

Biological and Medical Physics, Biomedical Engineering

Bharat Bhushan

# Biophysics of Skin and Its Treatments

Structural, Nanotribological, and  
Nanomechanical Studies



Springer

# Biophysics of Skin and Its Treatments

More information about this series at <http://www.springer.com/series/3740>

# BIOLOGICAL AND MEDICAL PHYSICS, BIOMEDICAL ENGINEERING

---

The fields of biological and medical physics and biomedical engineering are broad, multidisciplinary and dynamic. They lie at the crossroads of frontier research in physics, biology, chemistry, and medicine. The Biological and Medical Physics, Biomedical Engineering Series is intended to be comprehensive, covering a broad range of topics important to the study of the physical, chemical and biological sciences. Its goal is to provide scientists and engineers with textbooks, monographs, and reference works to address the growing need for information.

Books in the series emphasize established and emergent areas of science including molecular, membrane, and mathematical biophysics; photosynthetic energy harvesting and conversion; information processing; physical principles of genetics; sensory communications; automata networks, neural networks, and cellular automata. Equally important will be coverage of applied aspects of biological and medical physics and biomedical engineering such as molecular electronic components and devices, biosensors, medicine, imaging, physical principles of renewable energy production, advanced prostheses, and environmental control and engineering.

## Editor-in-Chief:

Elias Greenbaum, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

## Editorial Board:

Masuo Aizawa, Department of Bioengineering,  
Tokyo Institute of Technology, Yokohama, Japan

Olaf S. Andersen, Department of Physiology,  
Biophysics and Molecular Medicine,  
Cornell University, New York, USA

Robert H. Austin, Department of Physics,  
Princeton University, Princeton, New Jersey, USA

James Barber, Department of Biochemistry,  
Imperial College of Science, Technology  
and Medicine, London, England

Howard C. Berg, Department of Molecular  
and Cellular Biology, Harvard University,  
Cambridge, Massachusetts, USA

Victor Bloomfield, Department of Biochemistry,  
University of Minnesota, St. Paul, Minnesota, USA

Robert Callender, Department of Biochemistry,  
Albert Einstein College of Medicine,  
Bronx, New York, USA

Steven Chu, Lawrence Berkeley National  
Laboratory, Berkeley, California, USA

Louis J. DeFelice, Department of Pharmacology,  
Vanderbilt University, Nashville, Tennessee, USA

Johann Deisenhofer, Howard Hughes Medical  
Institute, The University of Texas, Dallas,  
Texas, USA

George Feher, Department of Physics,  
University of California, San Diego, La Jolla,  
California, USA

Hans Frauenfelder,

Los Alamos National Laboratory,  
Los Alamos, New Mexico, USA

Ivar Giaever, Rensselaer Polytechnic Institute,  
Troy, New York, USA

Sol M. Gruner, Cornell University,  
Ithaca, New York, USA

Judith Herzfeld, Department of Chemistry,  
Brandeis University, Waltham, Massachusetts, USA

Mark S. Humayun, Doheny Eye Institute,  
Los Angeles, California, USA

Pierre Joliot, Institute de Biologie

Physico-Chimique, Fondation Edmond  
de Rothschild, Paris, France

Lajos Keszthelyi, Institute of Biophysics, Hungarian  
Academy of Sciences, Szeged, Hungary

Paul W. King, Biosciences Center and Photobiology  
Group, National Renewable Energy Laboratory,  
Golden, Colorado, USA

Robert S. Knox, Department of Physics  
and Astronomy, University of Rochester, Rochester,  
New York, USA

Aaron Lewis, Department of Applied Physics,  
Hebrew University, Jerusalem, Israel

Stuart M. Lindsay, Department of Physics  
and Astronomy, Arizona State University,  
Tempe, Arizona, USA

David Mauzerall, Rockefeller University,  
New York, New York, USA

Eugenie V. Mielczarek, Department of Physics  
and Astronomy, George Mason University, Fairfax,  
Virginia, USA

Markolf Niemz, Medical Faculty Mannheim,  
University of Heidelberg, Mannheim, Germany

V. Adrian Parsegian, Physical Science Laboratory,  
National Institutes of Health, Bethesda,  
Maryland, USA

Linda S. Powers, University of Arizona,  
Tucson, Arizona, USA

Earl W. Prohofsky, Department of Physics,  
Purdue University, West Lafayette, Indiana, USA

