nature of the blades. This was believed to limit effectiveness over the speed range of the propeller due to cavitation. The oscillatory motions of flexible-bodied fish and dolphin were considered to be able to adjust to velocity changes and maintain effective thrust production



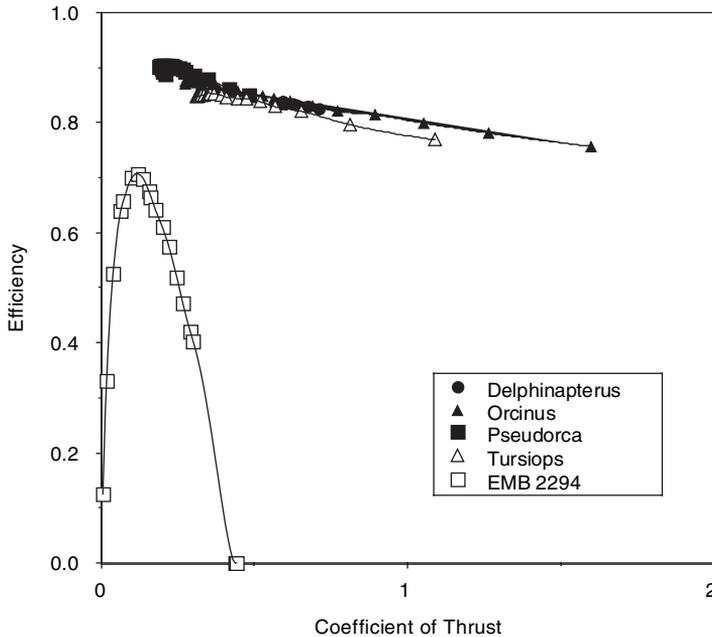


Figure 6: Comparison of relationships of propulsive efficiency and thrust coefficient for four species of small whales and a typical marine propeller. Data for the whales was obtained from Fish [65], based on lifting surface theory [64] and open-water test data for the propeller (EMB 2294) was from Saunders [154].

over a large speed range [153, 154]. The oscillatory flukes of dolphins function at higher efficiencies over a greater range of thrust coefficients compared to a standard propeller (Fig. 6). Conventional marine propellers operate at mechanical efficiencies of about 70% [155], whereas high-performance swimmers, such as tuna, dolphins, and seals, are able to produce mechanical efficiencies of over 80% [13, 99].

Presently, biomimetic robots are being produced that emulate the propulsive systems of fish, dolphins, and seals [2, 156–160]. A primary focus of this research is based on the idea that these animals can enhance thrust production and increase efficiency by controlling vorticity, which is shed from the body and propulsors [2, 5, 128, 129, 132, 159]. However, there are still limitations in understanding the natural propulsive systems as these systems rely on unsteady conditions and current mechanical systems are grounded in steady theory [161].

Replication of the turning performance of aquatic animals as an indication of maneuverability has been attempted. Autonomous fishlike robots with turning capabilities were constructed with jointed bodies [159]. Utilizing vorticity control, these flexible, biomimetic fish showed increased maneuvering capabilities compared to conventional unmanned underwater vehicles. Biomimetic fish can turn at a maximum rate of  $75^\circ/\text{s}$ , whereas conventional rigid-bodied robots and submarines turn at approximately  $3\text{--}5^\circ/\text{s}$  [159, 162]. Success has been attained also in matching the turn radius (47% of body length) with the group of fish (tuna) on which the robot's design was based [159]. Further refinements and use of alternate animal models could result in improved maneuverability. Various aquatic animals display turn rates up to  $5509^\circ/\text{s}$ , centripetal accelerations up to  $24.5g$ , and minimum turn radii of 24% of body length and lower [35, 163–165].

### 5.3 Limitations of biomimetics

Aquatic animals have existed in an environment which they mastered for millions of years. It is viewed that over this time, evolution (descent with modification) through the Darwinian process of 'natural selection' has fostered improvements in design which have culminated in adaptations for the survival of these organisms by enhanced levels of performance. Evolution is perceived to act as a natural laboratory where given a time scale that is geologic virtually all possible permutations of experiments have been attempted. Because natural selection acts on a wide range of design and performance possibilities as dictated by the genetic code and functional demand of the local environment, a variety of possible solutions to engineering problems are potentially available. However, the laws of physics and the physical properties of environment and structural materials available to biological forms impose constraints on evolution [165]. Possible structures and processes that potentially could benefit an organism are not all available. Wheels are not found in animals, despite their ubiquity in manufactured devices and their obvious benefit to energy economy in locomotion. Animals move through forceful contraction of the muscles transmitted to a jointed skeleton by tendonous connections. Therefore, biological systems suffer lower efficiency due to periodic accelerations over a propulsive cycle. Large animals are unable to produce high rates of acceleration because, as size increases, the ability of the muscles to generate stresses relative to inertial forces decreases [21].

Evolution is not conscious or predictive. Evolution by the theory of natural selection is a response to changing environments. The biotic and abiotic environments of the time that a new design evolves dictate its selection without anticipation for potential future purpose and effectiveness. Indeed, it is difficult if not impossible for any design to be optimized. The environment is nearly always changing, producing a non-equilibrium state which places design criteria in a state of constant flux [166]. Both superior and poor designs with respect to present time may be lost if they did not function adequately in past environments or if they were accidentally lost due to chance events. Use of the term 'design' in a biological sense is simply an indication of the linkage between the structure and function of a characteristic possessed by an organism. For biologists, design does not infer construction or organization of an organism's feature toward a specific goal [167].

