Bionics: Biological insight into mechanical design

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When pressed with an engineering problem, humans often draw guidance and inspiration from the natural world (1). Through the process of evolution, organisms have experimented with form and function for at least 3 billion years before the first human manipulations of stone, bone, and antler. Although we cannot know for sure the extent to which biological models inspired our early ancestors, more recent examples of biomimetic designs are well documented. For example, birds and bats played a central role in one of the more triumphant feats of human engineering, the construction of an airplane. In the 16th century, Leonardo da Vinci sketched designs for gliding and flapping machines based on his anatomical study of birds. More than 300 years later, Otto Lilienthal built and flew gliding machines that were also patterned after birds (2). Sadly, Lilienthal died in one of his own creations, in part because he failed to solve a difficult problem for which animals would eventually provide another critical insight: how to steer and maneuver. The wing warping mechanism that enabled Orville and Wilbur Wright to steer their airplane past the cameras and into the history books is said to have been inspired by watching buzzards soar near their Ohio home (3).

It is perhaps not surprising that early aeronautical engineers were inspired by Nature given that the performance gap was so large and obvious. Because birds can fly and we cannot, only the most foolhardy or arrogant individual would design a flying craft without some reference to natural analogs. Most engineering projects, however, take place successfully without any explicit reference to Nature, in large part because natural analogs do not exist for most mechanical devices. One would need to search far and wide for a natural analog of a toaster. Nevertheless, in recent years there seems to be growing interest on the part of engineers to borrow design concepts from Nature. The discipline has grown to the point that books, articles, conference sessions, and university programs labeled *Bionics* or *Biomimetics* are quite common. Unfortunately, for many Americans the former term conjures up images of the *Six Million Dollar Man* using nuclear-powered legs to outrun bad guys in a Porsche. Such Hollywood images are ironic, because the dream of many mechanical engineers is to endow a robot with limbs and sense organs as elegant as those of a human, not to endow humans with structures as crude as those found on robots. As in the case of aerodynamics, biomimetic approaches appeal to roboticists, because the performance gap between mechanical devices and their natural analogs is so large.

One reason for the growing interest in *Bionics* is that fabrication methods are much more sophisticated than they used to be. Because of innovations in Materials Science, Electrical Engineering, Chemistry, and Molecular Genetics, it is possible to plan and construct complicated structures at the molecular or near molecular level. Examples include buckyballs, nanotubes, and the myriad of microelectromechanical devices (MEMs) constructed with technology derived from the silicon chip industry. Integrated circuits themselves play a role in *Bionics* projects aimed at constructing smart materials or mimicking the movement, behavior, and cognition of animals. In short, biological structures are complicated, and we are only now beginning to possess a sophisticated enough tool kit to mimic the salient features of that complexity.

Another reason for the increasing popularity of *Bionics* is simply that we know much more about how plants and animals work than we used to. The overwhelming success of Biology, practiced at the cellular and subcellular levels, has overshadowed many substantial advances in our knowledge of processes that operate at higher levels of biological complexity. Taking examples from studies on animal locomotion, biologists now understand how basilisk lizards walk on water (4), how penguins minimize drag (5), and how insects manage to remain airborne (6, 7), phenomena that, until recently, were poorly understood. The solutions to such puzzles do not impact the world of Science as does, say, sequencing the human genome. They do, however, identify specific structure–function relationships, and, as such, can provide assistance to engineers faced with analogous problems. The fields of Biology that use principles of Structural Engineering and Fluid Mechanics to draw structure–function relationships are *Functional Morphology* or *Biomechanics* (8). These disciplines are of particular use to *Bionics* engineers, because the behavior and performance of natural structures can be characterized with methods and units that are directly applicable to mechanical analogs. *Biomechanics* is hardly new; Galileo used physical principles to explain why the limb bones of large mammals are proportionally stouter, compared with those of small mammals. In his classic book, *On Growth and Form*, D'arcy Thomson used physical laws to explain developmental patterns in a variety of plants and animals. In recent years, however, *Biomechanics* has become increasingly sophisticated, aided by a battery of techniques including x-ray cinematography, atomic-force microscopy, high-speed video, sonomicrometry, particle–image velocimetry, and finite element analysis.

One lesson from biomechanical studies is that the salient features of a biological structure can reside entirely within its static morphology. A number of successful biomimetic designs are based on the clever morphology of biological materials. A simple and well-known example is Velcro, invented by George de Mestral, who was inspired by the hours wasted pulling burrs off his dog's fur after walks in the Swiss countryside. He devised the complementary hook and loop surfaces that have been holding our jacket cuffs together ever since.

Another example of a clever morphology is the lotus leaf. Although they live above muddy water and cannot actively groom themselves, lotus leaves remain pristine and dirt free. The self-cleaning ability of lotus leaves results from the tiny, wax-coated protuberances on their surface (9). When water falls on a leaf, it does not spread out and wet the surface, as it would on the smooth leaves of most plants, but rather forms tiny beads atop the knobby surface that collect dust and dirt as they roll off. A brand of paints (Lotusan, ISPO), is now available that makes use of a patented "Lotus-Effekt" to clean your house whenever it rains.

As do many fast-swimming marine organisms, sharks pay a large metabolic cost to overcome the drag on their body surface. The skin scales of some sharks possess tiny ridges that run parallel to the longitudinal body axis. The grooved body surface reduces drag through its influence on the boundary layer (10). Riblet sheets,

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modeled on shark skin, reduced the fuel consumption of an Airbus 320 when placed over the wings and fuselage.