Tatiana K. Rostovtseva  
NICHD, National Institutes of Health,  
Bethesda, Maryland, USA

Andrew Rubin, Department of Biophysics, Moscow  
State University, Moscow, Russia

Michael Seibert, National Renewable Energy  
Laboratory, Golden, Colorado, USA

David Thomas, Department of Biochemistry,  
University of Minnesota Medical School,  
Minneapolis, Minnesota, USA

Bharat Bhushan

# Biophysics of Skin and Its Treatments

Structural, Nanotribological, and  
Nanomechanical Studies

 Springer

Bharat Bhushan  
Nanoprobe Laboratory for Bio- &  
Nanotechnology and Biomimetics  
The Ohio State University  
Columbus, OH  
USA

ISSN 1618-7210                      ISSN 2197-5647 (electronic)  
Biological and Medical Physics, Biomedical Engineering  
ISBN 978-3-319-45706-2            ISBN 978-3-319-45708-6 (eBook)  
DOI 10.1007/978-3-319-45708-6

Library of Congress Control Number: 2016949581

© Springer International Publishing Switzerland 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer imprint is published by Springer Nature  
The registered company is Springer International Publishing AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

*To my grandkids Sahana,  
Ashwin, and Joya*

# Preface

Skin is the outer layer covering human or animal body and is a complex biological structure. Its function is to protect the body from physical and environmental assaults and to provide sensation, heat regulation, water resistance, and so on. Environmental conditions, such as dry and cold weather, can reduce the moisture content of skin and increase the skin roughness and physical discomfort. Skin is damaged as it goes through daily activities. Skin also ages with time. For healthy and beautiful human skin, cleaning and maintenance of skin is a daily process. Various beauty care products involve surface interaction between the product and the skin surface they are applied to. Skin cream is used to improve the skin health and create a smooth, soft, and flexible surface with moist perception by altering the surface roughness, adhesion, friction, elasticity, and surface charge of the skin surface. Rheology of skin cream as a function of cream thickness and strain rate and the binding interaction between skin cream and skin surface and operating environment are some of the important factors affecting the smooth feel and repair of the skin surface. The vibrations generated during the rubbing are a function of friction at the interface and govern the tactile perception of skin texture by the brain.

Atomic force microscopy (AFM) and nanoindentation have recently become important tools for studying micro-/nanoscale properties in beauty care, including human hair, hair conditioner, skin, and skin cream. In this book, we present an overview of the structural, nanotribological, and nanomechanical properties of skin with and without cream treatment as a function of operating environment. Relevant mechanisms are discussed. The result of a triboelectrification study of skin with and without cream treatment is presented. Next, an overview of attempts to develop a synthetic skin for research purposes is presented. Finally, data on tactile response of skin with and without cream treatment are presented.

This is the first book on nanotribological and nanomechanical properties of skin and skin treatment. The book is written for a novice in the field. It should serve as a reference book for researchers, practitioners, and users.

The author would like to thank his former students and senior colleagues who contributed to the research reported in the book. These include Prof. Shirong Ge, Dr. Wei Tang, Dr. Si Chen, and Shuyang Ding. The author would also like to thank Renee L. Ripley for many important contributions during the preparation of the manuscript.

Powel, OH, USA

Bharat Bhushan



# Contents

<b>1</b>	<b>Introduction</b> . . . . .	1
1.1	Tribological and Mechanical Properties and Triboelectric Effects. . . . .	2
1.2	Tactile Perception . . . . .	4
1.3	Application of Skin Cream, Tactile Perception, and Role of Tribology . . . . .	5
1.4	Organization of the Book . . . . .	7
	References. . . . .	7
<b>2</b>	<b>Skin and Skin Cream</b> . . . . .	11
2.1	Skin . . . . .	11
2.2	Pig and Rat Skin . . . . .	16
2.3	Skin Cream. . . . .	16
2.4	Synthetic Skin for Cosmetics Science. . . . .	19
	References. . . . .	20
<b>3</b>	<b>Experimental Techniques</b> . . . . .	25
3.1	Animal Skins and Skin Creams . . . . .	25
3.1.1	Animal Skin . . . . .	25
3.1.2	Damaged Skin. . . . .	27
3.1.3	Various Skin Creams and Cream Treatment Procedure . . . . .	27
3.2	Synthetic Skin Samples . . . . .	29
3.2.1	Synthetic Skin-1 . . . . .	29
3.2.2	Synthetic Skin-2 . . . . .	30
3.3	Physical Characterization . . . . .	31
3.3.1	Contact Angle Measurements . . . . .	31
3.3.2	Dynamic Viscosity Measurements. . . . .	31
3.3.3	Nanoscale Surface Roughness, Friction, Adhesive Force, and Wear Resistance Measurements. . . . .	32
3.3.4	Film Thickness, Adhesive Forces, and Young's Modulus Mapping. . . . .	33

