PAPER

Batoid Fishes: Inspiration for the Next Generation of Underwater Robots

AUTHORS
Keith W. Moored
Mechanical and Aerospace
Engineering Department,
Princeton University

Frank E. Fish
Department of Biology,
University of West Chester

Trevor H. Kemp
Hilary Bart-Smith
Mechanical and Aerospace
Engineering Department,
University of Virginia

ABSTRACT

For millions of years, aquatic species have utilized the principles of unsteady hydrodynamics for propulsion and maneuvering. They have evolved high-endurance swimming that can outperform current underwater vehicle technology in the areas of stealth, maneuverability and control authority. Batoid fishes, including the manta ray, *Manta birostris*, the cownose ray, *Rhinoptera bonasus*, and the Atlantic stingray, *Dasyatis sabina*, have been identified as a high-performing species due to their ability to migrate long distances, maneuver in spaces the size of their tip-to-tip wing span, produce enough thrust to leap out of the water, populate many underwater regions, and attain sustained swimming speeds of 2.8 m/s with low flapping/undulating frequencies. These characteristics make batoid fishes an ideal platform to emulate in the design of a bio-inspired autonomous underwater vehicle. The enlarged pectoral fins of each ray undergoes complex motions that couple spanwise curvature with a chordwise traveling wave to produce thrust and to maneuver. Researchers are investigating these amazing species to understand the biological principles for locomotion. The continuum of swimming motions—from undulatory to oscillatory—demonstrates the range of capabilities, environments, and behaviors exhibited by these fishes. Direct comparisons between observed swimming motions and the underlying cartilage structure of the pectoral fin have been made. A simple yet powerful analytical model to describe the swimming motions of batoid fishes has been developed and is being used to quantify their hydrodynamic performance. This model is also being used as the design target for artificial pectoral fin design. Various strategies have been employed to replicate pectoral fin motion. Active tensegrity structures, electro-active polymers, and fluid muscles are three structure/actuator approaches that have successfully demonstrated pectoral-fin-like motions. This paper explores these recent studies to understand the relationship between form and swimming function of batoid fishes and describes attempts to emulate their abilities in the next generation of bio-inspired underwater vehicles.

Keywords: biomimicry, bioinspired, autonomous underwater vehicle, manta ray, tensegrity structures

Introduction

There has been an explosion of activity in the area of biomimicry and bioinspired engineering research. *Biomimicry* directly emulates the form and function of species to illuminate the physical principles behind nature's designs. *Bioinspired* engineering takes advantage of the knowledge gained through biomimetic studies to judiciously apply novel physical principles to develop solutions with added functionality over conventional engineering approaches. Biology, biomimetics and bioinspired engineering are intimately linked. Thus it comes as no surprise that biologists and engineers are collaborating by developing biorobotic devices to: (1) elucidate key insights into biological form and function and (2) develop bioinspired autonomous underwater vehicles (BAUVs) to improve functionality of autonomous underwater vehicles (AUVs).

Aquatic species outperform conventional AUVs in the areas of maneuverability and control authority (Bandyopadhyay, 2005), while having a low-noise signature that blends into the background and high swimming efficiencies. Batoid rays excel in all of these areas, giving them an abundance of recent attention. The focus of this paper is to present the growing body of work being done to understand and quantify the swimming performance of batoid fishes (i.e., skates, sting rays, manta rays) and the state-of-the-art in robotic mimicry. Of particular interest are the mechanisms associated with the swimming of these fishes, which employ flattened pectoral fins to propel and maneuver in the ocean and in rivers.

Understanding Biological Foundation will discuss our current biological understanding of batoid rays. *Rationale for Mimicking Batoid Rays* will present compelling reasons for scientists and engineers to study batoids rays, highlighting their swimming characteristics that would be desired in an underwater vehicle. *Bioinspired Robotics* delves into the expanding world of bio-inspired underwater vehicles, with particular emphasis on ray-like platforms. *Concluding Comments and Future Directions* concludes with a discussion on critical areas that need to be addressed in order for the next generation of underwater vehicles to be truly bioinspired.

Understanding Biological Foundation

Fish swim by imparting momentum to water from the movements of a variety of propulsors, which can include the body, median fins, and paired fins (Sfakiotakis et al., 1999). Although primitive batoid fishes use the body and caudal fin to swim, more advanced batoids have become specialized to swim with enlarged pectoral fins. It is emphasized that pectoral fin locomotion can have significant advantages in maneuvering and station-keeping (Sfakiotakis et al., 1999). In recent years, more attention is being paid to pectoral fin hydrodynamics as their importance is being realized in not only steady-state locomotion but also in transient maneuvers (Bandyopadhyay, 2005; Lauder et al., 2002; Combes & Daniel, 2001; Palmisano et al., 2007).

Batoid rays take pectoral fin locomotion to an evolutionary extreme (Figure 1). Rays have a dorso-ventrally flattened body with enlarged pectoral fins that are seamlessly merged with their body to form a biological blended wing-body configuration. Propulsive waves are passed through the fins by serial contraction of the appendicular musculature. The waves have their greatest amplitude toward the periphery of the fin.

Even though among rays there is similar morphology, their locomotor strategies can be very different. Undulatory motion, defined as having greater than one or more waves present on a fin (Rosenberger, 2001), is one extreme of kinematic motion and was termed ‘rajiform’ by Breder (1926). These fishes swim just over the ocean floor. The other extreme is oscillatory motion, defined as having less than half of a wave present (flapping) on a fin, and was coined ‘mobuliform’ by Webb (1994). The mobuliform swimming mode appears as a wing-like flapping motion and is associated with rays that have a more pelagic existence. The various species of batoids exhibit a continuum of kinematic motions between the two extremes of undulation and oscillation (Rosenberger, 2001). Myliobatoids, i.e., the mid-water rays, including manta, eagle, bat, and cownose rays, nearly exclusively utilize oscillatory motion (Klausewitz, 1964; Sasko et al., 2006; Heine, 1992). Some research has been done to characterize the biology and behavior of myliobatoids (Schaefer & Summers, 2005; Summers, 2000). Heine (1992) studied the kinematics of the cownose ray by videotaping live rays swimming in a flow tank. Rosenberger (2001) compared the kinematics of many batoid rays spanning the undulation-oscillation continuum and suggested that oscillatory rays have evolved to have efficient locomotion. Klausewitz (1964) describes the kinematic motions of the manta ray while Moored et al. (Moored, 2010; Moored et al., 2011b) developed a simple yet powerful analytical model to quantify the kinematics of different species of batoid rays (such as the manta ray, Atlantic stingray, and the cownose ray). This model is used as a target deformation field for a bio-inspired fin (Moored et al., 2011b) and to calculate the swimming performance of different batoid ray species (Moored et al., 2011b; Pederzani et al., 2011).

