Steven Vogel and His Theory of Comparative Biomechanics

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In the current milieu of interdisciplinary research, it is important to be clear about the meaning and connotation of the title of a new field before delving into it. The titles of two or more existing fields are combined to coin a new title, sometimes with an adjective prefixed to it. The order of the constituent titles seems to matter: biochemistry is different from chemical biology. Today, biology is perhaps the most used title, either as a prefix (e.g., Bio-Cyber Physical Systems) or a suffix (e.g., Mathematical Biology). The traditional fields of biology and mechanics present a peculiar problem when they are combined together because biomechanics and mechanobiology are both used, the latter being much younger than the former. How is mechanobiology different from biomechanics? Jay D Humphrey makes an earnest attempt to explain the difference. According to him, biomechanics is “the development, extension, and application of mechanics for the purposes of understanding better the influence of applied loads on the structure, properties, and function of living things and the structures with which they interact”. Mechanobiology, on the other hand, is the study of the effects of mechanical stimuli on the development, physiology, and disease of living things. I have a simpler approach to distinguish the two fields. Who is an African American? An American who lives in America with origins in Africa. Who is an Anglo Indian? An Indian who lived in India but was of British descent. On this basis, biomechanics is essentially mechanics with the problems studied in it originating from biology. Likewise, mechanobiology is biology where the investigation stems from mechanical stimuli.

What then is comparative biomechanics? It is a field developed and promoted by Steven Vogel, a distinguished biologist who studied and wrote about life’s devices and the physics underlying the biological world. Vogel was a prolific writer of popular science articles and books. He wrote about a dozen books and all of them with enticing titles: Life in Moving Fluids (1981), Life’s Devices (1988), Vital Circuits (1993), Cats’ Paws and Catapults (1998), Prime Mover: a Natural History of Muscle (2002), Comparative Biomechanics (2003), Glimpses of Creatures in their Mechanical World (2009), Life of a Leaf (2012), and so on. Vogel, an able wordsmith and a clever expositor of complicated ideas in simple terms, played with the order of the same words in the sub-titles (taglines) of his books. The sub-title of his Life’s Devices (1988) is “the
Vogel propounds that there are two fields of biomechanics. The first is the human functional biology that is concerned with “efficient design of devices to be used by humans, mechanical prostheses, locomotion as related to rehabilitation or athletics, and similar matters”. The other biomechanics, he says, “takes for its concern biological systems in their full diversity of size, structure, ancestry, and habitat”. The latter kind is comparative biomechanics. What does it compare? Vogel has compelling arguments made using intriguing observations. Let us consider two examples.

Example 1: Why is the size of a cell invariant, despite the variety of species across the evolutionary tree, and among creatures of sizes that span eight orders of magnitude? Biological cells of animals, as is well known, measure about 10 microns with only a factor of two variability irrespective of the size of the animal? If there is such constancy in a diverse animal kingdom, Vogel argues, it must be due to the laws of physics and not natural selection. He also talks about the invariance of the sizes of the smallest capillaries and tracheae. Thus, if there is anything invariant in living things, one is justified in attributing that to mechanics. Therefore, it is possible to compare biological systems on the basis of underlying mechanics. Comparative Biomechanics thus enables the study of the living world from a perspective that is different from the traditional biomechanics, which is limited only to humans.

Example 2: There are some quantities that are different for different animals but there might be a pattern to that variability. Vogel observes that animals that walk on two, four, or six legs switch from walking to running gait at different critical speeds. One way is to measure the speed at which animals switch from walking to running and then normalize them and see if there is a pattern. There is a better way. Using simple mechanics-based arguments, Vogel shows that that critical speed is proportional to \( \sqrt{\frac{g}{l}} \) where \( l \) is the size of the animal and \( g \) is acceleration due to gravity. He says it fits very well with the measured data for a number of animals if the constant of proportionality is 2.2 for terrestrial animals that may have any number of legs. Now, this is interesting – we can now compare different biological species without having to do experiments on all of them.

Thus, Vogel begins his book explaining what exactly he means by comparative biomechanics. He motivates the subject with intriguing examples where biological organs are compared with simple mechanical analogues. Aneurism in an artery can be explained by the way a cylindrical balloon inflates when gas is blown into it. Using the theory of bending of slender structures and aerodynamic drag, he justifies how weak leaves hold themselves in gales without getting torn away. Those who
know biology are amazed with these explanations, and those familiar with mechanics are humbled at the incisive look at the mechanics of the living world. He demystifies biomechanics that, in his own words, is “a field that should not be a private domain of initiates, insulated and isolated within its journals and jargon”.

Vogel notes that his earlier book *Life’s Devices* was a simple book as he had “tiptoed around logarithms and even the simplest calculus”, which limited his technical arguments. That book was an appetizer and a dessert. This book (*Comparative Biomechanics*) is intended to be a textbook and is meant to be a proper entrée. I would say, it is a 25-course sumptuous dinner for the readers to devour. This voluminous book has 25 chapters. Incidentally, the idea of writing this book occurred to the author when he was visiting the Raman Research Institute, Bengaluru.