As the above examples show, engineers and designers can mimic and utilize biological structures, provided that it is possible to fabricate the artificial material with the precision required to produce the desired effect. In the case of synthetic shark skin, once engineers determined the correct groove geometry, it was relatively easy to mold plastic sheets that reproduce the pattern. House paints replicating lotus leaves are presumably laced with a material to mimic the rough surface of the leaves.

But mimicking biological structures is not always easy. The trick in bringing Velcro to market was not figuring out how a burr works, but rather how to fabricate and mass-produce the fuzz and hook surfaces. An example that well illustrates the crudeness of our microfabrication techniques is spider silk. Silks are proteins secreted by specialized glands found in many groups of arthropods. More than 4,000 years ago, the Chinese domesticated the moth *Bombyx mori*, the primary source of textile silk. Although the quality of moth silk was great enough to have fueled the oldest intercontinental trade route in world history, its properties pale compared to spider silk (11). Spiders make a variety of different silks to serve different functions, but most research focuses on the drag-line silk that individual spiders use to hoist and lower their bodies. This silk can extend and stretch by 30% without snapping; it is stronger than the best metal alloys or synthetic polymers. The idea of ropes, parachutes, and bulletproof vests spun of spider silk has motivated the search for genes that encode silk proteins. Knowing the gene sequence, protein composition, and tertiary structure of silk is one thing; its manufacture is quite another. A large part of what makes silk silk is the elaborate plumbing and nozzle structures that spiders use to spin the protein into its functional form. Merely expressing silk proteins in cells lines or chemically synthesizing silk proteins en masse is insufficient to fabricate the elegant fibers.

The spider silk example illustrates one of the most enviable properties of biological systems: the ability to fabricate structures at a fine scale. Although the building blocks of bone, cartilage, cuticle, mucus, and silk can be relatively simple, they are arranged in rather complicated ways. Such geometric complexity is possible because the manufacture, deposition, and secretion of biological materials is regulated at the cellular and subcellular level. A good example of this structural sophistication is the exoskeleton of insects (12, 13). The cuticle surrounding an insect is composed of one topologically continuous sheet composed of proteins, lipids, and the polysaccharide chitin. Preceding each molt, the cuticle is secreted by an underlying layer of epithelial cells. Complex interactions of genes and signaling molecules spatially regulate the exact composition, density, and orientation of proteins and chitin molecules during cuticle formation. Temporal regulation of protein synthesis and deposition permits construction of elaborate layered cuticles that display the toughness of composite materials.

The result of such precise spatial and temporal regulation is a complex exoskeleton that is tagmatized into functional zones. Limbs consist of tough, rigid tubes made of molecular plywood, connected by complex joints made of hard junctures separated by rubbery membrane. The most elaborate example of an arthropod joint is the wing hinge, the morphological centerpiece of flight behavior (14). The hinge consists of a complex interconnected tangle of five hard scleratized elements, imbedded within thinner, more elastic cuticle, and bordered by the thick side walls of the thorax. In most insects, the muscles that actually power the wings are not attached to the hinge. Instead, flight muscles cause small strains within the walls of the thorax, which the hinge then amplifies into large oscillations of the wing. Small control muscles attached directly to the hinge enable the insect to alter wing motion during steering maneuvers (15). Although the material properties of the elements within the hinge are indeed remarkable, it is the structural complexity as much as the material properties that endow the wing hinge with its astonishing characteristics.

Sometimes it is not the actual morphology that endows a biological structure with its functional properties, but the intelligence with which it is used. Intelligence does not necessarily imply cognition; it may simply reflect the ability to use a structure in an efficient and flexible manner. Although most biological structures are not intelligent by human standards, they nevertheless outperform most bricks and I-beams. A good example is the insect wing. Engineers and biologists have long struggled to explain how a bumblebee (or any insect) remains in the air by flapping its wings. Conventional steady-state aerodynamic theory is based on rigid wings moving at a uniform speed. Such theory cannot account for the force required to keep an insect in the air. The solution to this paradox resides not in the intrinsic properties of wings, but rather in the way that insects use them. By flapping the wings back and forth, insects take advantage of the unsteady mechanisms that produce forces above and beyond those possible under steady-state conditions (6, 7). Several research groups are actively attempting to construct miniature flying devices patterned after insects. Their challenge is not simply to replicate an insect wing, but to create a mechanism that flaps it just as effectively.

Intelligent structures do not always function the same way; they adapt to local functional requirements. Even the simplest plants and animals sense their world, integrate information, and act accordingly. Feedback-control mechanisms are extremely important features that endow organisms with flexibility and robustness. Even plants, which lack a nervous system, can nevertheless grow leaves and branches toward light, roots toward water, or spatially regulate growth so as to minimize mechanical stress. The functions of biological structures cannot be fully understood or accurately mimicked without taking this complex dynamic feedback into account. Of all the properties of biological entities (with the possible exception of self-replication), it is their intelligence and flexibility that is perhaps the most difficult to duplicate in an artificial device.

The next decade should be exciting for the field of *Bionics*. Just as biologists are discovering the structural and physiological mechanisms that underlie the functional properties of plants and animals, engineers are beginning to develop a fabrication tool kit that is sophisticated enough to capture their salient features. As the performance gap between biological structures and our mechanical analogs shortens, engineers may feel increasingly encouraged to seek and adopt design concepts from Nature. Although the devices they construct may at first appear alien, their origins in the organic world may endow them with an odd familiarity.

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