FIGURE 1

(a) Image of a manta ray. (b) Image of a cownose ray. Both rays are part of the batoid family and swim via an oscillatory motion.

Morphometrics

The greatly enlarged pectoral fins form wide lateral extensions of the body that range in morphology from a circular disc to triangular, wing-like planforms. Species of batoids show over a 90-fold range in size with the largest being the manta (*Manta birostris*). Rays that swim by undulations of the fin in the rajiform mode have fin shapes with relatively low aspect ratios (the ratio of span to chord). Oscillatory swimmers, using the mobuliform mode, possess higher aspect ratio fins with longer spans.

The cross-sectional geometry of batoid rays has a streamlined appearance. Rajiform swimmers have a body and pectoral fins with a flattened ventral side and low vaulted dorsum, giving a design similar to a cambered wing. Although the central portion of the body shows a slight asymmetry with a flattened ventral surface and convex dorsal surface, the pectoral fins of mobuliform swimmers display symmetrical cross-sectional profiles reminiscent of engineered foils (Abbott & von Doenhoff, 1949).

The internal skeleton of the pectoral fins of batoids are composed of numerous short, cylindrical cartilaginous elements (Heine, 1992; Schaefer & Summers, 2005). These cartilaginous elements are the supportive radials of the fin. The radials are stacked end to end. The radial cartilages are mineralized to varying degree depending on the species of batoid, where the mineralization is found on the exterior of the cartilaginous element with the core being unmineralized (Schaefer & Summers, 2005). Rajiform swimming rays display joint staggering with little calcification of the joints, whereas the skeleton of oscillatory swimmers shows cross-bracing and calcification. The skeleton is moved by long thin muscles that run from the expanded pectoral girdle along each fin ray to every radial. The range of motion of the articulated radials is small (~15°), but the large number of components in the pectoral fins permits sufficient spanwise and chordwise flexibility for propulsion and maneuvering (Rosenberger, 2001; Klausewitz, 1964; Heine, 1992; Schaefer & Summers, 2005).

Rationale for Mimicking Batoid Rays

With respect to pursuing bioinspired engineering, a key question to be answered is to explain/justify why a particular species is a good candidate to emulate. These reasons can be very diverse and are motivated by the particular application envisioned. In the case of AUVs, compelling reasons to consider biology as a starting point for the development of the next generation vehicle are (1) a stealthy signature, (2) high efficiency and economy, (3) expanded working environment, and (4) scalability/payload capacity. Additionally, a key justification for this approach is that there are tangible improvements that can be made over current AUV technologies. The pool of species to emulate is vast. However, recent studies of batoid rays have demonstrated significant swimming abilities that would be desirable in an underwater vehicle.

Stealth means either quiet operation or the ability to blend into the background noise. A biomimetic approach naturally fulfills these requirements by creating a vehicle whose minimal noise signature blends in with the environment. The noise signature of a fish is very different to that of a propeller (Bandyopadhyay, 2005). Even biomimetic sensor arrays such as an artificial lateral line (Yang et al., 2006) or artificial seal whiskers (Stocking et al., 2010) that are sensitive to hydrodynamic wake signatures would presumably delineate a flapping fin wake as an animal and a propeller wake as a man-made device. Given recent advances in underwater imaging technology including LIDAR systems (Jaffe et al., 2001), synthetic aperture sonar (Kocak & Caimi, 2005) and biomimetic sonar systems (Dobbins, 2007), the shape and movements of an AUV are becoming increasingly important. By mimicking the body form of an aquatic species, the identification of such a stealthy vehicle as a man-made device becomes difficult.

Batoid rays offer an intriguing design solution for a high-endurance vehicle. Pelagic rays, such as the manta ray or cownose ray, migrate thousands of miles a year. This suggests that these species have evolved to become high-endurance swimmers. As discussed previously, myliobatoid rays have a dorso-ventrally flattened body with enlarged pectoral fins, forming a natural gliding morphology. In terms of a vehicle, a batoid-inspired UV is an advance on current underwater glider technology. This bioinspired platform would enable a vehicle to have high-endurance capabilities like current underwater gliders, such as the Slocum AUV (Webb & Simonetti, 1999). Additionally, this system has the potential to transition to a faster, more maneuverable vehicle that can operate in dynamic environments such as the littoral zone or areas with large currents and high wave action. Observations of various rays show them to be highly maneuverable and adaptable to local conditions—for example, to station keep and even swim backwards. Their ability to control their stability via the pectoral fins, especially when compensating for challenging environments, must also be considered as a desirable characteristic to emulate in an underwater vehicle.

Scalability is an attractive feature in any artificial system. With respect to bioinspired underwater vehicles, batoids display an extraordinary range of dimensions, growing in excess of 9 m tip-to-tip in the case of manta rays. Thus, the size and speed that batoids perform at are equivalent to the operation range of marine vehicles. The size of the vehicle will very much depend on the mission requirements, but by using the batoid as the foundation, it is feasible to produce a variety of sized vehicles that can explore and traverse a wide range of ocean space while performing a wide range of tasks. Moreover, a batoid-inspired vehicle would have a large planform surface area, making this platform an excellent candidate for flexible solar cells to extend its range (Dennler et al., 2008), similar to the solar powered SAUV II vehicle (Jalbert et al., 2003). In addition, the rigid body of batoids permits space for control systems, sensory devices and increased payload.