3.3.5	Macroscale Friction and Wear Resistance (Durability) Measurements . . . . .	36
3.3.6	Nanomechanical Properties Measurements . . . . .	36
3.3.7	Surface Potential Measurements . . . . .	38
3.3.8	Humidity and Temperature Control. . . . .	40
	References. . . . .	40

**Part I Rat Skin—Virgin**

<b>4</b>	<b>Adhesion, Friction, and Wear of Rat Skin With and Without a Common Cream Treatment. . . . .</b>	<b>47</b>
4.1	A Common Cream Treatment. . . . .	47
4.1.1	Surface Roughness and Friction on the Nanoscale . . . . .	47
4.1.2	Effect of the Duration of Cream Treatment on Film Thickness and Effect of Cream Film Thickness, Velocity, and Normal Load on Adhesion and Friction on the Nanoscale. . . . .	49
4.1.3	Effect of Relative Humidity and Temperature on Adhesion and Friction on the Nanoscale . . . . .	52
4.1.4	Wear Resistance on the Nanoscale . . . . .	53
4.1.5	Effect of Cream Film Thickness, Velocity and Normal Load on Friction as Well as Wear Resistance on the Macroscale. . . . .	55
4.1.6	Summary. . . . .	58
4.2	Various Cream Treatments . . . . .	58
4.2.1	Duration of Cream Treatment, Adhesion, Friction, Dynamic Viscosity and Wear Resistance on the Nanoscale. . . . .	59
4.2.2	Effect of Relative Humidity on Film Thickness, Adhesive Forces and Effective Young’s Modulus Mappings on the Nanoscale . . . . .	62
4.2.3	Summary. . . . .	66
	References. . . . .	66
<b>5</b>	<b>Nanomechanical Properties of Rat Skin With and Without a Common Cream Treatment. . . . .</b>	<b>69</b>
5.1	Nanoscratch . . . . .	69
5.2	Nanoindentation . . . . .	71
5.3	In Situ Tensile Measurements. . . . .	72
5.4	Summary . . . . .	74
	References. . . . .	75

**6 Triboelectrification of Rat Skin With and Without a Common Cream Treatment. . . . . 77**

6.1 Understanding of Triboelectric Charge Generation Between Skin and Polystyrene . . . . . 77

6.2 Effect of Velocity, Load, and Rubbing Time in Macroscale and Microscale Rubbing. . . . . 78

6.2.1 Surface Potential Maps . . . . . 78

6.2.2 Effect of Skin Cream Treatment . . . . . 81

6.2.3 Comparison of Macroscale and Microscale Rubbing Data . . . . . 83

6.2.4 Effect of Velocity, Normal Load, and Rubbing Time on Absolute Surface Potential . . . . . 83

6.3 Effect of Relative Humidity on Surface Potential in Microscale Rubbing . . . . . 84

6.4 Summary . . . . . 86

References. . . . . 86

**Part II Rat Skin and Pig Skin—Virgin and Damaged**

**7 Friction, Wear, and Nanomechanical Properties of Virgin and Damaged Rat Skin and Pig Skin With and Without a Common Cream Treatment. . . . . 91**

7.1 Surface Roughness, Contact Angle, Friction, and Wear Properties With and Without a Common Cream Treatment—Rat Skin . . . . . 91

