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SYMPOSIUM

Bioinspiration: Applying Mechanical Design to Experimental Biology

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Synopsis The production of bioinspired and biomimetic constructs has fostered much collaboration between biologists and engineers, although the extent of biological accuracy employed in the designs produced has not always been a priority. Even the exact definitions of "bioinspired" and "biomimetic" differ among biologists, engineers, and industrial designers, leading to confusion regarding the level of integration and replication of biological principles and physiology. By any name, biologically-inspired mechanical constructs have become an increasingly important research tool in experimental biology, offering the opportunity to focus research by creating model organisms that can be easily manipulated to fill a desired parameter space of structural and functional repertoires. Innovative researchers with both biological and engineering backgrounds have found ways to use bioinspired models to explore the biomechanics of organisms from all kingdoms to answer a variety of different questions. Bringing together these biologists and engineers will hopefully result in an open discourse of techniques and fruitful collaborations for experimental and industrial endeavors.

Semantics

Research involving bioinspired and biomimetic models has become increasingly important in biology and engineering, as well as in applications to industrial design. Within academics, however, there is a disparity in the meaning of these different terms as to the level of biological accuracy they imply in their definition. This issue of semantics is especially problematic for the possibilities of collaborative relationships between biologists and engineers in creating bioinspired and biomimetic constructs. Biomimetics, by literal definition, refers to the imitation of nature. Whether the level of imitation is in outward appearance only (Anderson and Chhabra 2002), with the internal workings of the model behaving and looking nothing like the biological analog, or whether the device is the most accurate prosthetic device imaginable, virtually indistinguishable from a human limb, for example, varies wildly from model to model. Similarly, the term bioinspired has been used to explain everything from model constructs that may be only loosely based on a biological muse, to scientific devices that are meant to operate on the same principles as actual organisms but need not resemble them (Chan et al. 2005; Long et al. 2006).

Another perspective avoids confusing terminology and highlights the reason for creating a biologically-inspired model: the need for robotic models is usually either problem-based or solution-based (Yen and Weissburg 2006). Problem-based robotic constructs are more familiar to biologists and engineers and are designed with the goal of investigating a particular question (Lauder et al. 2007). Solution-based models generally use known biological processes or physiology in an industrially useful application (Solga et al. 2007). Whatever the terminology used, it is essential that biologists, engineers, and designers are able to clearly communicate their intentions and goals in designing robotic models to one another, as the opportunities and need for collaboration among these three fields has grown immensely with our knowledge of biological systems and available technology.

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Robotic "model organisms"

There has been a rapid increase in the use of bioinspired robotic models in biological research over the past decade, and for good reason. From a biological perspective, robotic models of living systems perform two major functions: validation of a conceptual understanding of physical processes (Long et al. 2006; Lauder et al. 2007; Phelan et al. 2010) and, more commonly, exploration of biological parameter-spaces, including those not readily occupied by a living organism (Doorly et al. 2009). Regarding the former, a living organism is subject to the same laws of physics that an engineer creating a model system would be; physiological systems can be replicated by attempting to match material, structural, mechanical, electrical, and fluid properties. Once a suitable model is constructed, it can be used to address numerous scientific questions, some of which would be nearly impossible to investigate solely by relying on a live biological organism to repeatedly perform the behavior of interest. For example, trying to get a fish to swim in a flow tank, in a particular way and location so as to orient its fin at just such an angle and move in a particular direction may not occur very often, even if that motion is part of the fish's natural repertoire (Flammang and Lauder 2009). It might be possible to get kinematic data from a few sequences, but getting the fish to perform repeatedly in order to analyze the fluid dynamics created by a specific behavior is something else entirely; this phenomenon, affectionately known as the "Harvard Law of Animal Behavior" is all too familiar to experimental biologists (Fig. 1) (Maye et al. 2007). Enter the bioinspired robotic model. With the appropriate model it is possible to replicate the known or desired kinematic pattern and examine the motion in simplified terms using only selected component variables (Phelan et al. 2010), or to produce a motion that fills a parameter-space but is not observed under normal conditions (Long 2007).

There are several difficulties in using a robotic model for experimental biology. One of the greatest is in building a robot that has sufficiently accurate biological properties to act as an analog for a model organism. Attaining such a model is generally achieved through several iterations of design and testing until an appropriate robotic model has the necessary physical qualities to address the biological question at hand. This process itself can be very valuable to a researcher, as it requires in-depth understanding of the biological organism being modeled. In this summary, we highlight current bioinspired work using mechanical or physical models and what is learned about the organisms that inspired them.