Bioinspired Robotics

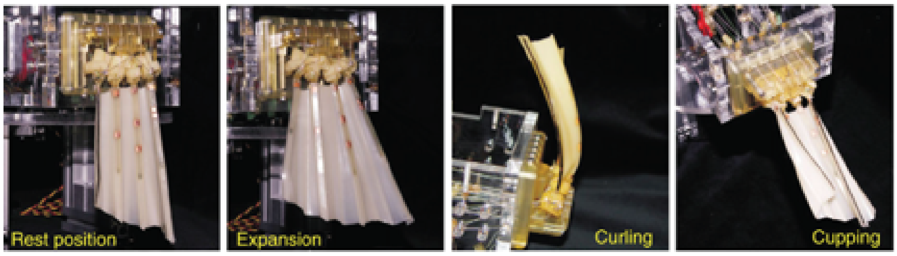
There has been growing use of AUVs in recent years with over 240 different AUV platforms developed and used in the field (Bandyopadhyay, 2005). These AUVs typically are built for reconnaissance/surveying and were originally designed for endurance (Blidberg, 2001). This gave rise to the design of underwater gliders using conventional design principles (i.e., steady-state hydrodynamics) that have high endurance but little maneuverability (Webb & Simonetti, 1999). From another perspective, biology has created thousands of swimming platforms that can outmaneuver the best AUVs while still having highly efficient, high-speed and high-endurance performance. Moreover, many of these biological systems can also hover in place with no forward locomotion, generate large enough forces to hold station under adverse environmental conditions, burst with incredible acceleration and have a significantly reduced noise signature compared to man-made AUVs (Fish & Lauder, 2006). In an attempt to bridge the performance gap between conventional AUVs and biological systems, engineers have been shifting focus to BAUVs, which is a highly multi-disciplinary research area (Bandyopadhyay, 2005; Colgate & Lynch, 2004). To reach some of these goals, there is a spectrum of first generation BAUVs that have been developed. Some form an exotic collection mimicking lamprey (Ayers et al., 2000; Crespi et al., 2004), tuna (Barrett et al., 1996; Yu et al., 2004; Anderson & Chhabra, 2002), and dolphins (Yu et al., 2007), while others are more conventional style AUV designs outfitted with bioinspired flapping propulsors (Fish et al., 2003; Low & Willy, 2006; Listak et al., 2005; Borgen et al., 2003; Mojarrad, 2000; Licht et al., 2004). These different BAUV designs were made possible partly from advances in our understanding of unsteady hydrodynamics and the biology of nektonic (swimming) organisms. However, this BAUV technology still has a long way to go before the performance gap is bridged.

Recently, researchers have turned to pectoral fin locomotion for inspiration. Pectoral fin motions utilized by sunfish, perch, bass and bird wrasse for low-speed swimming and maneuvering have been studied (Gibb et al., 1994; Drucker & Jensen, 1997; Lauder & Jayne, 1996; Walker & Westneat, 1997). To understand the forces and moments produced by these pectoral fins, biorobotic solutions began with paddle-like fins that mimic the bulk kinematics of labriform swimming (Kato, 1998; Kato & Furushima, 2002). In recent years, devices have been constructed to more accurately replicate the kinematics utilized by the fish with the advent of actively flexible fins that can produce chordwise undulations as well as spanwise curvature (Yan et al., 2010; Palmisano et al., 2008; Kato et al., 2008; Tangorra et al., 2007). *Actively flexible* fins deform due to the presence of actuators instead of undergoing rigid body motions, like the heave and pitch of oscillating airfoils. The motion of actively flexible fins is fully prescribed. In contrast, *passively flexible* fins deform under fluid loading such that their motion is not fully prescribed, but a function of the forces applied to the fin. Tangorra et al. (2008a, 2008b) advanced their artificial pectoral fin (Figure 2) by not only matching the kinematics of the sunfish but also replicating the internal fin structure and material properties, which allowed the fin to have a greater degree of passive flexibility. This fin was used to fully characterize how sunfish produce and manipulate fluid forces to propel themselves and maneuver. With equivalent passive flexibility as the fins of the sunfish, the artificial fin was able to produce thrust on both the outstroke *and* instroke of its fin beat, as observed of the animal.

An excellent example demonstrating the link between biology, biomimetics, and bioinspired engineering

FIGURE 2

A biomimetic sunfish pectoral fin (Tangorra et al., 2008a, 2008b).



is in the development of an artificial ghost knifefish (Curet et al., 2010). Through observation of biology, a biorobotic device was developed and used to understand the locomotion strategies of this fish. Particle image velocimetry, in conjunction with computational fluid dynamics, were employed to explore the propulsive and station-keeping characteristics of this fascinating fish.

Batoid-Inspired Devices

There have also been attempts by researchers to develop batoid-inspired fins and AUVs. These devices mimic both the undulatory swimming seen in benthic rays (similar to the locomotion of the ghost knifefish) as well as the oscillatory swimming seen in pelagic rays, such as the manta. Many of these batoid-inspired devices are used as a platform for exploring actuation technologies.

Motors and servomotors are used in ray-like devices due to their simple controllability, high-speed operation and repeatability. Some motor-driven devices mimic undulatory rays (Low & Willy, 2006; V. y Alvarado et al., 2010), while others mimic oscillatory rays (Yang et al., 2009; Zhou & Low, 2010; Gao et al., 2007). Researchers have developed oscillatory ray-like vehicles based on pneumatic pectoral fins (Brower, 2006; Cai et al., 2010; Suzumori et al., 2007). Sfakiotakis et al. (2005) also used pneumatically driven "fin rays" to produce an undulatory ray-like device. Festo (2008) has built a BAUV called AquaRay, utilizing fluidic muscles. This robot uses an oscillatory flapping motion to swim, but no quantitative data on the performance is given. Takagi et al. (2007) utilized ionic polymer-metal composites (IPMCs) actuators to develop a stingray-like device that could achieve a swimming speed of 0.24 BL/s. Chen et al. (2011) developed a novel fabrication method to produce IPMCs that can deform with complex three-dimensional kinematics. This fabrication technology was used to produce a manta ray-like device. Shape memory alloys have also been employed in the design of artificial pectoral fins (Yong-hua et al., 2007; Wang et al., 2008). Wang et al. (2008) presented a robotic squid utilizing a rajiform mode of swimming to achieve 0.24 BL/s swimming speed. The best swimming speed performance of these actuator platforms was 1.4 BL/s achieved by the servomotor driven devices; however, the associated power cost is not given.

These studies showcase the plethora of actuator technologies that can be utilized to produce deformations similar to that of rays. One concern with this approach is that the actuator choice is directly coupled with the fin technology. An alternative approach is to start with a fin design that is actuator independent and so the choice of actuator is dependent on the application of the vehicle. For instance, if actuator efficiency is not a concern but noiseless operation is of prime importance, an SMA actuator could be chosen. Also, this approach opens up the possibility of replacing current actuators with new technologies that may be superior. Solutions like this are discussed next.

In a study to increase our understanding of the hydrodynamics of batoid locomotion, Clark and Smits (2006) designed and built an active artificial oscillating fin that was independent of the actuator. They quantified the performance of the fin by measuring the efficiency and thrust production, as well as determining an optimal traveling wave wavelength. Furthermore, by using dye flow visualization, they characterized the wake structure as a series of interacting trailing edge vortices forming a three-dimensional reverse von Kármán vortex street. In free swimming tests (Moored et al., 2011a), a swimming speed of 2 BL/s and a swimming economy, ζ ($\zeta = U = P_f$, where U is the swimming speed and P_f is the power consumption), of 0:132 BL/J was reached for an actively flexible single fin. When some passive flexibility was introduced, the swimming speed dropped to 1:7 BL/s while the economy rose to 0:18 BL/J at the same flapping frequency of 2 Hz. This work has also highlighted the prime importance of the traveling wave in ray-like propulsion.