7.1.1 Surface Roughness, Contact Angle, and Nanoscale Friction . . . . . 91

7.1.2 Effect of Velocity, Normal Load, Relative Humidity, and Number of Cycles on Nanoscale Friction. . . . . 94

7.1.3 Macroscale Friction and the Effect of Velocity, Normal Load, and Number of Cycles . . . . . 97

7.2 Surface Roughness, Contact Angle, and Friction Properties with a Common Cream Treatment—Pig Skin . . . . . 99

7.2.1 Surface Roughness, Contact Angle, and Nanoscale Friction . . . . . 99

7.2.2 Effect of Velocity, Normal Load, Relative Humidity, and Number of Cycles on Nanoscale Friction. . . . . 100

7.2.3 Macroscale Friction and Effect of Velocity, Normal Load, and Number of Cycles . . . . . 102

7.3 Nanomechanical Properties of Rat and Pig Skin. . . . . 104

7.4 Summary . . . . . 106

References. . . . . 107

**Part III Synthetic Skin**

**8 Nanotribological and Nanomechanical Characterization of Synthetic Skins With and Without Common Cream Treatment for Cosmetic Science. . . . . 111**

8.1 Surface Roughness and Contact Angle for Rat Skin, Pig Skin, Synthetic Skin-1, and Synthetic Skin-2 . . . . . 111

8.2 Coefficient of Friction, Adhesive Force and Film Thickness for Rat Skin, Pig Skin, Synthetic Skin-1, and Synthetic Skin-2. . . . . 114

8.3 Adhesive Force and Film Thickness Maps for Rat Skin, Pig Skin, Synthetic Skin-1, and Synthetic Skin-2 . . . . . 114

8.4 Nanomechanical Properties of Rat Skin, Pig Skin, Synthetic Skin-1, and Synthetic Skin-2. . . . . 116

8.5 Summary . . . . . 119

References. . . . . 119

**Part IV Skin Tactile Perception**

**9 Skin Vibrations Created During Touch. . . . . 123**

9.1 Introduction . . . . . 123

9.2 Experimental Apparatus and Procedure . . . . . 123

9.2.1 Artificial Finger. . . . . 124

9.2.2 Vibration Sensor Selection . . . . . 124

9.2.3 Description of Tribometer Apparatus and Procedure . . . . . 125

9.3 Results and Discussion. . . . . 127

9.3.1 PMMA, Pig Skin, and Synthetic Skin with and Without Cream Treatment . . . . . 128

9.3.2 Effect of Normal Load and Velocity . . . . . 130

9.3.3 Effect of Cream Treatment Time. . . . . 134

9.4 Summary . . . . . 135

References. . . . . 135

**Part V Closure**

**10 Overall Summary and Outlook . . . . . 139**

**Appendix A: Primer to Tribology . . . . . 141**

**Subject Index. . . . . 161**

## About the Author



**Dr. Bharat Bhushan** received an M.S. in mechanical engineering from the Massachusetts Institute of Technology in 1971; an M.S. in mechanics and a Ph.D. in mechanical engineering from the University of Colorado at Boulder in 1973 and 1976, respectively; an MBA from Rensselaer Polytechnic Institute at Troy, NY in 1980; Doctor Technicae from the University of Trondheim at Trondheim, Norway, in 1990; a Doctor of Technical Sciences from the Warsaw University of Technology at Warsaw, Poland, in 1996; and Doctor Honouris Causa from the National Academy of Sciences at Gomel, Belarus, in 2000 and

University of Kragujevac, Serbia, in 2011. He is a registered professional engineer. He is presently an Ohio Eminent Scholar and The Howard D. Winbigler Professor in the College of Engineering, and the Director of the Nanoprobe Laboratory for Bio- & Nanotechnology and Biomimetics (NLB<sup>2</sup>) and affiliated faculty in John Glenn College of Public Affairs at the Ohio State University, Columbus, Ohio. In 2013–2014, he served as an ASME/AAAS Science and Technology Policy Fellow, House Committee on Science, Space and Technology, United States Congress, Washington, DC. His research interests include fundamental studies with a focus on scanning probe techniques in the interdisciplinary areas of bio-/nanotribology, bio-/nanomechanics, and bio-/nanomaterials characterization and applications to bio-/nanotechnology, and biomimetics. He is an internationally recognized expert of bio-/nanotribology and bio-/nanomechanics using scanning probe microscopy and is one of the most prolific authors. He is considered by some a pioneer of the tribology and mechanics of magnetic storage devices. He has authored 8 scientific books, 90+ handbook chapters, 800+ scientific papers (Goggle Scholar h-index—105+ with 50k+ citations; Web of Science h-index—80+; ISI Highly Cited Researcher in Materials Science since 2007 and in Biology and Biochemistry, 2013; ISI Top 5% Cited Authors for Journals in Chemistry, 2011), and 60+ technical reports. He has also edited 50+ books and holds 20 US and foreign patents. He

is a coeditor of Springer NanoScience and Technology Series and coeditor of Microsystem Technologies, and member of Editorial Board of PNAS. He has given more than 400 invited presentations on six continents and more than 200 keynote/plenary addresses at major international conferences.

