Biomechanics

Proceedings of the First Rock Island Arsenal Biomechanics Symposium
April 5-6, 1967

Edited by

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Preface

The two-day symposium held on the campus of Augustana College, Rock Island, Illinois, April 5 and 6, 1967, explored the interrelationship between the life sciences and engineering and attempted to make the scientific community more aware of an interdisciplinary approach to engineering. The symposium sought to stimulate new mechanical engineering concepts perhaps not possible utilizing data available only through ideas derived from the traditional physical sciences.

Devoted to closed loop biomechanical systems in which biological forces and feedback influence mechanical, physical, and chemical systems, this first Rock Island Arsenal Biomechanics Symposium was cosponsored by Rock Island Arsenal, U. S. Army Weapons Command, U. S. Army Research Office Durham, and Augustana College. It strived for academic excellance, and the sponsors are indebted to the Advisory Committee in providing the guidance and participation required to achieve this objective as reflected in these proceedings.

Personal thanks are extended to Drs. Ross C. Bean, George Bugliarello, Robert G. Gesteland, Warren S. McCullough, Lawrence M. Patrick, Ali Seirig, and Heinz Von Foerster.

The planning committee, which included Prof. John E. Ekblad, Edwin M. Vaughan, Alan G. Galbavy, and the editors, are also to be commended for their efforts in arranging this successful symposium.

We hope that the publication of these proceedings will further stimulate the interest in biomechanics and encourage scientists to look at living organisms from an engineering point of view. It is anticipated that a second Rock Island Arsenal Biomechanics Symposium will be held in the not too distant future. The views of the authors do not purport to reflect the position of the Department of the Army or Department of Defense.

David Bootzin

Harry C. Muffley

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Keynote Address — The Army Looks at Biomechanics*

Jay Tol Thomas †
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Washington, D. C.

My purpose here is to discuss the Army Materiel Command's interest in biomechanics. I should make it clear at the outset that I am speaking only for the Army Materiel Command and not for the Army as a whole. Although the biomechanical approach is relatively new to the Army Materiel Command, the Army's Medical Service has been engaged in a closely related effort under the heading of biomedical engineering. This includes the remarkable developments in prosthetic devices and the mechanical heart pump. In connection with the heart pump, I'm sure that most of you know that the physical scientists and engineers of the Army Material Command's Harry Diamond Laboratories, working closely with the Army Surgeon General's medical personnel, designed and engineered this highly successful device, employing the fluid amplification technology pioneered by the Harry Diamond Laboratories.

Another kind of biomechanics effort is described by studies on the impact of mechanical stress, represented by vibration, acceleration, and deceleration, on biological systems. The medical departments of the Armed Services have been conducting and sponsoring noteworthy fundamental and applied programs in this interdisciplinary area for many years. Our Human Engineering Laboratories and Tank-Automotive Command Laboratories have kept abreast of these biologically oriented studies from the practical viewpoint of assessing the degradation of troop effectiveness resulting from exposure to vibration, and designing vehicles to minimize this effect.

Both of these types of biomechanical programs plus the type represented by the theme of this symposium — the study of structures, functions, and mechanisms in animals and plants, and the application of this knowledge to the design of mechanical equipment for military and other purposes — represent examples of this relatively new area of biotechnology. Mechanics, along with such other technologies as electronics, materials, aeronautics, aquatics, acoustics, communications, navigation, etc., is being teamed up in the Army Materiel Command with the study of life systems, hopefully to the mutual benefit of both, and to the synergistic benefit of AMC.

*Dr. Jay Tol Thomas was unable, at the time, to attend the Biomechanics Conference at Rock Island Arsenal. The keynote address was delivered by Col. Harvey E. Sheppard, U.S.A.
†Deceased.

The interdisciplinary approach represented by these biotechnologies is not new. As a matter of fact, most of the disciplines, other than biology, joined forces some time before. Thus, the combined integrated efforts of physical scientists and engineers were able to produce the tremendous growth of nuclear energy technology in the 1940's and 50's. More recently, in the late 50's and early 60's, the space program, primarily as an offshoot of the miltary rocket and missile program, brought together the combined efforts of physical scientists and engine neers in the solution of different kinds of engineering problems. With evolvement of the space effort to include manned-flight, the life sciences have become an increasingly important component of this mixture.