Another restriction to design is that animals have evolved along lines of common descent with shared developmental patterns. Radical redesigns are not permitted to expedite enhancing performance; instead, it is existing designs which are modified [7]. Within a given lineage, phenotypic change is expressed as variation on a theme. Design is constrained by the evolutionary history of an organism. Swimming in whales would be more efficient if these animals remained submerged like fish, because drag increases due to the formation of waves as a body moves in close proximity to the water surface; however, their common evolutionary history with other air-breathing mammals requires that they periodically return to the water surface to fill their lungs despite increased energy cost.

Animals are multitasking entities. While machines can be designed for a single function, animals must endure compromises in their designs to perform multiple and sometimes antithetical functions. Increased performance by one feature that benefits an organism for a particular function may handicap the organism with respect to another function. Depending on the local environment and immediate selection forces, genetic linkages between traits and pleiotrophic effects can produce changes in one characteristic that produce a correlated effect in other characteristics [166]. In total, the organism as a mosaic of integrated structures and functions may achieve evolutionary success (i.e. survive and reproduce), but not perform optimally for any specific function.



Efficiency is an important factor that has received attention from engineers wishing to employ a biomimetic approach to the propulsive systems of marine robots [1, 2, 159]. Oscillatory mechanisms employing stiff, high-aspect ratio hydrofoils, as displayed by tuna, dolphins, and seals, have been targeted for technology transfer for increased efficiency. The assumption is that any mechanism that allows for increased energy efficiency can provide an important evolutionary advantage to an animal. However, natural selection does not necessarily act on efficiency. Efficiency is measured as the ratio of the useful work performed to the total work produced. The oscillating hydrofoil propulsor of an animal performs useful work by generating thrust from the acceleration of water in the opposite direction to the animal's progression; whereas the total work performed is the sum of the useful work and the work on water in the transverse direction. Because work is performed on the environment to effect locomotion, this is the external work. Internal work is performed by the muscles to accelerate and decelerate individual body segments. The total energy cost for locomotion will be high from the internal work associated with an oscillatory system, despite the high efficiency of the oscillating hydrofoil with respect to external work.

Natural selection will act on energy economy rather than efficiency. Economy refers to the total cost of a given task, and thus considers rate of energy consumption with respect to the available supply of energy and the rate at which energy can be re-supplied. For an animal, swimming at a high speed is more efficient than swimming at a low speed, but the rate at which energy is consumed to swim fast is disproportionately higher to swimming slowly. High speeds cannot be maintained for extended periods as total energy reserves are depleted rapidly and new energy resources cannot be mobilized quickly enough. Rapid swimming is limited to those instances where survival of the animal is at stake. Escape by prey and bursts by predators demands large and rapid energy expenditures without concern about efficiency.

For routine swimming speeds, energy economy determines the time and distance that can be traversed. Animals will swim at their optimal speed. Optimal speed is the speed at which the total cost of energy per unit distance is minimal [13]. Optimal speed for animals is typically found at intermediate swimming speeds. The cost of maintaining the metabolism is high relative to the locomotor costs at low speeds and the cost to traverse a given distance is high. At speeds greater than the optimum, locomotor costs increase exponentially, driving up the cost per distance, although the time to cover that distance is decreased. Migratory species and animals that travel long distances for prey that have a patchy distribution will swim at speeds near optimal.

## 6 Conclusions

The technology associated with the development of robots is becoming more dependent on biomimetics and biologically-inspired designs. As engineers move from the world of large, stiff, right-angled pieces of metal to one of small, compliant, curved-surface pieces of heterogeneous parts, nature will become a more influential teacher. Animal systems hold promise for improved performance by machines in the aquatic realm. As matters of energy economy and greater locomotor performance are desired in engineered systems, imaginative solutions from nature may serve as the inspiration for new technologies. Enhanced propulsion for engineered systems may be possible by biomimetic mechanisms involved with oscillating propellers, flexible wings, boundary layer stabilization, laminar flow maintenance, and active vortex control. In addition, natural propulsive systems can be self-stabilizing and self-correcting. The potential benefits from biological innovations applied to manufactured systems operating in water are high speeds, reduced detection, energy economy, and enhanced maneuverability.



Progress in technologies concerned with aquatic locomotion comes from discovery and refinement of new designs. New insights into aquatic propulsion by animals will permit the collection of information that can be exploited for the development of advanced technologies. These insights include an interpretation of the unsteady nature of animal movement, measurement of movement in two and three dimensions, the use of computational methods that model both the animal's movement and its effect on the fluid surrounding it, physiological and biomechanical studies of locomotor tissues in relation to thrust production and energy recycling, and analysis of the use of appendages in thrust production, trajectory control, and stability [11].

Perhaps the process of evolution can be used directly in a biomimetic approach. By using high-speed computers and genetic algorithms, an initial design can be subjected to various combinations of selection pressures. As the design 'evolves', each configuration could be tested virtually to assess its level of performance. Like evolution, this would be an open-ended process and new selection pressures could be introduced to produce alternative branching pathways. Designs considered useful could be manufactured without a haphazard development phase and without a prolonged period of testing prototypes.

In comparison to engineers who can limit variables in their systems, biologists examine systems of complexity. These biological systems interact with their environments in a multitude of behavioral and morphological pathways and are composed of structural elements for which the physical characteristics have not been fully described. Nature, therefore, retains a store of untouched knowledge, which would be beneficial to engineers. In an ever-increasing era of specialization and proliferation of information, it is nearly impossible to find novel solutions from disparate fields other than one's own. Thus, collaborations become essential and the union between biologists and engineers is critical to biomimetics [9].

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