Biologically-Inspired Systems

Volume 10

Series editor
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Motto: Structure and function of biological systems as inspiration for technical developments

Throughout evolution, nature has constantly been called upon to act as an engineer in solving technical problems. Organisms have evolved an immense variety of shapes and structures from macro down to the nanoscale. Zoologists and botanists have collected a huge amount of information about the structure and functions of biological materials and systems. This information can be also utilized to mimic biological solutions in further technical developments. The most important feature of the evolution of biological systems is multiple origins of similar solutions in different lineages of living organisms. These examples should be the best candidates for biomimetics. This book series will deal with topics related to structure and function in biological systems and show how knowledge from biology can be used for technical developments in engineering and materials science. It is intended to accelerate interdisciplinary research on biological functional systems and to promote technical developments. Documenting of the advances in the field will be important for fellow scientists, students, public officials, and for the public in general. Each of the books in this series is expected to provide a comprehensive, authoritative synthesis of the topic.

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Editors

Functional Surfaces in Biology III

Diversity of the Physical Phenomena

Springer

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Preface: Diversity of the Physical Phenomena in Biological Surfaces

In 2009, in two volumes of "Functional Surfaces in Biology I and II", we quite naively tried to cover the diversity of the physical phenomena in biological surfaces (Gorb 2009a, b). However, it turned out that the field of functional biological surfaces is a very rapidly growing one with an increasing number of subfields, which are difficult to comprise even within several issues. The "Functional Surfaces in Biology III" continues the idea of the two previous issues and presents a new collection of chapters written in form either of topical reviews or original papers and devoted to structure-property relationships of biological surfaces.

Meanwhile it is well known that this kind of studies can inspire further technological developments (Heepe et al. 2017); however, the present book is primarily concentrated on interesting aspects of biological systems rather than on the development of technical systems inspired by mechanisms observed in biological systems. In other words, this issue aimed at revealing novel functional aspects of biological surfaces rather than implementing this knowledge in biomimetics.

The "Functional Surfaces in Biology III" shows a broad variety of facets of structural and experimental research on various biological surfaces in general. It covers a wide range of biological systems (from infrared receptors, photonic systems, moisture harvesting microstructures, water/oil absorbing surfaces, gas exchanging interfaces to adhesion enhancing and friction reducing systems) and their structure-function relationships and can be therefore interesting for biologists, physicists, chemists as well as materials scientists and engineers fascinated by the idea of biomimetics.

The first chapter by Anke Schmitz and Helmut Schmitz is devoted to the role of the cuticular surfaces in infrared reception of pyrophilous ('fire-loving') insects that rely on forest fires for their reproduction. In these insects, both the navigation towards a fire and short-range orientation on a freshly burnt material depend on a variety of specialized infrared sensors located on the thorax and abdomen. The chapter reviews the studied insect infrared receptors with an emphasis on the cuticle role in infrared perception. The authors distinguish three designs of receptors based on two different functional principles, which in turn rely on specialized types of cuticle serving as an interface between incoming radiation and sensory cells.

The Chap. 2 by Mikhail Kryuchkov, Artem Blagodatski, Vsevolod Cherepanov, and Vladimir L. Katanaev opens biophotonic section of the book. It provides an overview of the diversity of arthropod corneal nanostructures, which can be of nipple-, ridge-, maze-, or dimple-type with various transitions among them. With a diameter being thinner than the wavelength of the visible light, these structures provide a variety of functions ranging from reflection reduction to the enhancement of water-repellence. Interestingly, the entire diversity of these structures can be described by simple reaction-diffusion models that can explain formation of arthropod corneal nanostructures during eye development. The authors' vision is that real molecular identities, responsible for these reactions, can be revealed in model insect organisms and potentially used in bioengineering of novel nanocoatings.

In the Chap. 3, Villads Egede Johansen, Olimpia Domitilla Onelli, Lisa Maria Steiner, and Silvia Vignolini discuss biological structural colours caused by pigments organized in specific nano-scale architectures. Interestingly, these architectures in biological systems are very often not perfectly ordered, and such a disorder provides a broad range of functional optical effects. The authors discuss the influence of disorders on the photonic effects of biological surfaces by taking an example of the blue-winged *Morpho* butterfly. The role of hierarchical organization and pixelated surfaces is also demonstrated in the context of their role in tuning optical appearances of biological surfaces. Finally, this chapter provides mathematical tools for disorder analysis and using them describes examples of completely disordered structures having white appearance, such as in the dorsal surface of *Cyphochilus* beetle.

The Chap. 4 by Anna-Christin Joel, Gerda Buchberger, and Philipp Comanns opens section on the surface wettability by the review of structure-function relationships in moisture-harvesting reptiles that live in arid environments. The authors reveal special microstructural adaptations of the reptile integument enabling additional moisture-harvesting from various sources. Interestingly, this ability is often accompanied by a specific animal behavior. Most of these reptiles possess highly-specialized skin structures in form of microscopical capillary channels facilitating water flow in the anterior direction of the body. The authors discuss biomimetic potential (especially in the field of microfluidics) of these structural and experimental studies on reptiles.

The Chap. 5 by Anita Roth-Nebelsick, Frank Hauber, and Wilfried Konrad on porous structures for water absorption and gas exchange in orchids continues the wettability section. It is known that epiphytic orchids possess aerial roots with a special outer tissue layer, so called the velamen radicum, aiding in water condensation from the air and its absorption. The velamen radicum presumably played a very important role in successful radiation of epiphytic orchids. The authors show here that this tissue consists of dead cells building up a porous material with highly adapted surface and underlying tissues with interesting water draining behavior strongly depending on the thickness and structure of the tissue. They also provide comparison of velamen radicum in various orchid taxa and discuss structure-function relationships of this system.