Wing deformation: material and design

Understanding the differences between active and passive wing movements is important when thinking about insect flight. Insect wings do not contain muscles that actively control shape and bending, and therefore control of aerodynamics during flight is greatly influenced by wing structure. Artificial models of wings allow authors to compare different designs and test the role of morphological features under controlled conditions. In robotic insect models, it is difficult to recreate wing deformation due to inertial forces, and as a result, these models often cannot fly. However, using a series of complex molding techniques, Tanaka and Wood (2011) have created an at-scale flying flapper model that exhibits passive wing deformation and can fly much like an actual butterfly. At-scale wings have similar morphology and flexibility as butterfly wings, and these variables can be modified in the flapping model for the purpose of testing hypotheses. For example, by adding veins to the wing of the model butterfly, both the angle of attack and the lift coefficient increased. In a hoverfly model, corrugation of the wings impacted bending stiffness.

As with the insect wings above, bat wings are pliant and deform during flight. Deformation is promoted by skin that is corrugated and stretches under loads, but also expands similar to foam with a

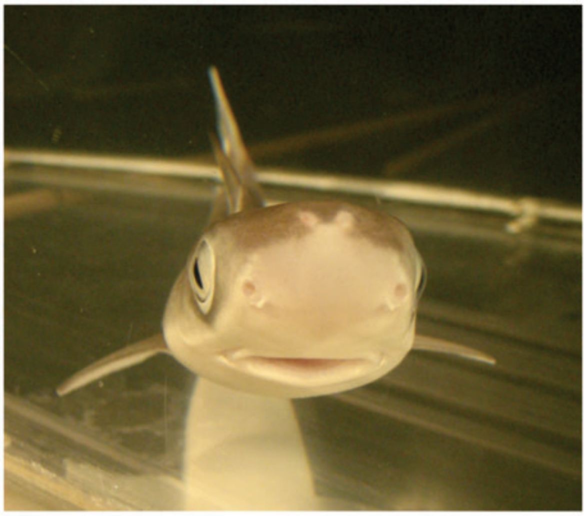

Fig. 1 Mechanical designs are programmed to perform specific actions at designated times. On the other hand, biological organisms often perform of their own volition. For example, this spiny dogfish (*Squalus acanthias*) refusing to swim in flow tank. Photo by B. Flammang.

negative Poisson's ratio (Cheney et al. 2011). Members of Sharon Swartz's laboratory at Brown University are collaborating with an engineering group to develop and build physical models of the bat skeletal system for use in a robotic flying device (Swartz and Breuer 2011). However, the desired biological accuracy of the model may not be achievable as the number of bones and articulations in a mammalian skeleton may be too complex for bioinspired physical models.

Bioinspired design to understand performance in aquatic environments

Vortices are produced as the result of an organism applying a force and adding momentum to the fluid around it, resulting in the production of thrust. Vortices being shed behind a swimming organism leave a trailing-wake signature behind. Jellyfish may enhance propulsion in a way not previously studied, by entraining the fluid around them to increase the vorticity of the wake being shed. Following these findings, a propeller-driven unmanned vehicle was designed by Jon Dabiri's group at Caltech to use a pulsejet similar to that of the jellyfish. As in the biological model, the pulsejet increases hydrodynamic efficiency by 50% and consumed less power than a steady jet (Dabiri 2011).

By far, the most common biological solution to maneuvering through water is by using fins. As the most specious group of vertebrates, fishes demonstrate an extraordinary variety of fin morphologies and swimming kinematics. Research as to how the material properties and kinematics of fish's pectoral fins impact propulsion is being addressed using a biorobotic pectoral fin, inspired by the swimming kinematics and sensory physiology of the bluegill sunfish (Phelan et al. 2010; Tangorra et al. 2011). Closed-loop control of the pectoral fin uses mechanical and hydrodynamic feedback from fluid loading on the fin to produce information for corrective movement. Results suggest that fin curvature, actuator force, and pressure along the fish's body provide information to the fish on how to best modify propulsive forces, but none of these variables alone are predictive. In addition to the pectoral fin, these methods are currently being employed to determine the effects of material properties and kinematics in the caudal fin of fishes.

Vertebral number varies widely in fishes, and it may be correlated with maneuverability and performance in swimming (Brainerd and Patek 1998; Porter et al. 2009). In simulation, body stiffness has optimal values, mediated by muscular contraction, for both maximum acceleration and steady swimming (Tytell et al. 2010). Long et al. (2011) used a bioinspired robot propelled by biomimetic vertebral columns, to determine how vertebral column morphology, specifically vertebral number, and vertebral column stiffness influences swimming. This bioinspired robot allowed researchers to control motor output (frequency) and the physical properties (notochord stiffness and vertebral number). Performance parameters such as velocity and acceleration increased with increasing vertebral number and overall stiffness of the tail.