It is scarcely necessary to relate to this audience the exciting discoveries resulting from the union of the life sciences with other disciplines and technologies; these are legion, well known, and continuing. Moreover, except for the Army Medical Service, the Army's contribution has been relatively small to this interdisciplinary area generally identified as bionics.

Other agencies have sponsored the bulk of the Department of Defense bionics effort in biocomputer development, pattern recognition, communication, navigation, guidance, underwater propulsion, and flight. Within the Army Materiel Command, at the present time, bionics-related studies are conducted at Edgewood Arsenal, in biochemistry and pharmacology; at Fort Detrick, in biomathematics and genetics; at Natick Laboratories on the biochemistry and psychology of odor, taste, and flavor; and at the Human Engineering Laboratories on the biological, physical, and psychological aspects of man—machine relationships.

The Army is currently considering a study of biological systems having military application. This study is aimed in a somewhat different direction than the bionics program we have been discussing up to this point. The study is directed, not at duplication of some living system, but rather employing such systems directly in a military way. The use of dogs for ambush detection, and the training of pigeons for target detection, both of which have been used in the past with varying success, are examples.

Returning to the subject of biomechanics, we visualize the relevancy to the Army's interest primarily in the military technologies of land locomotion, floatation, stabilization and anchoring, fluid flow, propulsion, and armor design. All of these are embodied in the design of weapons systems. Several of these are included in the mission of the Weapons Command.

One might wonder why the Army has apparently only belatedly recognized the potential of this particular biotechnology. After all, the Navy has been studying for some time the methods used by the whale, porpoise, and other sea creatures to move through the water. The flight of birds and insects has also been the subject of considerable study. The reason given by Hertel in his excellent book Structure—Form—Movement probably comes closest to the truth. He places the invention of the wagon wheel about 6000 years ago, and notes the enormous progress that has been made in the technology based on the wheel since then. There is nothing in nature like a rotating wheel. Putting these last two facts together, it is perhaps understandable that we have ignored non-wheel-based, natural processes, for land locomotion and propulsion. Hertel thinks we may be overlooking some good bets. It has been reported, for example, that the Soviets have designed penguin-type vehicles which can travel in deep snow at speeds up to fifty kilometers per hour. We know, too, that vehicles being designed for lunar exploration are not wheeled.

Similarly, solutions of the problems associated with weapons and armor design have proceeded along predictable lines throughout the recorded history of warfare. Many of the problems still remain and their solution is still sought by the traditional engineering approach. The ubiquitous marshy terrain in Vietnam has highlighted the long-sought need for a technique of stabilizing and anchoring artillery pieces. In other parts of the world where U. S. Army forces might be engaged, loose soil and frozen ground, likewise, are terrain features that plague weapon emplacement.

At the other extreme of warfare, the "shoot and scoot" philosophy imposed by the threat of nuclear weapons on the battlefield, makes it imperative that such stabilization and anchoring be accomplished rapidly, and just as rapidly be disengaged. A proposed Weapons Command study of the Water Strider; an aquatic insect, appears to offer a new perspective.

The Weapons Command has shown commendable initiative in embarking on this new venture. They have recognized a need for new approaches to the solution of several of their long-standing engineering problems in weapons design. They reviewed existing knowledge and current efforts and concluded therefrom that there are indeed gaps that could be profitably explored.

Long-range plans for the Army Materiel Command visualize centralization of functions into rather large, complex research and development centers. However, except for particularly extensive and militarily relevant technologies such as materials and ballistics, it is not contemplated to separately collocate any given scientific discipline or technology. Consequently, there will be no single center for chemists, physicists, biologists, or biomechanicists. From a management viewpoint, to obviate undue duplication of effort among them, each of the various functional centers might, additionally, be recognized as a "center of excellence" in one or more given areas of technology. It is, thus, entirely conceivable that a weapons center or a mobility center might incorporate the dominant capability within the Army Materiel Command, for biomechanics research, development, and engineering.