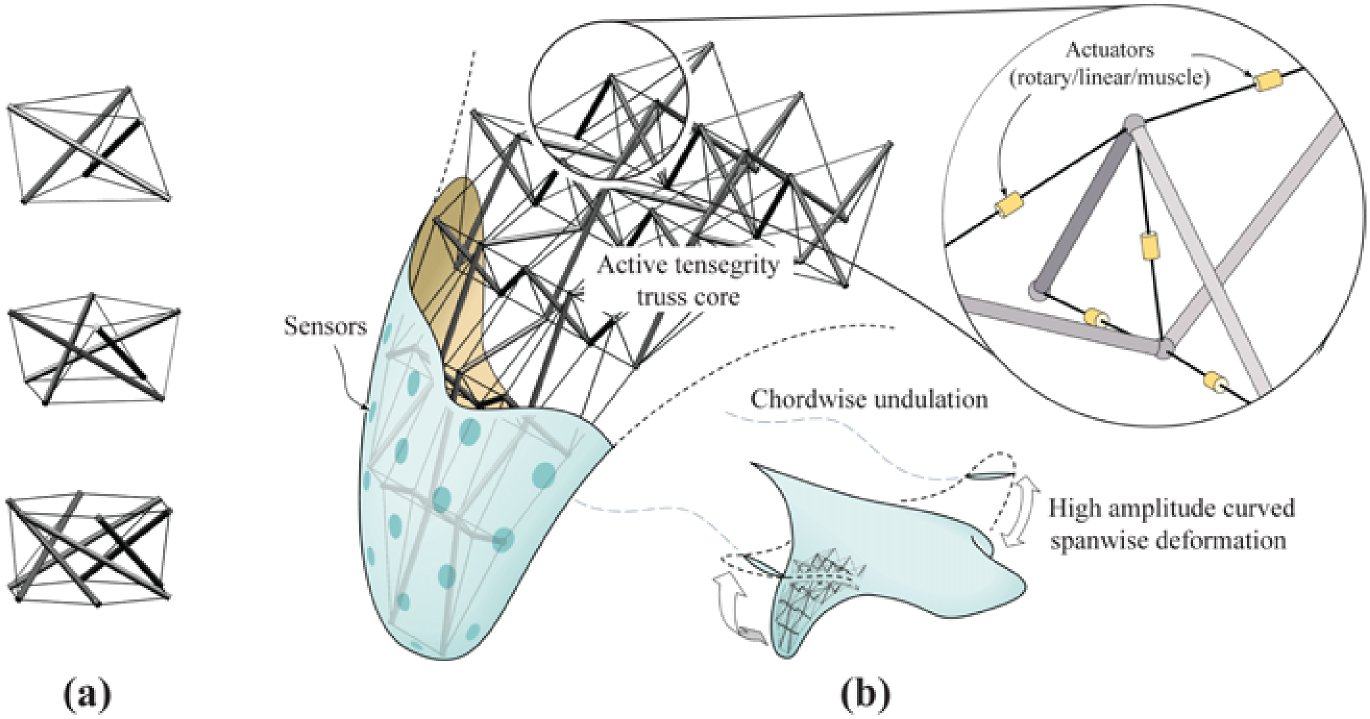
Another actuator-independent approach has been developed using active tensegrity structures. Tensegrity structures are truss-like structures where some of the rigid elements have been replaced by cable elements (Figure 3).

The cable elements must be in a state of tension for the structure to have integrity, giving rise to the contraction of "tensional-integrity" to tensegrity. Tensegrity structures act as a "skeleton-tendon" foundation that can use any actuator type to support the generation of large loads, match the kinematics of batoid rays, and perform with minimal actuation energy (Moored et al., 2011b; Moored & Bart-Smith, 2009).

Various tensegrity actuation strategies are explored that are capable of matching the key kinematic features of batoid-propulsion: a chordwise traveling wave coupled with a large amplitude curved spanwise deformation. The strategies involve either embedding the actuators into the tensegrity structure (*embedded actuation*) or migrating the actuators outside of

FIGURE 3

(a) Three-dimensional tensegrity structures (three, four, and six strut prismatic structures). (b) Tensegrity-based fin concept. The fin can deform with coupled curved spanwise motion and chordwise undulation to mimic the kinematics of the manta ray and the batoid family in general. The tensegrity deforms when active elements contract or expand.



the structure (*remote actuation*). With respect to embedded actuation, optimal solutions have been calculated that give the location and actuation strain necessary to match a target displacement field (Moored & Bart-Smith, 2007). However, embedded actuation is problematic, as it requires many actuators to match the complex ray kinematics, adds mass to the active structure (thereby requiring more power to flap) and limits the scalability of solutions to the size of the actuator. Remote actuation overcomes these limitations by placing the actuators outside of the active region and connecting to the structure via a routed cable. A general numerical model—applicable to any topology and any actuation strategy––has been derived (Moored & Bart-Smith, 2009).

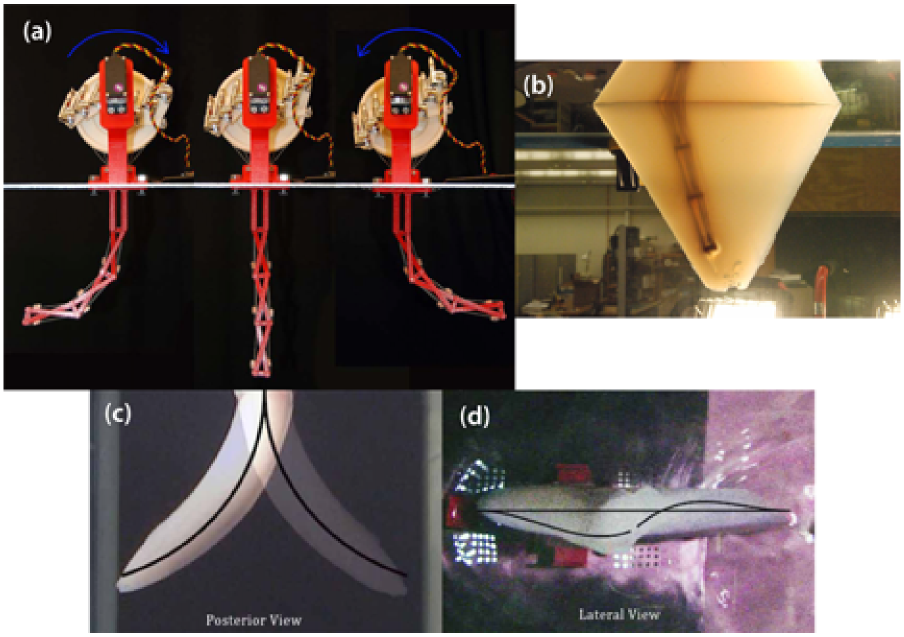
Moored et al. (2011) derive analytical solutions for active planar tensegrity beam structures. These solutions coupled with the numerical solution are utilized to identify optimal stiffness-to-mass and strength-to-mass strategies. Structural performance metrics were calculated showing that the fin structure can closely match the kinematics of the manta ray, under external loading, using open-loop actuation of four actuators remotely located outside of the active structure (Moored et al., 2011b). In an attempt to simplify the experimental design of an artificial fin, actuated via remote actuation, a single tensegrity beam was built and placed within an elastomer fin. Figure 4a shows images of a single tensegrity beam as it is actuated. The beam enables leading-edge actuation of the artificial fin (Figure 4b). This fin was then tested in a flow tank to observe the influence of frequency on the wake topology. Figures 4c and 4d show the actuating fin in water from the side and below. The black lines superimposed on these images represent the kinematical model for the kinematics of a cownose ray—note the excellent agreement between experiment and theory, especially with the passive response of the elastomer fin. This approach costs minimal power consumption and shows the simple design of a high-performance tensegrity-based artificial pectoral fin.