Investigators Winter et al. (2011), have extended their queries deeper within the aquatic environment, examining organisms that can burrow into the substrate. The Atlantic razor clam, *Ensis directus*, uses energy-saving mechanics allowing them to burrow up to five times their body length by fluidizing the sand around their shell. By uplifting their body with their muscular foot, and then contracting their shell, clams loosen the sand directly around their bodies. The goal was to generate a low power, compact, and lightweight reversible burrowing technology using the sand-fluidization method inspired by the razor clam. The resulting robot, Roboclam, was programmed with a genetic algorithm such that it 'learned' to dig efficiently in its environment. This technology may be useful for marine engineers to design low-impact anchors and for lying down undersea cables.

Robust designs

Animals are robust; they are persistent and able to withstand perturbations and modifications in their environment. When faced with hardships, they can heal, learn, and adapt to various situations. On the other hand, robots are limited to a particular suite of behaviors they are programmed to perform but cannot deal with multiple perturbations. Systems developed using genetic algorithms, such as Roboclam (Winter et al. 2011), are able to adapt and learn, but the number of sensors inputting information about their environment limits them. Overcoming robustness and scaling of resistance to damage are huge problems for building bioinspired designs. The arthropod exoskeleton is a potential solution to this problem. Arthropods are robust and their ability to continue to operate even after the loss of limbs or feet has been documented for several species (Spagna et al. 2007). Using an exoskeleton in a bioinspired robot will help overcome issues of robustness and there is also the potential for simplifying control (Full et al. 2011). This is bringing about a series of robots, like Rex presented herein, that operate using smart bodies rather than sensor systems.

In addition to an exoskeleton, another way to model a robust system is to design robust actuators in the joints. Biomechanics research focused on four-legged locomotion in dogs and goats inspired the design of a four-legged robotic model, BigDog. Studying the limb mechanics of walking, trotting, and galloping animals aided the design of limbs. The goal was to understand how compliance, center of mass, and gait worked in the biological models and then to transfer those principles to a quadrupedal robot (Lee and Biewener 2011). Using these mechanical principles, BigDog is able to walk and run.

Industrial considerations

In addition to building robotic models for experimental purposes, some biologists have applied their insights into physical phenomena toward useful marketable designs. A recent example of this incorporates the fluid dynamic properties of the bumps on the leading edge of whales' pectoral fins into designing a fan blade (Fish et al. 2011). Typically, this sort of marketing endeavor stems from an ''ah-ha'' moment following an understanding of a given biological system. While biological collaborations with industrial designers have been few, there is the possibility of incorporating biomechanical properties into the design of mass-produced items.

Transportation and medicine

Humpback whales are known for their graceful swimming and maneuverability despite their behemoth size and weight. The secret is in the large, bulbous tubercles along the leading edges of their pectoral fins, which act as passive-flow controllers increasing maneuverability (Fish et al. 2011). These tubercles delay the angle of attack until stall, increasing lift and decreasing drag by causing changes in vortex generation and boundary-layer flow. Now, tubercle-inspired designs have been added to foils for just these reasons, and are being used to improve performance of lifting bodies such as fans, airplanes, and windmills.

Cellular mechanics are moderated by biochemical environmental changes and vice versa. For example, the cytoskeleton provides the cell with structural support, but it is a dynamic material that changes with environmental conditions. Understanding cell function can be used to build bioinspired devices such as nanofactories (LeDuc et al. 2007). Conceptually, nanofactories can be used to isolate pathways of interest and modulate the way they process chemicals; as was illustrated by the example of the pathways of phenylketonurics (Leduc and Ruder 2011).

Finally, designs that take into account new biological data are also being used to developed new surgical devices. Many surgical instruments have not had an update in design for decades, if not longer. Using new data on material properties and morphology of structures can lead to novel updates that can improve patient recovery by patients. For example, devices such as rib spreaders, used during open-heart surgery, operate using an incremental arrangement of notches to spread the ribs. These notches do not take into account the forces at play and often result in broken ribs. However, new devices are being developed, that take forces into account and rather than using incremental notches, to use real-time information from the patient's body to determine the best rate for opening the surgical site (Pell 2011).

Conclusions

The rapid, recent growth in the number of investigators using bioinspired designs provides evidence for its utility in experimental biology. The examples herein are representative of a number of taxa but are not by any means an exhaustive list of the research being conducted on the use of bioinspired and biomimetic devices to address problem-based and solution-based questions (Yen and Weissburg 2006). Recently, Lentink and Biewener (2010) reviewed research on flight biomechanics and bioinspired designs and Lauder and Madden (2006) reviewed work on the use of bioinspired devices in biomechanics research in fishes. These projects and those presented here are truly interdisciplinary, drawing on expertise from artists, biologists, engineers, and others to address these research questions. If researchers can overcome communication issues, their collective efforts will greatly enable achievement of their common goals and have a broader impact on experimental biology, mechanical innovation, and industrial design.

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