This symposium, the Army's first on biomechanics, has been arranged to provide a mutual setting for the scientific community, for discussion of our present programs and projected ideas, and to stimulate a fruitful exchange of information. We need help and talent in the development and conduct of a knowledgeable, worthwhile, and forward-looking program.

Design for Living

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SCOPE

Meaning

Not so long ago I was questioned by a colleague about the term "BIOmechanics." Why not simply "mechanics?" Is this not just as meaningful and a good deal less pretentious? The answer is NO. The laws of living things have a most intriguing way of manipulating the laws of physics. So, if we want to look to biological structures for models from which to develop future mechanical systems, we have first to be quite clear about the uniqueness of the biological device. Thus the purpose of this chapter is twofold: first, to explore principles in the design of living things and, second, to expose implementation of these principles for particular biological purposes.

Life and Death

The Big Idea in biology is Enduring Order—order distinct from the surrounding vast universe of disorder. And the trend toward increasing orderliness is what we have called evolution. Now the most curious fact about a live thing is that it stays alive for a time. But stranger still, life itself has been such a stable continuum on this planet that even newcomers like mammals are older than most of our mountains. The first special contrivance for this sort of perseverance is startling. It is death! This is a devious device by which the problem of long-term maintenance is managed. The individual machine, after having punctiliously replicated itself, is discarded as it wears out. But its precise information for reconstruction is kept forever alive and passed on as the gene.

Stability

The crux of the matter is that this sort of order has found a way to build into itself unique devices that ensure ever more probable persistence of the order. Thus, a living thing is a homeostat, distinct from its environment but peculiarly coupled with it. The goals that the homeostat seeks in the environment make up its behavior which consistently returns it to the steady state. Although biomechanics is primarily concerned with the movable parts that perform this behavior, the inseparable structure that makes the movements meaningful is the nervous system. This is the computer for the homeostat, the memory-learning selector that decides the course by which the most prompt return to the steady state can be made. Thus, the information compiled in this system serves the survival of the individual, while the information compiled in the gene serves evolution, which is simply long-term homeostasis.

LIVING MACHINES

The Principles of Construction Technique

The fundamental, general biomechanical design of a class of organisms is drawn around distinct target sites of primary genetic impact. Genetic influence diminishes with the distance from the bull's eye. Coded commands from the genetic battery play upon the targets as a musician hits the keys of a piano — lightly here, heavily there. Changes (mutations) in the codescript play varying tunes to present varying structures and behaviors to a severely critical audience, the environment. It selects only those compositions in harmony with itself.