Concluding Comments and Future Directions

The idea to look to nature for inspiration is not new, and this rich arena

FIGURE 4

Example of a tensegrity-based actuating fin. (a) Photos of a tensegrity beams employing remote actuation. (b) Dorsal view of elastomer fin with leading edge actuation via tensegrity beam. (c) Posterior view of actuating fin shown in (b). (d) Lateral view of actuating fin. Note the lines in (c) and (d) represent the mathematical model derived to describe kinematic motions of a manta ray pectoral fin.



continues to be a source for engineers to aid in solving challenging problems. From Leonardo Da Vinci's flying machine, *Helical Air Screw*, to leading edge *whale-like* tubercles on wind turbine blades to improve efficiencies (Fish et al., 2011). The opportunities to learn from nature and emulate its unique approach to overcoming challenges seem endless. In this paper, we have touched upon the challenge of creating efficient, economic, and maneuverable underwater swimming platforms. We have focused on batoid fishes for inspiration in the design of the next generation of bioinspired underwater vehicles, as emulation of its swimming characteristics—efficiency, maneuverability, stealth, working environments, scalability—has the potential to significantly improve upon current state-of-the-art in AUV technologies.

The development of a batoid-inspired underwater vehicle can be classified in terms of the approach taken to achieve ray-like swimming. The first is developing a batoid-inspired AUV that performs as a platform to test the capabilities of a variety of traditional and novel actuating technologies. The motivation here is to demonstrate the capabilities of such devices—usually in terms of force and stroke—and is not necessarily a desire to truly replicate the biological system. These actuators include electroactive polymers, fluidic muscles, shape memory alloys, motors and servomotors. Of particular interest in testing these actuators has been the challenge of quantifying the swimming performance of the particular vehicle, many of which do not necessarily mimic the kinematics of batoid fishes. As biology has limitations due to the materials available to construct a body and the evolutionary process that produces an organism, possible improvements to the basic body plan can perhaps be engineered to enhance performance beyond the capabilities of nature.

The second approach considers fundamental questions associated with biology's solutions to propulsion, maneuverability, stability, and stealth. Technology is used in this case to replicate the biology to help answer these questions. Using the underlying biology as the basis for inquiry, the mechanisms that dictate batoid swimming performance are explored. This is being done through the design and development of artificial systems—either real or virtual—that can achieve near identical kinematic motions of the rays being studied. Specifically, researchers are working to elucidate the dominant mechanisms in batoid swimming that dictate efficiency and maneuverability. A key outcome of this work is to fully explore nature's design space and beyond. By mimicking biology, we attempt to elucidate the key features that control and optimize function. Nature evolves solutions that satisfy multiple constraints; engineers and scientists can design for a single desired outcome. By identifying and quantifying the key features/characteristics that dictate optimality, we can judiciously choose to build these into an artificial system, depending on the required functionality of the device. For example, one may desire a vehicle that can swim for as long as possible or as fast as possible—two different solutions may be necessary for these two requirements.

As mentioned in Understanding Biological Foundation, there has been an extensive study of the underlying cartilage structure of various batoid rays (Schaefer & Summers, 2005). Biomechanical studies of the cartilage arrangement have been carried out to examine the relationship between the form of the underlying structure and its impact on the function (Russo et al., 2011). In this work, Russo et al. have taken the cartilage architecture and developed a numerical model to study the kinematic function of this form. This initial study is beginning to explore the relationship between form and function.

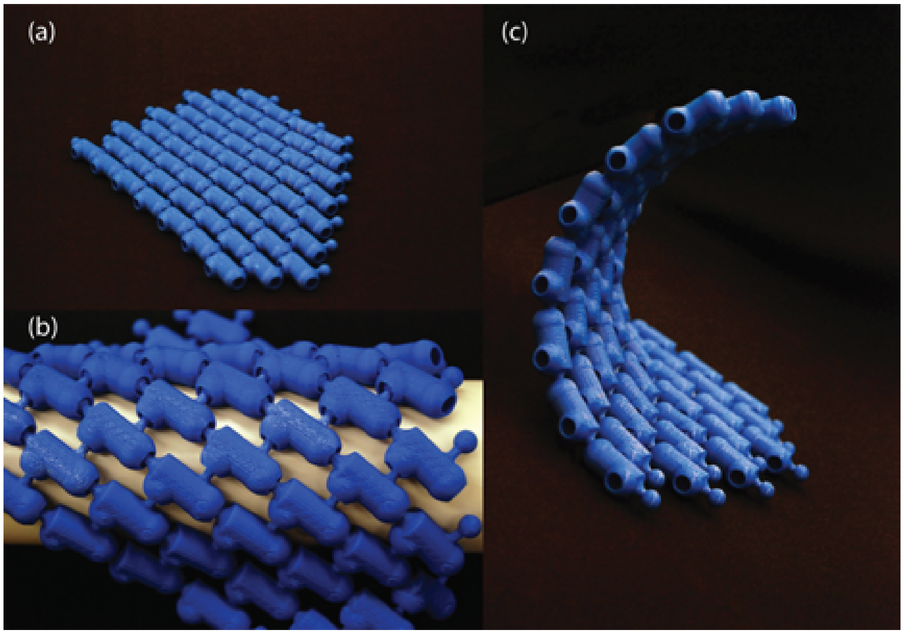
One of the most exciting developments in the creation of these bio-inspired devices and vehicles is in the development of rapid prototyping fabrication (Figure 5). This has opened the possibility to build a cartilage structure that uses the same design principles observed in nature, as described by Schaefer & Summers (2005). In this physical model, cartilage elements are connected in the spanwise direction with cross-bracing in the chordwise direction to mimic the architecture of the Atlantic stingray (www.bartsmithlabs.com). This technology enables the design to be quickly and easily varied so as to answer questions regarding the influence of the architecture on kinematic performance. The images in Figure 5 are compelling, as they demonstrate kinematic capabilities and possibilities of such a structure. By mimicking the underlying structure of biology, we can explore the capabilities of these species and potentially expand upon them.