*Comparative Biomechanics* can be seen as a culmination of the ideas, theories, arguments, insights, and calculations that Vogel considered in his research papers and his earlier books. It gives one the impression of being the final analysis of this subject by him. There is much overlap with the earlier books in terms of examples, figures, and even text. But there is a new line of thinking here.

Even though the author intends this to be a textbook (just as he had intended *Life’s Devices* to be), it does not have the usual characteristics of a textbook. There are no worked-out examples and end-of-the-chapter problems. As no prior background in biology or mechanics is assumed, most readers can understand what is being said. But whether the readers can do similar analysis on a different problem remains unclear. For example, the argument that establishes the critical speed at which an animal switches from walking to running is easily understandable. However, someone not familiar with mechanics will be at a loss as to how to simulate this using a computer model. So, if a question is framed differently, say, at what speed an animal walking on the bottom floor of a pond would switch from walking to running, the reader will be clueless unless he/she is familiar with mechanics. In *Life’s Devices*, he did include some problems and suggestions for do-it-yourself experiments. A sample question from that list will tell us how difficult and open-ended the questions are. Consider this: “Imagine a world in which the surface tension at the air-water interface is only 2% of the value in our world, and then describe how biological life is affected by this change”. To answer this question, one needs to be aware of the mechanical activities of animals that are influenced by surface tension and also know how to quantify the effect of change of surface tension. It is possible for only those individuals who completely imbibe the spirit of Vogel’s line of thought.

This book is a research monograph or a collection of intriguing essays. It has a rich set of references. Incidentally, there are a number of books of this type, but none as enlightening, educational, and entertaining as his books. As
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we read the book, it becomes clear to us what sort of a thinker Vogel was. The analogies he uses to explain a difficult concept takes one by surprise. His writing introduces science in popular articles. It may be because he sees science in articles written by others where science was not intended or alluded. For example, while discussing soaring of an albatross, he cites a passage from *Great Antarctic Rescue: Shackleton’s Boat Journey*. Only the ones who has a trained eye to analyze the surroundings with a scientific eye can do it. Vogel could do that.

The explanations he gives for mechanics are definitely correct and he mostly does so using mere words. One would usually resort to equations and calculations to explain how shear modulus is related to Young’s modulus and Poisson’s ratio. But that is not necessary for Vogel. Talking about anisotropy (i.e., a quantity has different values in different directions) of biological materials, he says “…biological materials seem complex along every imaginable axis…the wonder is that we can make any sense out of the subject at all”.

Well, it takes a Vogel to do it well as he does with so many examples concerning solids, liquids, and gases. By the way, this is how he distinguishes these three terms: gases resist only compression, liquids resist compression and tension, and solids resist compression, tension, and shear. What equations cannot do, he does it with simple words. His arguments remind one of Richard Feynman’s *Lectures on Physics*. This analogy brings home another point. All seems clear when you read Feynman’s lectures but then you may not be able to solve problems. So, just as a companion book is needed to learn physics using Feynman’s lectures, perhaps a companion book is needed for *Comparative Biomechanics* to work with biomechanics head on.

The book is a great resource for someone with sufficient knowledge of mechanics and eagerness to learn about biological systems from the mechanics viewpoint. Vogel concludes at the end of the book that “Biomechanics explains aspects of one’s immediate world as satisfyingly as any area of contemporary science”. He also says “biomimetics is the applied science of biomechanics just as chemotherapy is to biochemistry”. He is right on both counts. When we come across a plethora of books with titles that have ‘Biomechanics’ in them, we are mostly disappointed that those books merely talk about mechanics with some motivating examples of biological systems. Vogel’s books are different. He truly talks about biomechanics or rather comparative biomechanics.

The book is perfect for teaching biomechanics to biology students. It will surely sensitize them to mechanics. But what about engineering students who presumably know mechanics well? The book may fall short in this regard. What more could there be in this book to make it suitable to teach engineering students? As mentioned earlier, there should be detailed worked out examples, clear end-of-the-chapter problems, computer programs, and more and more equations. Does the last one
become an antithesis of Vogel’s philosophy? Perhaps not, he only tried to see the essence of a phenomenon to explain what is observed in the living world.

If we follow Vogel’s theory of comparative biomechanics, one might learn much more than observation-based studies specific to an organism or to a situation that are characteristics of biological research. Generality ensues only when one believes that there are underlying physical explanations to all that variety and seeming inconsistency we see in the living world. He tries to tie the loose ends in the last chapter. What catches our attention there is the notion of the word “design”. It can be used both as a noun and a verb in active voice. When we talk about Nature’s design, it becomes uncomfortable. The living world is replete with designs that were possibly not designed. This notion, Vogel, says haunts us throughout the last chapter. As one reads that chapter, we begin to contemplate all the rest that is said in the book and begin to see the world around us differently – or rather, we begin to see it the way Steven Vogel did. By the way, having done so much to establish a field that is rightfully called ‘Comparative Biomechanics’, Vogel’s name will probably be immortalized in an eponymous non-dimensional number, \( Vo = \) Vogel number, that indicates the flatness of an object. It is defined as the ratio of square root of the surface area to the cube root of the volume. Sphere has \( Vo = 2.2 \), which is the least value an object can have because spheres are the least flat objects as per this number. What are the implications of \( Vo \)? Those interested should pick up *Comparative Biomechanics* and be enlightened!

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