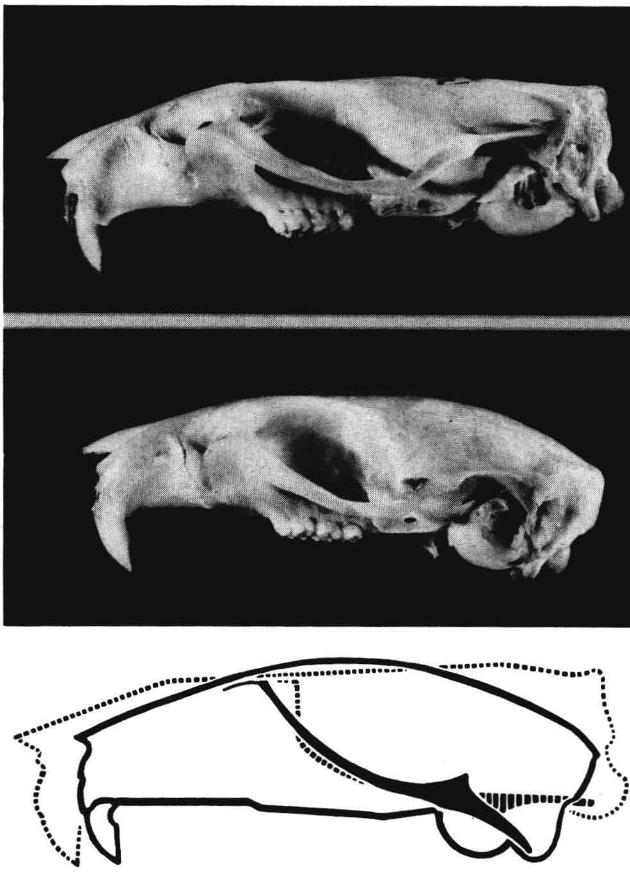

Fig. 1. Construction technique of living things. Top: Sharply rectangular skull of a normal adult male rat in lateral view; Middle: Shortened and rounded skull of a litter mate male in which only one target site was excised from the skull base. Bottom: Traced outlines of x rays of these skulls superposed one on the other.

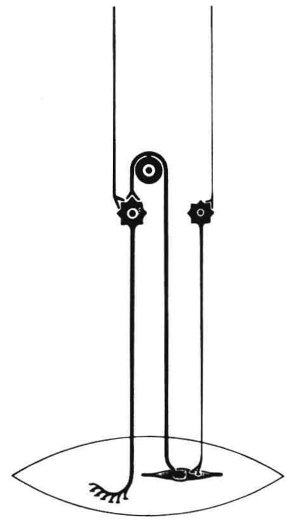

Fig. 2. Construction technique of living things. Simplified design of the neural structures that make a muscle move. The usual sequence begins firing down the thin gamma fiber on the right causing muscle spindle to contract. Its central segment is stretched. This causes the large proprioceptor fiber to fire back into the nervous system, and this, in turn, fires off the thick, fast-firing, alpha fiber which causes the voluntary, somatic muscle to contract. The pattern of genetic control is exactly the reverse of the above sequence. The number of voluntary muscle fibers prescribes the number of alpha fibers; these determine the number of proprioceptors, which then decide the number of gamma fibers, etc. (from DuBrul 1967).

Hence it has been the actual programmer of these highly improbable structurations from the beginning. The operation of such a model can be seen clearly even in an intricate structural complex like the skull. Cartilagenous plates set in series along the skull base are centers of growth, i.e., target sites of gene action. Simply changing the timing of growth (mutation) at these sites causes allometry that can change the skull shape from a long rectangular box to a near sphere, as happened in the evolution of the human skull. Experimentally, this has been reproduced by simply removing one of these plates from the base of the box-like rat skull: growth stops, the bottom buckles up, and the top bends round in the most primate-like manner (Du Brul and Laskin, 1961) (Fig. 1). The muscle—nerve relationships are even more interesting. The peculiar servomechanism called the neuromuscular spindle is also involved in a highly sensitive genetic target site. It seems that certain mutations, striking squarely on a peripheral target site like a somatic muscle, can have surprisingly permeating spheres of influence. The effect is quantitative. It works its way up the neural chain in a precise sequence into the depths of the central nervous system which, then, profoundly influences the evolution of behavior (Du Brul, 1967) (Fig. 2).

The local biomechanical design utilizes all the simple machines except wheels. The unity of the kind of order we talk about here precludes any separation of parts like the wheel spinning on its axle. Twisting just tears unity into little bits of entropy. All the distinct parts must have a continuity of general tissue systems, maintenance systems, and communications systems. And so levers are used repetitiously to substitute for wheels. They are used in ways that seem to disregard mechanical advantage. But the mechanisms of muscle are such that they develop greater power under high tensions so that a third-class lever with a short power arm becomes surprisingly effective. Inclined planes are extensively used, often in joints like the knee or neck. Pulleys are used to change the direction of forces and combinations of all these tools are used to increase mechanical advantage in critical, adaptive postures.

Each living structural complex must meet four crucial requirements:

1. It must be designed to perform a particular activity, at least well enough to survive in competition with closely similar designs.
2. It must be designed to support itself satisfactorily within the total animal economy.
3. It must be designed to help support and accommodate neighboring structural complexes.
4. It must be designed to protect its own supporting and maintenance structures.