Dr. Bhushan is an accomplished organizer. He organized the 1st Symposium on Tribology and Mechanics of Magnetic Storage Systems in 1984 and the 1st Int. Symposium on Advances in Information Storage Systems in 1990, both of which are now held annually. He organized two international NATO institutes in Europe. He is the founder of an ASME Information Storage and Processing Systems Division founded in 1993 and served as the founding chair during 1993–1998. His biography has been listed in over two dozen Who's Who books including Who's Who in the World. He has received more than two dozen awards for his contributions to science and technology from professional societies, industry, and US government agencies including Life Achievement Tribology Award and Institution of Chemical Engineers (UK) Global Award. His research was listed as the top ten science stories of 2015. He is also the recipient of various international fellowships including the Alexander von Humboldt Research Prize for Senior Scientists, Max Planck Foundation Research Award for Outstanding Foreign Scientists, and Fulbright Senior Scholar Award. He is a foreign member of the International Academy of Engineering (Russia), Byelorussian Academy of Engineering and Technology, and the Academy of Triboengineering of Ukraine; an honorary member of the Society of Tribologists of Belarus and STLE; a fellow of ASME, IEEE, and the New York Academy of Sciences; and a member of ASEE, Sigma Xi, and Tau Beta Pi.

Dr. Bhushan has previously worked for Mechanical Technology Inc., Latham, NY; SKF Industries Inc., King of Prussia, PA; IBM, Tucson, AZ; and IBM Almaden Research Center, San Jose, CA. He has held visiting professorship at University of California at Berkeley; University of Cambridge, UK; Technical University Vienna, Austria; University of Paris, Orsay; ETH Zurich, EPFL Lausanne; University of Southampton, UK; University of Kragujevac, Serbia; Tsinghua University, China; Harbin Institute, China; and KFUPM, Saudi Arabia. <https://nlbb.engineering.osu.edu/>

# Chapter 1

## Introduction

Skin is the outer layer covering a human or animal body. It is the largest organ and for humans covers an average surface area of 1.5–2 m<sup>2</sup>. Its function is to protect the body from physical and environmental assaults, and to provide sensation, heat regulation, water resistance, and other such functions. Skin ages over time, resulting in changes in skin properties. The skin aging process is the result of two biological processes called intrinsic aging, where changes accumulate over a lifetime, and extrinsic aging, attributed to environmental influences. Aging is a degeneration of tissue (such as degradation of mechanical properties as a result of decreases in collagen) and loss of lipids (responsible for creating a water barrier), and leads to various issues such as sagging skin and wrinkles. In addition to aging, skin also is damaged as it goes through various daily activities. Environmental conditions, such as dry and cold weather, can reduce the moisture content of skin temporarily, and can induce epidermal hyperplasia, mast cell degranulation, cytokine secretion, increased skin roughness, and physical discomfort (Harding et al. 2000; Leyden and Rawlings 2002; Tang and Bhushan 2010; Bhushan 2012; Bhushan et al. 2012).

For healthy and beautiful human skin, cleaning and maintenance of skin is a daily process. The demand for skin care products that prevent or relieve skin damage has created a \$2 billion dollar industry in the U.S. alone, as of 2015. As commonly-used skin care products, skin cream and moisturizer increase the moisture content in the outer layer of skin. This hydration creates a smooth, soft, moist, and flexible surface, and alters the tribological properties (surface roughness, adhesion, friction, and wear) and mechanical properties (elastic modulus, hardness, and viscous damping) of the skin surface. Hydration changes the surface feel or tactile perception of cream treated skin when it touches a surface. Beauty care science is interested in the way in which skin cream changes the tribological and mechanical properties, tactile perception, and the effect of the operating environment of skin, as these properties are closely tied to product performance and, ultimately, guide consumers' likes or dislikes of the product (Bhushan et al. 2010,