Significant progress has been made, but there is still much to be done. Information on the kinematics of swimming is being generated, but there is still much to be learned, especially with respect to some of the more fine motor skills observed. Also, not much is known about the hydroacoustic properties of the biology. Material properties of the constituent parts of the pectoral fin are needed to improve the fidelity biomechanical models that describe form and function. Lastly, more investigation of the sensing and control strategies of batoids is needed. This improved understanding will provide valuable insight when more sophisticated vehicles are developed. With regard to engineering a batoid-inspired AUV, there are huge opportunities in actuator design and development. Structural and material design and selection also are areas that need to be addressed. For example, how do we design a skin that can accommodate both the out-of-place hydrodynamic forces and the potential in-plane stretching experienced during actuation. How do the properties of the artificial system scale with the biological properties? Actuation technology is an area that has the potential to revolutionize the field of biomimicry and bio-inspired engineering.

In this paper, we have focused on a small subset of bio-inspired underwater vehicles. We have presented a review of work related to the development of a bio-inspired underwater robot—actuation technology integrated into a batoid-like vehicle and understanding the biological foundation to explore the full design space. It is clear though that these two categories are very closely related. Without actuator development, it may not be possible to achieve anything close to what biology achieves. But a clear picture of biology function is needed so that actuator requirements can be quantified. Synergy between biology, biomimicry, and bio-inspired engineering is essential if we want to develop the next generation of underwater vehicles.

FIGURE 5

Example of artificial cartilage structure design using rapid-prototyping technology. The individual elements represent the cartilage elements found in the pectoral fins of batoid rays. The arrangement and connectivity are similar to portions found in the Atlantic stingray.



Acknowledgments

The authors would like to acknowledge funding from the Office of Naval Research through the MURI program on Biologically Inspired Autonomous Sea Vehicles (Program Manager: Dr. R. Brizzolara, Contract No. N00014-08-1-0642) and the David and Lucille Packard Foundation.

References

Abbott, I.H., & von Doenhoff, A.E. 1949. Theory of Wing Sections: Including a Summary of Airfoil Data. New York: McGraw-Hill.

Ayers, J., Wilbur, C., & Olcott, C. 2000. Lamprey robots. In: Proceedings of 1st International Symposium on Aqua Bio-mechanisms, eds. Wu, T., & Kato, N. Honolulu, Hawaii: Tokai University Pacific Center.

Anderson, J.M., & Chhabra, N.K. 2002. Maneuvering and stability performance of a robotic tuna. Integr Comp Biol. 42(1): 118-26. doi: 10.1093/42.1.118.

Bandyopadhyay, P.R. 2005. Trends in bio-robotic autonomous undersea vehicles. IEEE J Oceanic Eng. 30(1):109-139. doi: 10.1109/JOE.2005.843748.

Barrett, D., Grosenbaugh, M., & Triantafyllou, M. 1996. The optimal control of a flexible hull robotic undersea vehicle propelled by an oscillating foil. In: Proceedings of the Symposium on Autonomous Underwater Vehicle Technology, AUV'96. 1-9. Monterey, CA: IEEE. doi: 10.1109/AUV.1996.532833.

Blidberg, D.R. 2001. The development of autonomous underwater vehicles (AUVs): A brief summary. In: IEEE ICRA Conference, Seoul Korea, May 21-25, 2001.

Borgen, M.G., Washington, G.N., & Kinzel, G.L. 2003. Design and evolution of a piezoelectrically actuated miniature swimming vehicle. IEEE-ASME T Mech. 8(1):66-76. doi: 10.1109/TMECH.2003.809131.

Breder, C.M., Jr. 1926. The locomotion of fishes. Zoologica. 4:159-297.

Brower, T.P.L. 2006. Design of a manta ray inspired underwater propulsive mechanism for long range, low power operation. Master's thesis, Tufts University.

Cai, Y., Bi, S., & Zheng, L. 2010. Design and experiments of a robotic fish imitating cow-nosed ray. J Bionic Eng. 7(2):120-6. doi: 10.1016/S1672-6529(09)60204-3.

Chen, Z., Um, T.I., & Bart-Smith, H. 2011. A novel fabrication of ionic polymer-metal composite membrane actuator capable of 3-dimensional kinematic motions. Sensor Actuat A-Phys. 168(1):131-9. doi: 10.1016/j.sna.2011.02.034.

Clark, R.P., & Smits, A.J. 2006. Thrust production and wake structure of a batoid-inspired oscillating fin. J Fluid Mech. 562: 415-29. doi: 10.1017/S0022112006001297.

Colgate, J.E., & Lynch, K.M. 2004. Mechanics and control of swimming: A review. IEEE J Oceanic Eng. 29(3):660-73.

Combes, S.A., & Daniel, T.L. 2001. Shape, flapping and flexion: wing and fin design for forward flight. J Exp Biol. 204(12):2073-85.

Crespi, A., Badertscher, A., Guignard, A., & Ijspeert, A.J. 2004. An amphibious robot capable of snake and lamprey-like locomotion. In: Proceedings of the 35th International Symposium on Robotics ISR 2004. Paris, France: ISR publisher.

Curet, O.M., Patankar, N.A., Lauder, G.V., & MacIver, M.A. 2010. Aquatic manoeuvering with counter-propagating waves: a novel locomotive strategy. J R Soc Interface. 8(60):1041-50.

Dennler, G., Scharber, M., Ameri, T., Denk, P., Forberich, K., Waldauf, C., & Brabec, C. 2008. Design rules for donors in bulk-heterojunction tandem solar cells? Towards 15% Energy-Conversion Efficiency. Adv Mater. 20(3):579-83. doi: 10.1002/adma.200702337.

Dobbins, P. 2007. Dolphin sonar: Modelling a new receiver concept. Bioinspir Biomim. 2:19. doi: 10.1088/1748-3182/2/1/003.