To repeat, it must meet all these requirements without wheels.

The Great Principle of Getting Some Good Out of a Bad Situation

This elusive process is usually discussed under the term "preadaptation" but this seems a sorry label, tinctured too strongly with antiquated teleology. A few examples of the implementation of this potential will point up the essence of the phenomenon.

A predatory fish has a highly specialized body designed for straight speed, quick turns, short stops. To stop at a precise spot, pectoral and pelvic fins slam out flat surfaces as brakes at right angles to the body axis. But when about to clamp onto the prey the attacker must slam out jaws with almost as large braking surfaces, suffering the loss of an agile victim. To overcome this, many parallel forms redesigned their solid, fixed skulls into completely kinetic ones. Fused bones were mobilized, elongated as levers, and so hinged as to be able to shoot the whole front of the head forward at the instant of contact. This expands the entire foregut, causing a strong negative pressure within it. This not only sucks the prey into the gaping maw but, in principle, jerks the fish trap forward onto the prey. Other solutions to this problem are necessary in large beasts where the principle of similitudes looms on the scene. But the one above seems much more interesting.

There is a land form of locomotion in a bad situation that illustrates great nicety in the pragmatic take-over of an old device for the management of a new emergency. The "sidewinder" is a rattlesnake readjusted to skim swiftly over shifting sands. Now the primordial vertebrate sequence of muscle contraction in locomotion runs down the segments from head to tail. It bends the backbone in sinuous waves flowing from fore to aft and this is how an ordinary fish swims. But our special kind of snake flings these bends out in enlarged loops, and, although the old muscle firing sequence is exactly the same, the movement of the body is lateral, along the parallel parts of the loop – hence the name sidewinder. Essentially, the animal travels on tank tread scales, picking one segment up as the next is laid down. This leaves peculiar, parallel, discontinuous tracks in the

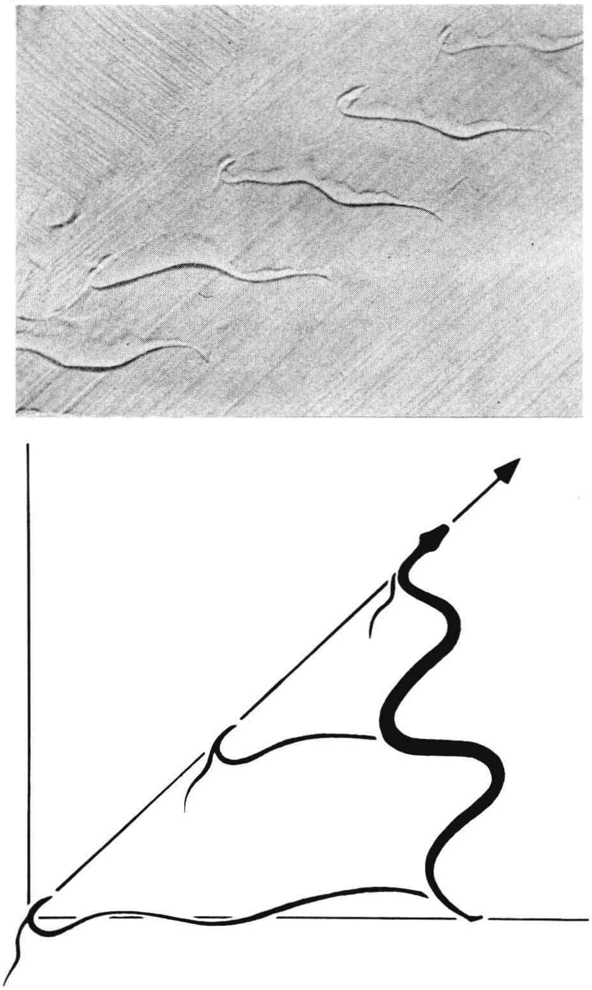

Fig. 3. Good locomotion in a bad situation. Top: Discontinuous tank tread tracks left in loose sand by a speeding sidewinder. Bottom: Diagram made by tracing motion picture sequences when above tracks were laid down. The head with its special sense organs is the orienting device. It is first slapped into a fixed position unerringly pointing to the line of attack. This makes the hook in the sand track. The body then unrolls laterally along the ground where the tracks are left but free of the ground at the connecting curve. At the beginning of each new track, the head is snapped to the new position and fixed until the new track is unrolled.