The Chap. 6 by Elena V. Gorb, Philipp Hofmann, Alexander E. Filippov, and Stanislav N. Gorb deals with the adsorption ability of epicuticular wax coverages in plants that have been often shown to be impeding locomotion and reducing attachment of insects. One of mechanisms responsible for these effects, a possible adsorption of insect adhesive fluid by highly porous wax coverage, has been previously proposed. This chapter reports on experimental tests proving the adsorption ability of different fluids by plant wax blooms. Using a cryo scanning electron microscopy approach, high-speed video recordings of fluid drops behavior and numerical analysis of experimental data, the authors show that the wax coverage in the waxy zone of *Nepenthes alata*pitcher can strongly adsorb oil, but not water, which is a strong evidence that three-dimensional plant wax coverages will be anti-adhesive for insects relying on wet adhesion by oily substances.

The Chap. 7 by Janek von Byern, Carsten Müller, Karin Voigtländer, Victoria Dorrer, Martina Marchetti-Deschmann, Patrick Flammang, and Georg Mayer provides an overview of biological adhesives utilized by more than 100 marine and terrestrial organisms for defence and predation. These functions require specific combination of particular behaviours and properties of the adhesive, such as fast curing process, squirting over distance, bonding to various substrates, but organisms' protection against own glue. These organisms have a very wide environmental and phylogenetic diversity: hagfish, comb jellies, centipedes, salamanders, spiders, glowworms, velvet worms, etc. The review collects scattered published information about the composition, production, secretion mechanisms and mechanical properties of these glues, however, it concludes that only little is known about their functional principles. We are very much convinced that this chapter will facilitate new experimental studies on biological adhesives.

A case study from bioadhesion research is provided in the Chap. 8 by Lars Heepe, Constanze Grohmann, and Stanislav N. Gorb. This chapter deals with the visualization of tarsal adhesive setae in contact during normal and ceiling walk in the ladybird beetle. These setae form an intimate contact with the substrate and generate adhesion supporting insect walk on vertical walls or even on the ceiling. Previous adhesive force measurements at the level of individual setae provided estimation of the maximum adhesive capability of animals by assuming all setae being in contact. However, these values do not coincide with the results of adhesion measurements performed at the level of the whole animal. This discrepancy is due to the fact that not all setae are simultaneously applied during locomotion and this chapter deals with quantification of the beetle adhesive setae used during locomotion. It turned out that beetles use considerably more setae in contact during ceiling walk than during normal walk. The authors conclude that in order to control adhesion, animals are capable of controlling not only the amount of tarsal setae in contact, but also the type of setae depending on the type of substrate.

Another example of an effective high-speed biological adhesion is an adhesive tongue of frogs, which is an efficient tool capable of capturing fast moving prey. It is obvious that the interaction between the tongue surface and an adhesive mucus coating is crucial for generating strong pull-off forces with the prey surface. The Chap. 9 by Thomas Kleinteich and Stanislav N. Gorb is a comparative study of tongue surfaces in nine frog species bearing microscopical papillae of different size and shape. The specific microstructure presumably contributes to the particular adhesive performance of different frog species and may correlate with the prey spectra between the taxa studied. This study also opens an interesting possibility of combining surface microstructure with adhesive fluids to enhance dynamical performance of the next generation of adhesives.

In fish, the combination of the scale surface structure with mucus leads to the friction reduction and generation of slippery surfaces. Dylan K. Wainwright and George V. Lauder discuss this system in detail in the Chap. 10 called "Mucus matters". The authors describe different categories of scales (cycloid, crenate, spinoid, ctenoid) and discuss structure-function relationships of sub-scale features, such as spines, ctenii, radii, and circuli. The authors suggest that three-dimensionality of these features is crucial for their hydrodynamic and protective functions. Additionally, fishskin is covered by mucus which was often ignored in previous studies. This chapter presents three-dimensional analyses of intact fish skin surfaces from seven species and compares them to the skin with the removed epidermis and mucus. This approach allowed demonstrating how mucus and epidermis interact with the scale surface and result in the functional surface texture, which remains a largely unexplored area. A very important feature of this chapter is the discussion on techniques for investigation and imaging the structure of fish surface, such as for example gel-based surface profilometry.

Another friction-related study is the book final Chap. 11 by Yoko Matsumura, Alexander E. Kovalev, Alexander E. Filippov, and Stanislav N. Gorb. It is devoted to the friction reduction mechanism during the super-long penis propulsion in beetles. There is no doubt that surface interactions of the male and female genitalia during copulation play a key role in evolution, but the morpho/physical diversity of interacting surfaces and their biomechanics in sexual intercourse of the vast majority of animals are not well studied. The authors take male and female genitalia in cassidinebeetles as a model system and using microscopical analysis of material composition reveal stiffness gradient in male penis. Furthermore, they numerically model its propulsion into the female duct. This simulation demonstrates that the type of the stiffness gradients observed in the real male (softer at the tip and stiffer at the base) aids in the faster propulsion than other types. This chapter indicates that previously ignored physical properties of genital surfaces may aid in understanding physical interactions of sexes and shed light on the evolution of genitalia.

In general, this book discusses numerous experimental methods for the characterization of the mechanical and optical properties of biological surfaces at the micro- and nanoscale. It combines approaches from biology, physics, chemistry, materials science, and engineering and therefore represents a good example of modern interdisciplinary science. Due to this latter reason, we hope that the contributions from this book will be of interest to both engineers and physicists, who use inspirations from biology to design technical surfaces and systems, as well as to biologists, who apply physical and engineering approaches to understand how biological systems function.

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