Drucker, E.G., & Jensen, J.S. 1997. Kinematic and electromyographic analysis of steady pectoral fin swimming in the surfperches. J Exp Biol. 200:1709-23.

Festo, M. 2008. Fluidic Muscle Brochure. http://www/festo.com/cms/en-us_us/5030.htm.

Fish, F.E., & Lauder, G.V. 2006. Passive and active flow control by swimming fishes and mammals. Annu Rev Fluid Mech. 38:193-224. doi: 10.1146/annurev.fluid.38.050304.092201.

Fish, F.E., Lauder, G.V., Mittal, R., Techet, A.H., Triantafyllou, M.S., Walker, J.A., & Webb, P.W. 2003. Conceptual design for the construction of a biorobotic AUV based on biological hydrodynamics. In: Proceedings of the 13th International Symposium on Unmanned Untethered Submersible Technology. Durham, NH: AUSI (Autonomous Undersea Systems Institute).

Fish, F.E., Weber, P.W., Murray, M.M., & Howle, L.E. 2011. The humpback whale's flipper: Application of bio-inspired tubercle technology. Integr Comp Biol. 211:1857-67.

Gao, J., Bi, S., Xu, Y., & Liu, C. 2007. Development and design of a robotic manta ray featuring flexible pectoral fins. In: IEEE International Conference on Robotics and Biomimetics, December 15-18, 2007. ROBIO 2007, 519-23. Yalong Bay of Sanya, China: IEEE.

Gibb, A., Jayne, B., & Lauder, G. 1994. Kinematics of pectoral fin locomotion in the bluegill sunfish *Lepomis machrochirus*. J Exp Biol. 189:133-61.

Heine, C. 1992. Mechanics of flapping fin locomotion in the cownose ray, *Rhinoptera bonasus* (Elasmobranchii, Myliobatidae). Ph.D. thesis, Duke University.

Jaffe, J., Moore, K., McLean, J., & Strand, M. 2001. Underwater optical imaging: status and prospects. Oceanography. 14(3):66-76.

Jalbert, J., Baker, J., Duchesney, J., Pietryka, P., Dalton, W., Blidberg, D., … Holappa, K. 2003. Solarpowered autonomous underwater vehicle development. In: Proceedings of the Thirteenth International Symposium on Unmanned Untethered Submersible Technology. Durham, NH: Autonomous Undersea Systems Institute.

Kato, N. 1998. Locomotion by mechanical pectoral fins. J Mar Sci Technol. 3(3):113-21. doi: 10.1007/BF02492918.

Kato, N., Ando, Y., Tomokazu, A., Suzuki, H., Suzumori, K., Kanda, T., & Endo, S. 2008. Elastic pectoral fin actuators for biomimetic underwater vehicles. In: Bio-mechanisms of Swimming and Flying, eds. Kato, N., & Kamimura, S., Part 3, 271-82. Springer. doi: 10.1007/978-4-431-73380-5_22.

Kato, N., & Furushima, M. 2002. Pectoral fin model for maneuver of underwater vehicles. In: Autonomous Underwater Vehicle Technology, 1996. AUV'96, Proceedings of the 1996 Symposium on IEEE. pp. 49-56. Durham, NH: Autonomous Undersea Systems Institute.

Klausewitz, W. 1964. Der lokomotionsmodus der Flugelrochen (Myliobatoidei). Zool Anz. 173:111-20.

Kocak, D., & Caimi, F. 2005. The current art of underwater imaging with a glimpse of the past and vision of the future. Mar Technol Soc J. 39(3):5-26. doi: 10.4031/002533205787442576.

Lauder, G.V., & Jayne, B.C. 1996. Pectoral fin locomotion in fishes: Testing drag-based models using three-dimensional kinematics. Am Zool. 36(6):567-81.

Lauder, G.V., Nauen, J.C., & Drucker, E.G. 2002. Experimental hydrodynamics and evolution: function of median fins in ray-finned fishes 1. Integr Comp Biol. 42(5):1009-17. doi: 10.1093/icb/42.5.1009.

Licht, S., Polidoro, V., Flores, M., Hover, F.S., & Triantafyllou, M.S. 2004. Design and projected performance of a apping foil AUV. IEEE J Oceanic Eng. 29(3):786-94. doi: 10.1109/JOE.2004.833126.

Listak, M., Martin, G., Pugal, D., Aabloo, A., & Kruusmaa, M. 2005. Design of a semiautonomous biomimetic underwater vehicle for environmental monitoring. In: Computational Intelligence in Robotics and Automation. Espoo, Finland: IEEE.

Low, K.H., & Willy, A. 2006. Biomimetic motion planning of an undulating robotic fish fin. J Vib Control. 12:1337-59. doi: 10.1177/1077546306070597.

Mojarrad, M. 2000. AUV biomimetic propulsion. In: OCEANS 2000 MTS/IEEE Conference and Exhibition. pp. 2141-6. Providence, RI: IEEE.

Moored, K.W. August 2010. The design of a novel tensegrity-based synthetic pectoral fin for bio-inspired propulsion. Ph.D. thesis, University of Virginia.

Moored, K.W., & Bart-Smith, H. 2007. The analysis of tensegrity structures for the design of a morphing wing. J Appl Mech. 74:668-76. doi: 10.1115/1.2424718.

Moored, K.W., & Bart-Smith, H. 2009. Investigation of clustered actuation in tensegrity structures. Int J Solids Struct. 46:3272-81. doi: 10.1016/j.ijsolstr.2009.04.026.

Moored, K.W., Dewey, P.A., Leftwich, M.C., Bart-Smith, H., & Smits, A.J. 2011a. Bio-inspired propulsion mechanisms based on manta ray locomotion. Mar Technol Soc J. 45(4):110-8.

Moored, K.W., Kemp, T.H., Houle, N.E., & Bart-Smith, H. 2011b. Analytical predictions, optimization and design of a tensegrity-based artificial pectoral fin. Int J Solids Struct. (Accepted for Publication).

Palmisano, J., Geder, J., Ramamurti, R., Liu, K.J., Cohen, J., Mengesha, T., … Ratna, B. 2008. Design, development, and testing of flapping fins with actively controlled curvature for an unmanned underwater vehicle. In: Bio-mechanisms of Swimming and Flying: Fluid Dynamics, Biomimetic Robots, and Sports Science, eds. Kato, N., & Kamimura, S., 283-94. Berlin: Springer.

Palmisano, J., Ramamurti, R., Lu, K.J., Cohen, J., Sandberg, W., & Ratna, B. 2007. Design of a biomimetic controlled-curvature robotic pectoral fin. In: IEEE International Conference on Robotics and Automation (ICRA). 966-73. IEEE.