sand because the curve connecting the parallel arms of the loop is lifted free of the ground. The operation is quite complicated, highly efficient, and best seen in slow-motion pictures (Fig. 3). Hence our beast has rearranged an old neuromuscular firing pattern to consummate, in fact, the operation of an attacking tank darting speedily over difficult terrain to destroy prey – and all *with no wheels.*

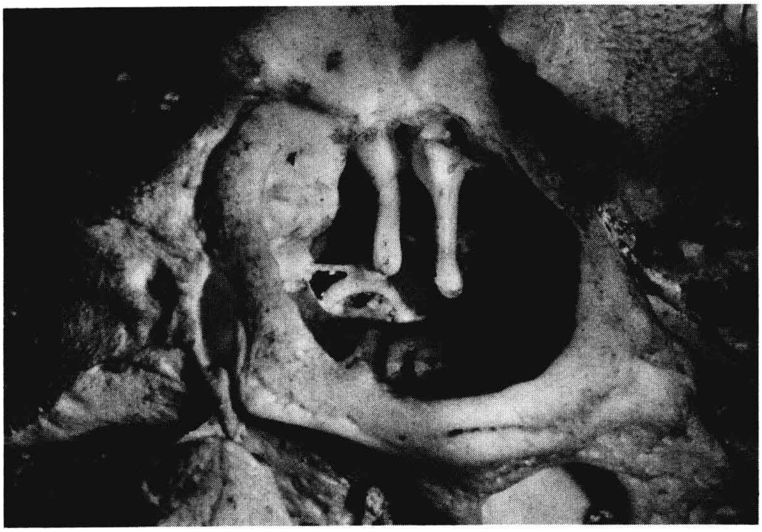

Fig. 4. The amazing jaw—ear evolution. Photograph of the tiny ossicles inside the right ear. They are the renovated primitive jaws rotated and squeezed into the skull. The vertical bar on the right was once the lower jaw and that on the left the upper jaw. The junction between them was the original jaw joint and its tiny muscle, hidden in a bony tube, is still fired by a diminutive branch of the present jaw muscle nerves. The stapes, anchored to the bottom of the bone on the left, was once part of the second gill arch.

The jaw→ear evolution of mammals is a curiously complicated instance of this peculiar principle. The earliest vertebrates were mud-grubbers, sucking food from ooze on slimy aquatic bottoms. Jaws were devised by enlarging the first gill arches which just happened to be lying along the edge of the mouth. Teeth and covering bony plates were plastered over these pincers to make them powerful, predatory, fish traps. The joint hinging these jaws was the underlying old gill arch joint. In a long and devious history, the outer bones progressively decreased in number to leave one solid, lower jaw bone that finally contacted the skull to form a new, stronger jaw joint in mammals. But in the meantime, the old jaw joint was crowded inward to shrink to tiny ossicles that still preserved the original hinge joint in miniature (Fig. 4). This seemingly useless arrangement was seized by the ever-ready opportunism of the living process to serve as a delicate transducer which could then convey the energy of sound waves for an entirely new apparatus, one for hearing. Luckily, this highly improbable sequence of events has been admirably documented by the fossil record.

Some birds have on-target signalers whose design reveals great elegance in the biological parsimony of re-use of antiquated equipage. A woodpecker has a weapons-storage-with-immediate-availability system which yields a highly effective performance in what might seem a most awkward situation. The animal attacks insect fortifications with the familiar pounding of his pneumatic drill-like beak. When the insect tunnel is breached, he immediately releases an extraordinarily long spear-tipped tongue. It either impales an insect or it does not. The

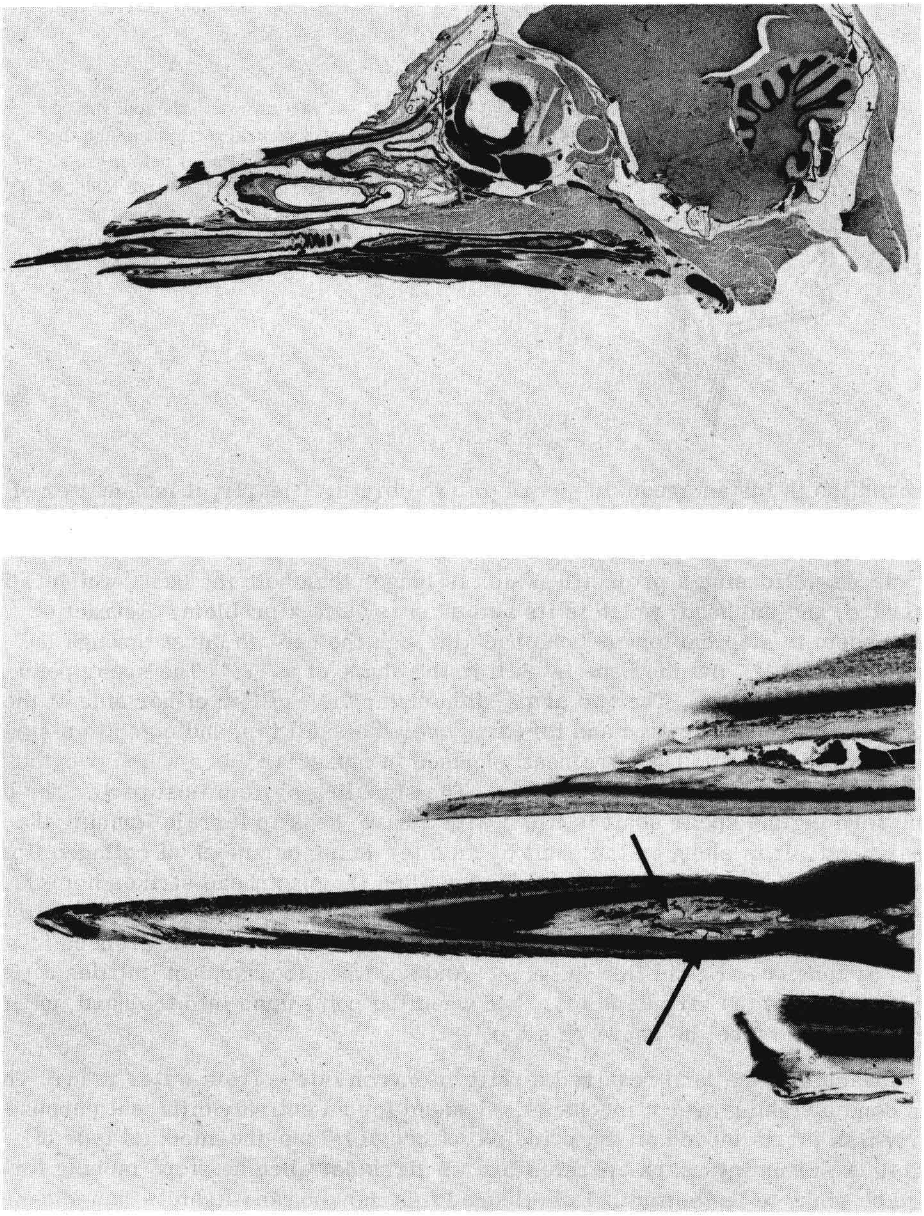

Fig. 5. The elegant on-target signaler. Top: Sagittal section through a woodpecker's skull in low power. The spear-tipped tongue is partly projected from the beak. The lateral arms of the tongue were cut off in slicing the section. Bottom: The spearhead under higher power. The double black outline is the keratin sheath. The thin, longitudinal strip centered in the base of the spearhead is the end of the tongue bone. The small, light ovals (arrows) above and below the bony strip are sensory recorders, measuring movement between spearhead and shaft.