Pederzani, J.-N., Moored, K.W., Fish, F.E., & Haj-Hariri, H. 2011. A numerical investigation of the hydrodynamic signature of batoid swimming. In: Society for Integrative and Comparative Biology, Annual meeting. Salt Lake City, UT: Oxford Univ Press Inc.

Rosenberger, L.J. 2001. Pectoral fin locomotion in batoid fishes: Undulation versus oscillation. J Exp Biol. 204(2):379-94.

Russo, R.S., Blemker, S., Fish, F.E., Moored, K.W., & Bart-Smith, H. 2011. Form function relationship between ray skeletal architecture and ray locomotion. In: Annual meeting of the Society for Integrative and Comparative Biology. Salt Lake City, UT: Oxford Univ Press Inc.

Sasko, D.E., Dean, M.N., Motta, P.J., & Hueter, R.E. 2006. Prey capture behavior and kinematics of the Atlantic cownose ray, *Rhinoptera bonasus*. Zoology. 109(3):171-81. doi: 10.1016/j.zool.2005.12.005.

Schaefer, J.T., & Summers, A.P. 2005. Batoid wing skeletal structure: Novel morphologies, mechanical implications, and phylogenetic patterns. J Morphol. 264(3): 298-313. doi: 10.1002/jmor.10331.

Sfakiotakis, M., Laue, D., & Davies, B. 2005. An experimental undulating-fin device using the parallel bellows actuator. In: Robotics and Automation, Proceedings 2001 ICRA. IEEE International Conference on. pp. 2356-62. Seoul, Korea: IEEE.

Sfakiotakis, M., Lane, D.M., & Davies, J.B.C. 1999. Review of fish swimming modes for aquatic locomotion. IEEE J Oceanic Eng. 24(2):237-52. doi: 10.1109/48.757275.

Stocking, J.B., Eberhardt, W.C., Shakhsheer, J.R., Paulus, M.A., & Calhoun, B.H. 2010. A capacitance-based whisker-like artificial sensor for fluid motion sensing. In: IEEE Sensors. Waikoloa, Big Island, Hawaii.

Summers, A. 2000. Stifiening the stingray skeleton: An investigation of durophagy in myliobatid stingrays (Chondrichthyes, Batoidea, Myliobatidae). J Morphol. 243(2):113-26. doi: 10.1002/(SICI)1097-4687(200002)243:2<113::AID-JMOR1>3.0.CO;2-A.

Suzumori, K., Endo, S., Kanda, T., Kato, N., & Suzuki, H. 2007. A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot. In: 2007 IEEE International

Conference on Robotics and Automation. pp. 4975-980. IEEE.

Takagi, K., Yamamura, M., Luo, Z., Onishi, M., Hirano, S., Asaka, K., & Hayakawa, Y. 2007. Development of a rajiform swimming robot using ionic polymer artificial muscles. In: Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on. pp. 1861-6. Beijing, China: IEEE.

Tangorra, J., Anquetil, P., Fofonoff, T., Chen, A., Zio, M., & Hunter, I. 2007. The application of conducting polymers to a biorobotic fin propulsor. Bioinspir Biomim. 2:S6. doi: 10.1088/1748-3182/2/2/S02.

Tangorra, J., Davidson, S., Hunter, I., Madden, P., Lauder, G., Haibo, D., … Mittal, R. 2008a. The development of a biologically inspired propulsor for unmanned underwater vehicles. IEEE J Oceanic Eng. 32(3):533-50.

Tangorra, J., Lauder, G., Madden, P., Mittal, R., Bozkurttas, M., & Hunter, I. 2008b. A biorobotic apping fin for propulsion and maneuvering. In: Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on. pp. 700-5. Pasadena, CA: IEEE.

V. y Alvarado, P., Chin, S., Larson, W., Mazumdar, A., & Youcef-Toumi, K. 2010. A soft body under-actuated approach to multi degree of freedom biomimetic robots: A stingray example. In: Biomedical Robotics and Biomechatronics (BioRob), 2010 3rd IEEE RAS and EMBS International Conference on. pp. 473-8. Tokyo, Japan: IEEE.

Walker, J.A., & Westneat, M.W. 1997. Labriform propulsion in fishes: kinematics of flapping aquatic flight in the bird wrasse *Gomphosus varius* (Labridae). J Exp Biol. 200:1549-69.

Wang, Z., Hang, G., Wang, Y., Li, J., & Du, W. 2008. Embedded SMA wire actuated biomimetic fin: a module for biomimetic underwater propulsion. Smart Mater Struct. 17:025039. doi: 10.1088/0964-1726/17/2/025039.

Webb, D., & Simonetti, P. 1999. The Slocum AUV: An environmentally propelled underwater glider. In: International Symposium on Unmanned Untethered Submersible Technology. 75-85. Durham, NH: Autonomous Undersea Systems Institute.

Webb, P.W. 1994. Mechanics and Physiology of Animal Swimming: The Biology of Fish Swimming. Cambridge, UK: Cambridge University Press. 45-62 pp.

Yan, Q., Zhang, S., & Yang, J. 2010. Initial implementation of basic actuated unit of a flexible pectoral fin driven by SMA. In: Mechatronics and Automation (ICMA), 2010 International Conference on. pp. 899-904. Xi’an, China: IEEE.

Yang, S., Qiu, J., & Han, X. 2009. Kinematics modeling and experiments of pectoral oscillation propulsion robotic fish. J Bionic Eng. 6(2):174-9. doi: 10.1016/S1672-6529(08)60114-6.

Yang, Y., Chen, J., Engel, J., Pandya, S., Chen, N., Tucker, C., … Liu, C. 2006. Distant touch hydrodynamic imaging with an artificial lateral line. P Natl Acad Sci. 103(50):18891.

Yong-hua, Z., Shi-wu, Z., Jie, Y., & Low, K. 2007. Morphologic optimal design of bionic undulating fin based on computational fluid dynamics. In: Mechatronics and Automation, 2007. ICMA 2007. International Conference on. pp. 491-6. Harbin, Heilongjian, China: IEEE.

Yu, J., Hu, Y., Fan, R., Wang, L., & Huo, J. 2007. Mechanical design and motion control of a biomimetic robotic dolphin. Adv Robotics. 21(3):499-513. doi: 10.1163/156855307780131974.

Yu, J., Tan, M., Wang, S., & Chen, E. 2004. Development of a biomimetic robotic fish and its control algorithm. IEEE Sys Man Cybern B. 34(4), 1798-810.

Zhou, C., & Low, K. 2010. Better endurance and load capacity: An improved design of manta ray robot. J Bionic Eng. 7:S137-44. doi: 10.1016/S1672-6529(09)60227-4.